UNIVERSIDADE ESTADUAL PAULISTA

Instituto de Geociências e Ciências Exatas

Campus de Rio Claro

EMPOBRECIMENTO E PODZOLIZAÇÃO DE SOLOS LATERÍTICOS DA BACIA DO RIO NEGRO E GÊNESE DOS PODZÓIS NA ALTA BACIA AMAZÔNICA

GUILHERME TAITSON BUENO

Orientadores: Nádia Regina do Nascimento (UNESP-Brasil)
Emmanuel Fritsch (IPGP-França)

Tese elaborada junto ao Programa de Pós-Graduação em Geografia, Área de Concentração em Análise Espacial (UNESP-Brasil), e ao Programa de Pós-Graduação em Ciências da Terra, Área de Concentração em Geoquímica Fundamental e Aplicada (IPGP-França) (regime de co-tutoria, convênio CAPES-COFECUB) para obtenção do título de Doutor em Geografia e em Ciências da Terra

Rio Claro (SP)
2009

551.41 Bueno, Guilherme Taitson
B928e Empobrecimento e podzolização de solos lateríticos da bacia do Rio Negro e gênese dos podzóis na alta Bacia Amazônica / Guilherme Taitson Bueno. - Rio Claro : [s.n.], 2009
157 f. : il., gráfs., tabs., fots., mapas

Tese (doutorado) - Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas
Orientador: Nádia Regina do Nascimento
Orientador: Emmanuel Fritsch

1. Ciência do solo. 2. Podzóis da Amazônia. 3. Podzolização. 4. Mineralogia. 5. Geoquímica. 6. Evolução da paisagem. I. Título.

Ficha Catalográfica elaborada pela STATI - Biblioteca da UNESP
Campus de Rio Claro/SP

Comissão Examinadora

Profa. Dra. Nádia Regina do Nascimento (orientadora)

Dr. Emmanuel Fritsch (orientador)

Dr. Marc Benedetti

Prof. Dr. Antônio José Teixeira Guerra

Dr. Georges Calas

Dr. Ary Bruand

Prof. Dr. Adolpho José Melfi

Dra. Sylvie Derenne

Guilherme Taitson Bueno
Aluno (a)

Paris, 6 de maio de 2009

Resultado: aprovado

RESUMO

Os podzóis (espodossolos) apresentam horizontes arenosos sobre níveis pouco permeáveis enriquecidos em matéria orgânica e metais. Ocupam grandes superfícies da alta bacia amazônica, sob influênica de lençóis suspensos e meios redutores e ácidos. Este trabalho trata da: (i) pré-podzolização, ou empobrecimento prévio dos solos lateríticos (latossolos); (ii) formação de podzóis sobre platôs, posteriormente dissecados pelos rios; (iii) dinâmica dos podzóis na escala da bacia do Rio Negro. Integra abordagens geoquímicas, petrográficas e mineralógicas, estudos de solos e de unidades de paisagem. A erosão química, mas, também, particulada, dos solos lateríticos, crescente da borda ao centro podzolizado dos platôs, afeta, separadamente, solos e saprolitos. O amarelecimento e o empobrecimento do solo devem-se à dissolução dos óxidos de Fe (hematita e depois goethita), e da caolinita. O desenvolvimento de lençóis suspensos no saprolito favorece o empalidecimento dos materiais e, os escoamentos laterais, a eluviação. Produzem reservatórios arenosos, explorados pela podzolização. A posterior incisão dos podzóis hidromórficos ativa a mineralização da matéria orgânica, a oxidação do Fe, e o aporte de areias aos rios. O desenvolvimento dos podzóis na bacia pode ser anterior à rede de drenagem moderna do Amazonas (2,5 Ma BP). Sua posterior incisão posterior teria limitado sua expansão lateral e fornecido areias brancas ao Rio Negro.

Palavras-chave: Amazônia, podzolização, mineralogia, geoquímica, evolução da paisagem

ABSTRACT

Podzols present spectacular morphology, with sandy horizons over less permeable and organo-metallic compartments. They occupy important surfaces of the upper Amazon basin, under the influence of perched watertables and reducing/acidic environments. This work focuses on: (i) lateritic soils impoverishment before podzolisation; (ii) hydromorphic podzol development on the plateaux and their latter incision; and (iii) podzol dynamics in the Rio Negro catchment scale. It associates geochemical, petrographic and mineralogical approaches, with investigations of soil catena and landscapes units. The increasing chemical but also particulate erosion of lateritic soils from the edge to the podzolised plateaux centre affect, separately, soils and saprolites. Selective dissolution of iron oxydes (hematite, then goethite), and ultimately of kaolinite, are associated with soil yellowing and impoverishment. In the saprolites, the groundwater promotes the material bleaching, and lateral flows, close to podzols, its eluviation. Chemical and physical erosions generate sandy horizons explored by podzolisation. River incisions into podzols enhance organic matter mineralisation, iron oxidation and the sand transport to the rivers. The apparition of podzols may preceed the formation of modern Amazon River system (2,5 Ma BP). Ultimate incisions of podzols restrict their spatial expansion and fill with white sands the Rio Negro sediment traps.

Keywords: Amazônia, podzolisation, mineralogy, geochemistry, landscape evolution

RÉSUMÉ

Les podzols sont des sols à morphologie spectaculaire présentant des horizons sableux sur des niveaux peu perméables, enrichis en matière organique et métaux. Ils occupent de grandes surfaces dans le haut bassin amazonien. Leur formation est attribuée à l'existence des nappes propices à des accumulations organo-métalliques en milieu réducteur et acide. Le travail traite: (i) de la pré-podzolisation (appauvrissement préalable des latérites); (ii) de la formation des podzols sur plateaux, posterieurement incisés par le reseau hydrographique; (iii) de la dynamique de ces podzols dans le bassin du Rio Negro. Il intègre des approches géochimiques, pétrographiques et minéralogiques, des études de séquences de sols et d'unités de paysages (terrain et traitement d'images). L'érosion chimique mais aussi particulaire des latérites, accrue depuis la bordure vers le centre des plateaux à podzols affecte séparément sols et saprolites. Le jaunissement et l'appauvrissement des sols sont attribués à la dissolution des oxydes de fer (hématite puis goethite) puis des kaolinites. Le développement des nappes dans les saprolites favorise le blanchiment et, leurs écoulements latéraux, l'éluviation. Ces érosions génèrent des réservoirs sableux en "double langue" qui vont être exploités par la podzolisation. L'incision posterieure de ces podzols hydromorphes par le reseau hydrographique active la minéralisation des matières organiques, l'oxydation du fer et l'apport de sable aux rivières. La distribution des podzols est fortement controlée par la pluviometrie et la géologie. Leur apparition peut être antérieure à l'établissement du réseau moderne de drainage de l'Amazone (2,5 Ma BP). L'incision posterieure des aires podzolisées aurait limitée leur expansion et alimentée en sable blanc le Rio Negro.

Mots-clés: Amazônia, podzolisation, mineralogie, géochimie, évolution du paysage

SUMARIO

Página

INTRODUCTION

Le bassin amazonien est l'un des plus grands bassins des surfaces émergées de la planète, avec une superficie totale d'environ 6,5 millions de km^2. Situé dans la zone tropicale forestière et en grande partie protégé des activités anthropiques, ce bassin contrôle les principaux cycles biogéochimiques de la planète (dont le cycle du carbone). Il constitue de ce fait une région emblématique pour aborder l'étude de ces cycles, et révéler d'une part les processus majeurs qui contrôlent la dynamique des métaux et des matières organiques et d'autre part l'impact du forçage anthropique (déforestation, effets de serre et changement climatique) sur la dynamique de ces processus et sur les re-mobilisations de matières aux interfaces atmosphère, biosphère, hydrosphère et lithosphère. Le fleuve Amazone exporte par ailleurs des quantités considérables de matières à l'océan (13,5 t/sec). Si les quantités de matières exportées par l'Amazone à l'océan Atlantique sont essentiellement attribuées à la surrection et érosion des Andes, des études récentes tendent à montrer que d'importantes quantités de matières ont pu également être remobilisées au sein des couvertures latéritiques du bassin et être exportées par érosion chimique au réseau hydrographique. Les processus associés à de telles exportations agissent essentiellement dans les régions amont les plus pluvieuses du bassin et la podzolisation marque le stade ultime de cette "fonte géochimique". La diversité des processus d'altération et d'érosion mis en jeu dans ce bassin est illustrée par la très célèbre "rencontre des eaux" ("*encontro das águas*") de la région de Manaus (partie centrale et amont du moyen basin amazonien) (Fig. 1a). Sur plusieurs kilomètres se rejoignent sans se mélanger les eaux brunes issues de l'érosion physique des sols andins et les eaux noires qui, comme nous le verrons par la suite, sont étroitement reliés à une érosion chimique et interne du sol et au développement de podzols au sein des paysages latéritiques du haut bassin amazonien.

Sur les 6,5 millions de km^2 du bassin, 4 millions de km^2 appartiennent au Brésil, ce qui représente prêt de la moitié de la surface de ce pays. Si les connaissances sur le milieu naturel des régions Sud, Sud Est et Nord Ouest du Brésil, qui regroupent la majeure partie de la population et des activités économiques du pays, sont très détaillés, celles portant sur les milieux amazoniens restent encore éparses. Le premier inventaire systématique des ressources naturelles de cette immense région forestière, souvent difficile d'accès, a été programmé dans les années 1970 par le gouvernement brésilien dans le cadre du Projet RadamBrasil. Ce projet a nécessité des moyens logistiques importants (dont avions et hélicoptères) et a mobilisé un nombre considérable de chercheurs de toutes disciplines (botanistes, géologues, pédologues,

géomorphologues, hydrologues…). Il a permis d'évaluer les ressources de cette grande région naturelle, où prédominent des plateaux de faibles altitudes associés à d'immenses réserves d'eau, et de révéler par la même occasion toute la diversité et complexité d'organisation de ses différentes composantes (roches, sédiments, végétations, sols et paysages) (Figs 2a et b).

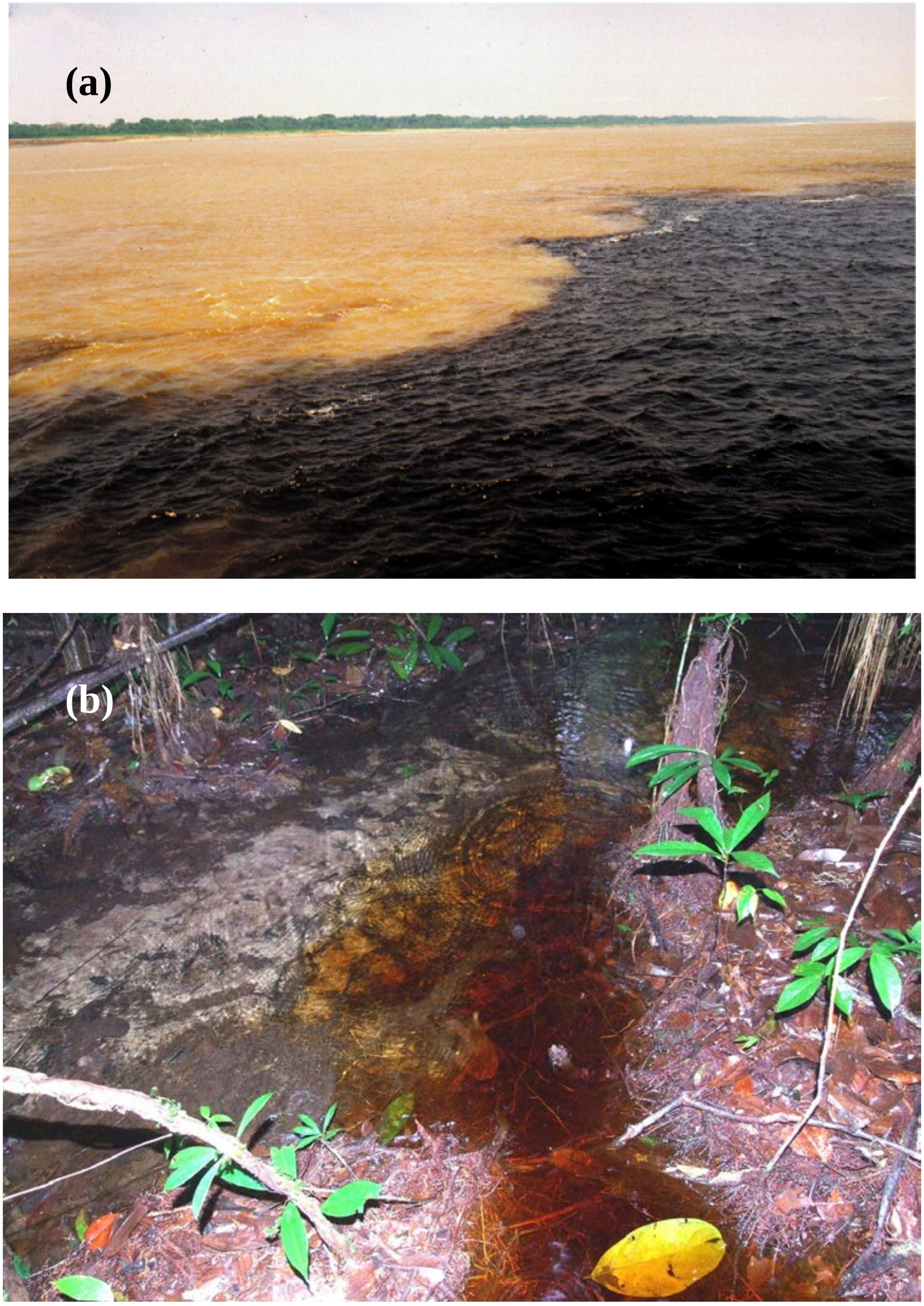


Figure 1*. La rencontre des eaux (a) à l'amont du fleuve Amazone et à l'aval de la ville de Manaus où les eaux noires du Rio Negro (à droite) rejoignent les eaux brunes du Rio Solimões (à gauche) (provenance Th Allard) et (b) au niveau d'une confluence de ruisseaux dans les bas plateaux (région de São Gabriel da Cachoeira) où les eaux noires des aires podzoliques (à droite) rejoignent les eaux claires des latérites (à gauche).*

La diversité des structures et ressources de cet écosystème est illustrée par les nombreux documents cartographiques et légendes élaborés dans le cadre de ce projet. La carte, établie à l'échelle 1 :2.500.000, permet d'avoir une perception d'ensemble du milieu physique et biologique du bassin. Des cartes plus détaillées à l'échelle 1 :1.000.000 donnent une vision plus précise des organisations régionales. Comme nous allons le voir dans ce mémoire, ces documents riches d'informations très variées sont à l'origine de travaux plus détaillés, en particulier sur les sols. Ces dernières entreprises sur des sites pilotes comprenant petites unités de paysages (ou bassin versants élémentaires) et séquences de sols, orientées sur des axes de plus forte pente (le plus souvent d'un pôle haut et bien drainé vers un pôle bas et mal drainé), sont de plus en plus nombreuses (Lucas *et al.,* 1984; 1988; 1996; Bravard & Righi, 1989; 1990; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1998; Nascimento *et al.,* 2004; Montes *et al.,* 2007). Elles ont révélé les processus associés à la mobilité des éléments majeurs et en traces dans différents types d'écosystèmes, mais ont également montré, dans certains cas, l'inexactitude des documents RadamBrasil dans la caractérisation de certaines structures ou les interprétations qu'on en donne. Cela a en particulier amené le Département National de Recherche Minérale (Departamento Nacional de Pesquisa Mineral : DNPM) à réviser la carte géologique du bassin en différentiant au sein de la formation Solimões une nouvelle formation plus récente : la formation Içá. Cette dernière marque l'un des derniers épisodes sédimentaires du Tertiaire. Comme nous le verrons par la suite, elle aura une importance considérable sur la compréhension de la genèse des sols du bassin.

Les documents du Projet RadamBrasil et les images satellitaires de plus en plus nombreuses et variées montrent que l'idée d'une Amazonie couverte par une forêt homogène et monotone est fausse. La forêt sempervirente, qui recouvre sur de très grandes surfaces les bas plateaux et les versants creusés par le réseau de drainage, est localement associée à des couverts végétaux plus bas, quelquefois étonnamment ouverts, où les sols sont exposés à l'érosion hydrique et éolienne. A ce titre, des paysages tout à fait insolites ont été reconnus dans le haut bassin du Rio Negro où de vaste étendues dépourvues de végétation font apparaître des dunes de sables blancs. La comparaison des différents documents cartographiques du Projet RadamBrasil suggère que la diversité du couvert forestier reflète des hétérogénéités lithologiques, des gradients pluviométriques mais surtout et aussi, une grande diversité d'altérites et de sols. Les cartes du projet RadamBrasil et les études plus ponctuelles sur séquence de sols montrent en effet qu'il existe une distribution ordonnée des sols à l'échelle des paysages et également une distribution ordonnée de ces paysages à l'échelle du bassin amazonien (Fig. 3).

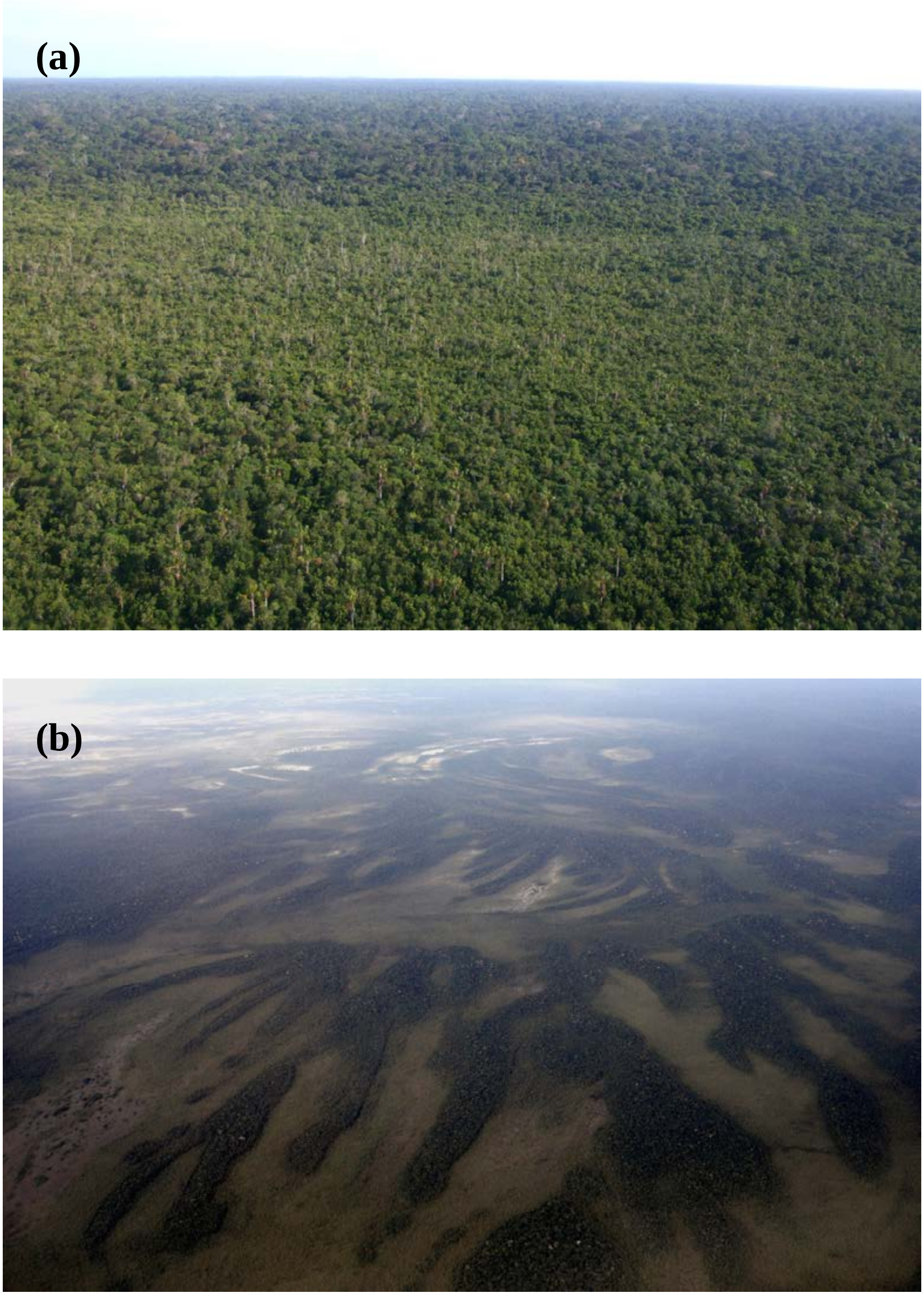


Figure 2. Diversité des paysages amazoniens : (a) Végétations de caatinga sur podzols (premier plan) et de fôret sur latérites (arrière plan), bas plateaux de la région de São Gabriel da Cachoeira ; (b) Bandes végétales en concordance avec les structures sédimentaires fluvio-lacustres de la formation Içá, région de Barcelos.

Les sols latéritiques les plus typiques (Latosols ou Ferralsols rouges, argileux et bien drainés) sont essentiellement présents à la périphérie du bassin et sont associés à des sols

hydromorphes (Gleys) dans les principaux axes de drainage et plaines alluviales. Ces latérites épaisses ont tendance à jaunir dans la partie centrale du bassin.

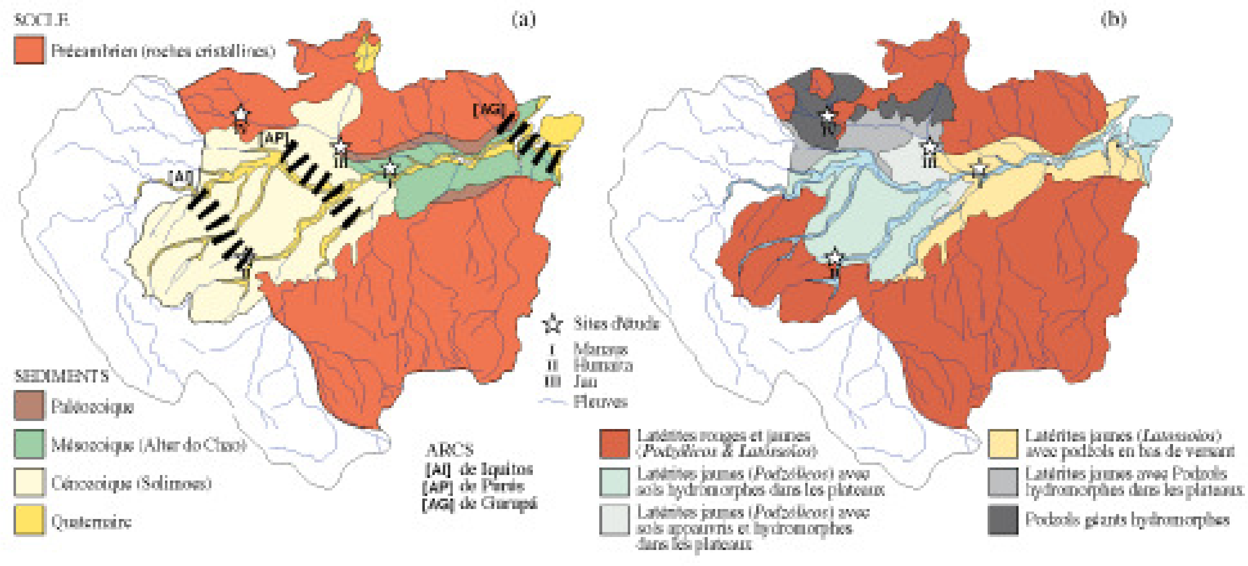


Figure 3. *Les roches (a) et les sols (b) du bassin amazonien brésilien (documents réduits et simplifiés à partir des cartes RadamBrasil au 1 :2.500.000) montrant l'extension des formations sédimentaires, la distribution des latérites rouges et jaunes et l'extension des zones hydromorphes et podzoliques dans la partie amont et centrale du bassin. (Fritsch et al., 2002).*

Sur des formations continentales plus récentes du haut bassin amazonien (Formation Içá), les formations latéritiques moins épaisses des bas plateaux amazoniens sont étroitement associées à des sols hydromorphes (Plinthosols, Gleys). Plus au nord dans le bassin du Rio Negro, les latérites s'appauvrissent en éléments fins (Ultisols) et se podzolisent (Podzols hydromorphes). Les podzols sont généralement situés sur les bas plateaux amazoniens. Dans la partie médiane du bassin du Rio Negro, ces podzols sont peu développés et s'observent, comme les sols hydromorphes (Gleys), dans les dépressions de ces plateaux (région du Jaú). Dans sa partie amont et plus pluvieuse (région de São Gabriel da Cachoeira), les podzols ont une extension beaucoup plus importante et sont directement connectés aux axes de drainage principaux du bassin du Rio Negro. Ils occupent alors de vastes pénéplaines inondées et les sols latéritiques n'apparaissent plus que sous la forme de collines résiduelles ou de reliques de rebords de plateaux. Dans la partie aval du bassin du Rio Negro (région de Manaus), les podzols sont généralement absents des plateaux. Ils sont par contre identifiés dans les bas de versants de ces plateaux. Ces distributions relatives de sols dans les paysages montrent ainsi que la mise

en place et la dégradation ultérieure des latérites du bassin amazonien peuvent être reliées à quatre processus majeurs : (1) la latéritisation, (2) l'appauvrissement, (3) l'oxydo-réduction et (4) la podzolisation.

Dans l'optique d'une meilleure connaissance de ces processus, des sols et des fonctionnements hydro-biogéochimiques qui leur sont associés, des projets scientifiques conjoints entre chercheurs brésiliens et français ont été élaborés. Ces projets étaient engagés de longue date dans les régions de Manaus et São Gabriel da Cachoeira (Lucas *et al.,* 1984, 1988, 1996; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1999). Ils ont été étendus en 1996 à l'ensemble du haut bassin amazonien dans le cadre d'un accord de coopération CNPq/IRD associant le Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera de l'Université de São Paulo et l'Unité de Recherche 12 "Géoscience de l'Environnement Tropical" du Département TOA de l'IRD (ex ORSTOM) sur un projet de recherche intitulé "Organisation et fonctionnement hydro-biogéochimique des couvertures latéritiques d'Amazonie" (Dylat Amazonie). Ils ont été ultérieurement financés par des projets FAPESP, PRONEX, et ECCO, et ont aussi reçu l'appui de l'Institut de Minéralogie et de Physique des Milieux Condensés (IMPMC) de Paris dans le cadre de la caractérisation minéralogique et spectroscopique des échantillons de sols. En 2004, ces travaux se sont progressivement focalisés sur l'étude des systèmes podzoliques d'Amazonie plus particulièrement dans le cadre d'un projet CAPES-COFECUB intitulé : "Podzolisation des latérites du haut bassin amazonien : Etudes des mécanismes et facteurs contrôlant la dynamique évolutive des podzols et les exportations de matières dans les têtes de rivières du bassin versant du Rio Negro et des dépôts de kaolins associés".

Les travaux, engagés dans le cadre de ces projets, correspondent essentiellement à des études multi-échelles de quatre sites pilotes (étoiles dans Fig. 3) : (1) région de Manaus, (2) région de Porto Velho, (3) région du Jaú et (4) région de São Gabriel da Cachoeira. Les sites (1) et (2) ont permis de mieux caractériser les processus de latéritisation et d'oxydo-réduction (Fritsch *et al.,* 2002, 2007). Dans le site (1) (région de Manaus), la latéritisation a été attribuée à des paragenèses affectant les principales phases minérales de ces sols, i.e. les kaolinites (Balan et al. 2005) et les oxydes de fer (Fritsch *et al.,* 2005). Cette latérisation a transformé des formations sédimentaires très anciennes (formation Alter do Chão, fin Crétacé – début Tertiaire) en latérites très épaisses (Latosols). Les latérites montrent de nombreuses failles normales liées à la réactivation de failles plus profondes, elles-mêmes associées à la mise en place du graben amazonien. Ces latérites sont localement affectées par l'hydromorphie

(développement au sein de ces latérites de poches réduites au-dessus de raies ferrugineuses) (Fritsch *et al.,* 2002). Dans le site (2) (région de Porto Velho), les latérites se sont formées sur des formations sédimentaires beaucoup plus récentes (Formation Içá) et sont de ce fait beaucoup moins épaisses (< 1m). A l'inverse, l'hydromorphie est beaucoup plus développée, en particulier dans les dépressions des bas plateaux amazoniens (Fritsch *et al.,* 2007). Les sites (3) et (4) ont par ailleurs permis d'étudier plus en détail l'appauvrissement et la podzolisation des couvertures latéritiques. L'étude du site (3) (région du Jaú), à laquelle j'ai contribué, a permis dans un premier temps de définir les grandes étapes dans la mise en place des "îlots" podzoliques des bas plateaux amazoniens (Nascimento *et al.*, 2004). La mise en place de ces podzols a pu être reliée au développement de nappes perchées en milieu réducteur et acide et la caractérisation géochimique de ces nappes a permis de mieux comprendre les mécanismes associés à la mobilisation des matières organiques et des métaux au sein des sols et des eaux noires qui les drainent (Nascimento *et al.*, 2008). Cette compréhension dans le fonctionnement hydro-biogéochimique de ces podzols hydromorphes a été fortement améliorée dans le cadre de la caractérisation des principaux groupements fonctionnels des matières organiques du sol (Bardy *et al.,* 2008) et dans l'étude de leur aptitude à complexer l'aluminium (Bardy *et al.*, 2007) et le fer (Fritsch *et al.*, 2009).

Figure 4*. Les eaux noires et les sables blancs (région de Barcelos) issus de l'érosion chimique et physique des vastes étendues podzolisées de la partie amont du bassin du Rio Negro (région de São Gabriel da Cachoeira).*

Les travaux présentés dans ce mémoire traitent essentiellement du site (4) (région de São Gabriel da Cachoeira). Ces travaux sont de ce fait complémentaires de ceux engagés dans le site (3) (région du Jaú). Comme nous l'avons déjà signalé, le site 4 est caractérisé par une extension optimale des podzols dans les paysages. Ces podzols sont alors directement reliés au réseau hydrographique principal du Rio Negro. Ils alimentent ce dernier en eaux noires mais aussi en sables blancs (Fig. 4). L'étude de ce quatrième site a permis de mieux comprendre les interactions entre les deux moteurs principaux de la morphogenèse des paysages dans cette partie du bassin amazonien : (1) la transformation des modelés en réponse à l'érosion chimique due à l'expansion latérale des systèmes podzoliques dans les paysages latéritiques, et (2) le processus d'incision des bas plateaux par le réseau hydrographique qui a de ce fait tendance à drainer ces formations hydromorphes. Nous avons par ailleurs étudié les mécanismes associés à l'appauvrissement préalable des couvertures latéritiques, comme processus majeur de pré-podzolisation. Enfin nous avons resitué ces processus d'appauvrissement et de podzolisation à l'échelle du haut bassin amazonien et ceci en relation avec l'histoire géodynamique de ce bassin. Cette étape ultime nous a amené à regrouper l'ensemble des travaux obtenus sur deux site-clés du bassin du Rio Negro ((3) et (4)), en associant études régionales (documents cartographiques) et études plus ponctuelles (de transects et séquences de sols sur des unités représentatives des paysages).

INTRODUÇÃO

A bacia amazônica é uma das maiores bacias hidrográficas da superfície emersa do planeta, com uma área total de cerca de 6,5 milhões de km^2. Situada na zona das florestas tropicais e em grande parte protegida das atividades antrópicas, essa bacia controla os principais ciclos biogeoquímicos do planeta (dentre eles o ciclo do carbono). Ela constitui, por isso, uma região emblemática para abordar o estudo destes ciclos e revelar, por um lado, os processos maiores que controlam a dinâmica dos metais e da matéria orgânica e, por outro, o impacto da pressão antrópica (desmatamento, efeito estufa e mudança climática) sobre a dinâmica destes processos e sobre a remobilização de matéria na interface atmosfera, biosfera, hidrosfera e litosfera. O rio Amazonas exporta quantidades consideráveis de matéria para o oceano (13,5 t/s). Se as quantidades de matéria exportadas pelo Amazonas para o oceano Atlântico são atribuídas essencialmente à orogênese e à erosão dos Andes, estudos recentes tendem a mostrar que importantes quantidades de matéria são também remobilizadas a partir das coberturas lateríticas da bacia e exportadas por erosão química para a rede hidrográfica. Os processos associados a estas exportações agem essencialmente nas regiões mais chuvosas da parte de montante da bacia e a podzolização marca o último estágio desta perda geoquímica. A diversidade de processos de alteração e de erosão que atuam nesta bacia é ilustrada pelo célebre “encontro das águas”, na região de Manaus (parte central da bacia amazônica) (Fig. 1a). Por mais de 60 km, as águas provenientes da erosão física dos Andes se encontram sem se misturar com as águas “negras” que, como veremos a seguir, estão estreitamente associadas à erosão química e interna do solo e ao desenvolvimento de podzóis nas paisagens lateríticas da alta bacia amazônica.

Dos 6,5 milhões de km^2 da bacia, 4 milhões de km^2 pertencem ao Brasil, o que corresponde a quase a metade da área deste país. Se o conhecimento dos meios naturais das regiões Sul, Sudeste e Nordeste do Brasil, que concentram a maior parte da população e das atividades econômicas do país, pode ser considerado satisfatório, o conhecimento dos meios amazônicos é ainda esparso e pouco detalhado. O primeiro inventário sistemático dos recursos naturais desta imensa região de florestas, quase sempre de difícil acesso, foi realizado nos anos 1970 pelo governo brasileiro no âmbito do Projeto RadamBrasil. Este projeto exigiu importantes meios de logística (como aviões e helicópteros) e a mobilização de uma vasta equipe de pesquisadores de diferentes áreas de conhecimento (botânicos, geólogos, pedólogos, geomorfólogos, hidrólogos...). Ele permitiu avaliar os recursos desta imensa região natural,

onde predominam platôs de baixas altitudes associados a imensas reservas de água, e revelar toda a diversidade e a complexidade de organizações de seus diferentes componentes (rochas, sedimentos, vegetações, solos e paisagens) (Fig. 2a e b). A diversidade das estruturas e recursos destes ecossistemas é ilustrada por numerosos documentos cartográficos e legendas elaborados por este amplo projeto. As cartas à escala 1:2.500.000 permitiram uma percepção do conjunto do meio físico e biológico da bacia. Cartas mais detalhadas, à escala 1:1.000.000 fornecem uma visão mais precisa das organizações regionais. Estes documentos, ricos em informações bastante variadas, serviram de base para trabalhos mais detalhados, particularmente sobre os solos. Estas investigações, realizadas em sítios-chave em pequenas unidades de paisagem (bacias elementares) e seqüências de solos ao longo de vertentes (frequentemente partindo de um pólo de montante, bem drenado, rumo a um pólo de jusante, mal drenado), são cada vez mais numerosas (Lucas *et al.*, 1984, 1988, 1996; Bravard & Righi, 1989, 1990; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.*, 1999; Nascimento *et al.*, 2004; Montes *et al.*, 2007). Elas revelaram os processos associados à mobilidade de elementos maiores e em traços nos diferentes ecossistemas, mas mostraram, ainda, em alguns casos, as imprecisões dos documentos do Projeto RadamBrasil na caracterização ou na interpretação de certas estruturas. Este último fato justifica posteriores revisões destes documentos, como a realizada pelo Departamento Nacional de Pesquisa Mineral (DNPM) sobre a carta geológica da bacia, que propôs a diferenciação de uma nova formação, mais recente, no interior da formação Solimões: a formação Içá. Esta formação marca os últimos episódios sedimentares do Terciário. Como será visto adiante, ela tem grande importância para a compreensão da gênese dos solos da bacia.

Os documentos do Projeto RadamBrasil e as imagens de satélite cada vez mais numerosas e detalhadas mostram que a idéia de uma Amazônia coberta por uma floresta homogênea e monótona é falsa. A floresta sempervirente, que cobre amplas superfícies dos baixos platôs e das vertentes abertas pela rede de drenagem, é associada a coberturas vegetais mais baixas, algumas vezes surpreendentemente abertas, onde os solos são expostos à erosão hídrica e eólica. Campos de dunas de areias brancas sem cobertura vegetal (região de Santa Isabel do Rio Negro, por exemplo), em meio à floresta constituem paisagens insólitas da alta bacia do Rio Negro. A comparação de diferentes documentos cartográficos do Projeto RadamBrasil sugere que a diversidade da cobertura vegetal reflete as heterogeneidades litológicas, os gradientes pluviométricos mas, sobretudo, uma grande diversidade de materiais de alteração e de solos.

As cartas do Projeto RadamBrasil e os estudos pontuais sobre sequencias de solos mostram que existe uma distribuição ordenada dos solos na escala da paisagem e, igualmente, uma distribuição ordenada destas paisagens na escala da bacia amazônica (Fig. 3). Os solos lateríticos mais típicos (Latossolos ou Ferralsols vermelhos, argilosos e bem drenados) são presentes essencialmente na periferia da bacia e estão associados aos solos hidromórficos (Gleissolos) ao longo dos principais eixos de drenagem e planícies aluviais. Estes solos lateríticos espessos tendem a ficar mais amarelos na parte central da bacia. Sobre as formações continentais mais recentes da alta bacia amazônica (Formação Içá), as formações lateríticas menos espessas dos baixos platôs amazônicos estão estreitamente associadas a solos hidromórficos (Plintossolos e Gleissolos). Mais ao norte, na bacia do Rio Negro, os solos lateríticos se empobrecem em elementos finos (Ultisols) e se podzolizam (Podzóis hidromóficos). Os podzóis se encontram geralmente sobre os baixos platôs amazônicos. Na parte média da bacia do Rio Negro estes solos são pouco desenvolvidos e ocupam, como os solos hidromórficos (Gleissolos), zonas deprimidas sobre estes platôs (região do Jaú). Na parte de montante e mais chuvosa (região de São Gabriel da Cachoeira), os podzóis têm uma extensão muito mais importante e estão diretamente conectados aos eixos de drenagem principais da bacia do Rio Negro. Eles ocupam vastos peneplanos inundados onde os solos lateríticos aparecem apenas como colinas residuais ou faixas relictuais nas bordas dos platôs. Na parte de jusante da bacia do Rio Negro (região de Manaus), os podzóis geralmente não aparecem sobre os platôs. Eles existem nas partes baixas e médias de vertentes elaboradas pelas incisões da rede de drenagem nestes platôs. Esta distribuição relativa de solos na paisagem mostra que a elaboração e a degradação posterior dos solos lateríticos da bacia amazônica pode ser associada a quatro processos maiores: (1) lateritização, (2) empobrecimento, (3) óxido-redução e (4) podzolização.

Na ótica de um melhor conhecimento destes processos, dos solos e dos funcionamentos hidro-biogeoquímicos a eles associados, foram elaborados projetos científicos em que colaboram pesquisadores brasileiros e franceses. Estes projetos têm início a partir dos anos 80 para a região de Manaus (Lucas et al., 1984; 1988; 1996) e dos anos 90 para a região de São Gabriel da Cachoeira (Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1999). Eles foram estendidos em 1996 ao conjunto da alta bacia amazônica no âmbito de um acordo de cooperação BNPq/IRD associando o Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera de l'Université de São Paulo e a Unidade de Pesquisa 12 (Unité de Recherche 12 "Géoscience de l'Environnement Tropical") do Departamento TOA do IRD (ex-ORSTOM) em um projeto de

pesquisa intitulado "Organização e funcionamento hidro-bioquímico das coberturas lateríticas da Amazônia (Dylat Amazonie). Eles foram posteriormente financiados por projetos FAPESP, PRONEX e ECCO e receberam também o apoio do Instituto de Mineralogia e Física dos Meios Condensados de Paris (IMPMC) para a caracterização mineralógica e espectroscópica de amostras de rocha e solo. Em 2004 estes trabalhos passaram a focalizar particularmente o estudo dos sistemas podzólicos da Amazônia, mais particularmente no âmbito de um projeto intitulado "Podzolização das lateritas da alta bacia amazônica: estudos dos mecanismos e fatores que controlam a dinâmica evolutiva dos podzóis e as exportações de matéria nas cabeceiras de drenagem da bacia do Rio Negro e os depósitos de caolim associados".

Os trabalhos desenvolvidos nestes projetos correspondem essencialmente a estudos em várias escalas de quatro sítios-chave (estrelas na Fig. 3): (1) região de Manaus, (2) região de Porto Velho, (3) região do Jaú e (4) região de São Gabriel da Cachoeira. Os sítios (1) e (2) permitiram melhor caracterizar os processos de lateritização e de óxido-redução (Fritsch *et al.,* 2002, 2007). No sítio (1) (região de Manaus), a lateritização foi associada às paragêneses que afetam as principais fases minerais destes solos, i.e. as caolinitas (Balan *et al.,* 2005) e os óxidos de Fe (Fritsch *et al.,* 2005). Esta lateritização transformou formações sedimentares muito antigas (Formação Alter do Chão, do final do Cretáceo-começo do Terciário em coberturas lateríticas muito espessas). Essas coberturas lateríticas móveis (ou solos lateríticos) apresentam numerosas falhas normais ligadas à reativação de falhas profundas, associadas ao estabelecimento do graben amazônico. Estes solos lateríticos são localmente afetados pela hidromorfia (desenvolvimento de zonas redutoras na forma de bolsas sobre camadas finas ferruginosas). No sítio (2) (região de Porto Velho), os solos lateríticos se formam sobre formações sedimentares muito mais recentes (Formação Içá) e são muito menos espessas (< 1 m). Inversamente, a hidromorfia é muito mais desenvolvida, particularmente nas depressões dos baixos platôs amazônicos (Fritsch *et al.,* 2007). Os sítios (3) e (4) permitiram o estudo mais detalhado do empobrecimento e da podzolização das coberturas lateríticas. O estudo do sítio (3) (região do Jaú), em que participei como colaborador, permitiu definir as grandes etapas da elaboração das "ilhas" podzolizadas dos baixos platôs amazônicos (Nascimento *et al.,* 2004). A instalação destes podzóis pôde ser associada ao desenvolvimento de lençóis suspensos em meio redutor ácido e a caracterização geoquímica destes lençóis permitiu uma melhor compreensão dos mecanismos associados à mobilização da matéria orgânica e dos metais nos solos e nas águas negras que os drenam (Nascimento *et al.,* 2008). Esta

compreensão do funcionamento hidro-biogeoquímico destes podzóis hidromórficos foi aprofundada com a caracterização das principais funções estruturais da matéria orgânica do solo (Bardy *et al.,* 2008) e com o estudo da aptidão das mesmas para a complexação do alumínio (Bardy *et al.,* 2007) e do ferro (Fristsch *et al.,* 2009).

Os resultados apresentados neste trabalho tratam essencialmente do sítio (4) (região de São Gabriel da Cachoeira). Estes trabalhos são complementares daqueles desenvolvidos no sítio (3) (região do Jaú). Como já assinalado, este sítio se caracteriza pela extensão máxima dos podzóis na paisagem. Estes podzóis estão diretamente ligados à rede de drenagem principal do Rio Negro. Eles alimentam este rio não somente em águas negras, mas, também, em areias brancas (Fig. 4). O estudo deste quarto sítio permitiu compreender melhor as interações entre os dois principais motores da morfogênese das paisagens nesta parte da bacia amazônica: (1) a transformação dos relevos em resposta à erosão química e à expansão lateral dos sistemas podzólicos nas paisagens lateríticas e (2) o processo de incisão dos baixos platôs pela rede hidrográfica, que tem como conseqüência a drenagem das formações hidromórficas. Foram estudados, ainda, os mecanismos associados ao empobrecimento dos solos lateríticos, como processo maior de pré-podzolização. Finalmente, os processos de empobrecimento e de podzolização foram situados espacialmente na escala da alta bacia amazônica e temporalmente na história geodinâmica desta bacia. Esta última etapa nos conduziu a reagrupar o conjunto dos trabalhos produzidos nestes dois sítios-chave da bacia do Rio Negro (3) e (4) associando estudos regionais (documentos cartográficos) e estudos pontuais (estudos de transeções e de seqüências de solos em unidades representativas das paisagens).

OS CINCO CAPITULOS DA TESE

Les résultats de cette étude sont regroupés dans cinq chapitres :

Le **Chapitre 1** est une brève revue bibliographique qui présente les podzols (distribution et horizons diagnostiques) et les mécanismes le plus souvent invoqués dans la mise en place de ces sols.

Le **Chapitre 2** présente le cadre naturel de cette étude. Il traite des grands ensembles structuraux du bassin amazonien, de ses sols et des processus majeurs (latérisation, appauvrissement, oxydo-réduction, podzolisation et incision du modelé) impliqués dans l'érosion chimique et physique des paysages.

Le **Chapitre 3** traite de l'appauvrissement des latérites comme étape préalable à la podzolisation. Cette étude a été réalisée dans la région de São Gabriel da Cachoeira (site (4)) à la bordure des aires fortement podzolisées du bassin versant du Curicuriari (bassin versant podzolisé sur prêt de 95% de sa superficie).

Le **Chapitre 4** présente les résultats d'une étude minéralogique et structurale d'une séquence de sols entreprise dans la même région (site 4) au niveau d'une relique de sols latéritique, dans un paysage fortement podzolisé et incisé par le réseau hydrographique. Cette étude a pour objectif de montrer les effets de ces incisions sur la morphologie des podzols et sur la dynamique de ces sols (rabattement des nappes perchées). Elle traitera en particulier des analogies et différences par rapport à ce qui a déjà été étudié sur le site (3) du Jaú.

Le **Chapitre 5** est un essai de reconstitution de la dynamique des podzols dans le bassin du Rio Negro à partir des études ponctuelles obtenues sur des séquences de sols (sites 3 et 4), de documents cartographiques obtenues à des échelles régionales et des connaissances actuelles sur l'histoire géodynamique et géologique du bassin amazonien.

VALORIZAÇÃO DOS RESULTADOS

Les résultats présentés dans cette thèse ont donné lieu à l'écriture de trois articles destinés à paraître dans des revues internationales. Ces articles constituent l'ossature de cette thèse. Ils sont brièvement introduits en début des Chapitres 3, 4 et 5 :

Chapitre 3

Yellowing, bleaching and clay depletion of laterites in the Negro River Catchment (upper Amazon Basin). Preliminary steps to Podzolisation. G. Bueno, E. Fritsch, N.R. DO Nascimento, M.E. Almeida & B.S. Arenare.

Chapitre 4

Podzolisation of clay depleted laterites and physical denudation of Podzols in the high rainfall region of the upper Negro River watershed. G. Bueno, E. Fritsch, N.R. DO Nascimento & A.J. Melfi.

Chapitre 5

Weathering and erosion in major Cenozoic land surfaces and genesis of waterlogged Podzols in the Negro River Catchment (upper Amazon Basin). G. Bueno, E. Fritsch, N.R. DO Nascimento, A.J. Melfi & G. Calas.

CAPITULO 1. PODZOIS E PODZOLIZAÇÃO

1.1. Définition

Le nom "Podzol" vient du russe "pod" pour sous et de "zola" pour cendre et caractérise de ce fait des sols présentant des horizons de sub-surface cendreux ou blanchis par des agents organiques acides (FAO, 1998). Ces sols sont vraisemblablement les plus connus de la planète du fait de leur morphologie spectaculaire avec la présence d'horizons éluviés, blanchis (aussi connu sous le terme d'horizons albiques) qui recouvrent plus en profondeur des horizons illuviés, brun foncé à brun rouge, enrichis en humus et parfois aussi en sesquioxydes (horizons également qualifiés de spodiques) (Fig. 5).

Le terme "Podzol" est utilisé dans la plupart des systèmes de classification des sols, en Russie bien sûr, mais aussi en Europe et par la FAO. La "Soil Taxonomy" américaine préfère néanmoins parler de "Spodosols" en référence aux horizons spodiques qui, comme nous le verrons, sont les horizons diagnostiques des podzols.

1.2. Morphologie et concept

Les podzols présentent deux catégories d'horizons : (1) des horizons supérieurs éluviés comprenant le plus souvent des horizons organiques de type Mor enrichis en résidus organiques (L, O, AE) et des horizons minéraux albiques (E), sans cohésion, essentiellement constitués de résidus quartzeux et minéraux lourds, et (2) des horizons inférieurs illuviés (Bh et Bs) enrichis en substances humiques acides susceptibles d'altérer les minéraux argileux du sol et de former des complexes organo-métalliques. Cette distribution relative indique ainsi des mécanismes de transfert ("chéluviation") et d'accumulation ("chilluviation"). L'illuviation de substances organiques en profondeur est confirmée par la présence de revêtements ou cutanes qui coiffent les quartz ou remplissent les interstices ménagés par ces derniers (Bardy *et al.*, 2008). Ces revêtements sont très fins, brun rouge, souvent craquelés sur lames minces dans les horizons Bs les plus profonds des podzols. Ils sont noirs, plus grossiers (fibres ou boulettes), dans les horizons Bh qui les surmontent, à la base des réservoirs sableux (Buurman & Jongmans, 2005; Bardy *et al.*, 2008). Ces horizons illuviés, aussi qualifiés d'horizons spodiques, sont riches en humus et en métaux (Duchaufour, 1982; Petersen, 1984; Macias-Vasquez, 1987). Deux critères géochimiques majeurs sont généralement requis pour les horizons spodiques des podzols (FAO, 1998): (1) des teneurs en carbone organique supérieures à 6 g/kg et (2) des rapports Al_o+1/2Fe_o supérieurs à 5, où "Al_o" et "Fe_o" réfèrent respectivement aux quantités d'aluminium et de fer extraites par le traitement oxalate (c.a.d. aux formes complexées aux matières organiques et aux oxydes mal cristallisés). Ces horizons peuvent de ce fait être considérés comme des zones d'accumulation de métaux (principalement Al mais aussi Fe), qui sont majoritairement chélatés à des groupements organiques (formation de complexes organo-métalliques).

Les associations entre substances organiques et phases minérales résiduelles du sol sont très tranchées entre horizons éluviés et illuviés. Dans les horizons éluviés, les résidus organiques sont nettement dissociés des quartz blancs. Dans ces niveaux organo-minéraux de surface ou de subsurface, les horizons présentent alors un aspect "poivre et sel" très caractéristique (horizons humifères ponctués de blanc). Dans les horizons illuviés, les substances organiques, souvent assimilées à des humus de faible ou haut poids moléculaire (e.g. acides fulviques, acides humiques et humine), recouvrent les grains de quartz. En masquant les quartz, ces substances organiques peuvent ainsi nous amener à surestimer visuellement les quantités de matières organiques accumulées dans les horizons spodiques de ces sols (Nascimento *et al.*, 2004).

Figure 5*. Les podzols de la partie médiane des aires podzolisées (profile IV) de la séquence du Curicuriari (site 4) montrant en surface les horizons humifères éluviés (AE), puis l'horizon blanchi ou albique (E) et les horizons spodiques en profondeur: l'horizon noir Bh et les horizons brun rouge BCs (noter entre ces deux horizons la naissance d'un nouvel horizon éluvié, gris clair)*

Dans les horizons éluviés organiques et minéraux (AE et E), les pHs sont généralement bas (< 4), les groupements hydroxyles des composés organiques sont protonés (prédominance de fonctions carboxyliques, faible occurrence de carboxylates), les phases argileuses du sol ont pratiquement disparues et les résidus grossiers organiques et minéraux (surtout quartz mais aussi minéraux lourds, tels que zircon et oxydes de Ti) tendent à s'accumuler. Dans les horizons illuviés ou spodiques, les pHs sont généralement plus élevés (> 4) et les métaux sont complexés (chélatés) aux substances organiques (prédominance de carboxylates). Une partie non négligeable de métaux peut également précipiter sous forme de composés inorganiques faiblement cristallisés, les plus connus correspondant aux ferrihydrites (à deux ou six raies sur spectres DRX) pour Fe et aux produits allophaniques (allophane, proto-imogolite et imogolite) pour Al (Ross, 1980; Buurman, 1987; Macias-Vasquez, 1987; Lundström ***et al.,***

2000). Ces gradients soulignent de ce fait le rôle essentiel du pH dans l'immobilisation ou la remobilisation des métaux lors d'une lixiviation et acidification ultime de ces sols (principalement pour Al) (Nascimento *et al.* 2004, 2008).

1.3. Les deux grands types de podzols

Les horizons spodiques des podzols doivent apparaître sous des horizons éluviés organiques (AE) ou minéraux (E) et montrer des évidences d'accumulation de matières organiques et de métaux pour que le processus central de podzolisation puisse être invoqué (Petersen, 1984 ; Lundström et al., 2000). Dès lors, deux grands types de podzols peuvent distingués suivant l'épaisseur de ces sols et l'absence ou présence d'horizon albique.

Dans les podzols peu évolués, les horizons éluviés et organiques de surface (A, AE) surmontent des horizons spodiques faiblement différenciés (Bhs). Ces sols peu épais, dépourvus d'horizon albique, marquent de ce faite une première étape dans le développement de la podzolisation (Nascimento *et al.*, 2004). Ils ont été qualifiés de sols crypto-podzoliques (Duchaufour, 1972) ou de podzols humiques (Thompson, 1992). Des podzols plus épais et mieux différenciés sont le plus souvent observés dans les paysages. Dans ces podzols, les horizons organiques éluviés et illuviés sont séparés par des horizons blanchis (albiques). D'autre part, les horizons illuviés sont nettement différenciés en deux types d'horizons spodiques : (1) des horizons humiques noirs (Bh) surmontant (2) des horizons brun-rouge riches en sequioxydes (Bs).

Enfin une troisième catégorie de podzols pourrait éventuellement être distinguée. Cette dernière catégorie marque une étape ultime dans le développement vertical des podzols dans les paysages. Elle correspond aux podzols géants, qui ont été identifiés en abondance dans la zone tropicale, plus particulièrement dans le haut bassin amazonien. Ces podzols sont caractérisés par la très grande épaisseur de ces horizons blancs, sableux (albiques) qui rendent de ce fait difficile la reconnaissance à plus grande profondeur des horizons spodiques (les horizons albiques, dépourvus de cohésion, tendent en effet à s'effondrer dans les fosses pédologiques ou lors de sondages). De tels sols ne sont en fait plus considérés comme des podzols dans la plupart des systèmes de classification. Ils ont été qualifiés d'arénosols dans les cartes pédologiques du projet RadamBrasil.

1.4. Régime hydrique et morphologie des podzols

Ils existent très peu de données sur le fonctionnement hydrique des podzols et donc sur les conditions redox qui ont pu contribuer à la mise en place de ces sols. De telles conditions (i.e. alternance aux rythmes des saisons d'épisodes anoxiques et oxiques) sont toutefois reconnues comme l'un des facteurs majeurs dans la différenciation verticale des sols. Il est néanmoins admis qu'il existe des podzols à nappes et des podzols bien drainés sans qu'un lien génétique ait pu être établi entre ces deux types de sols.

Dans les podzols à nappe, les contrastes de couleur entre horizons sont parfois tenus. En effet, les couleurs sont plus fades et sont nettement dominées par l'abondance de composés organiques brun foncé à noirs. La présence d'une nappe à faible profondeur est propice au développement de conditions réductrices et de ce fait à une grande mobilité du fer au sein de ces formations. Cet élément est exporté sous forme dissoute ou en association avec les composés organiques au réseau hydrographique lors d'écoulements hydriques latéraux (Nascimento *et al.,* 2004, Fritsch *et al.,* 2009). Les eaux de nappe baignant ces podzols, mais aussi les eaux de surface qui drainent ces aires podzoliques, ont alors une coloration noire caractéristique (Fig. 1b), attribuée à la présence d'acides fulviques et de colloïdes organiques en suspension dans les eaux (FAO, 1998; Allard et al., 2002; Benedetti *et al*., 2003a).

Dans les podzols bien drainés, les contrastes de couleur entre horizons sont plus forts et la morphologie de ces sols est de ce fait plus spectaculaire. La plus grande minéralisation des composés organiques dans ces sols limite leur accumulation dans les horizons spodiques, plus profonds. Ces composés masquent de ce fait moins les hétérogénéités texturales et structurales de ces sols. Par ailleurs, le développement à certaines périodes de l'année de conditions oxiques est propice à la précipitation du fer qui donne des colorations brun rouge à rouge vif aux horizons spodiques les plus profonds de ces sols (Bs). Des phénomènes d'induration ont parfois été invoqués. Par contre, la nature des agents de cimentation reste incertaine et mal définie (oxydes de fer et de Mn, complexes organo-métalliques …).

1.5. Mécanismes communément invoqués pour la podzolisation

La formation des podzols est généralement attribuée à l'accumulation et migration des substances organiques, à l'altération des phases argileuses résiduelles du sol et à la formation de composés mal cristallisés associés ou non aux phases organiques de ces sols (Gustafsson *et al.*, 1999; Lundström *et al.*, 2000, Van Hees & Lundström, 2000, Nascimento et al., 2004). Il n'existe toutefois pas de véritables consensus sur les zones des profils ou ces mécanismes sont susceptibles d'agir et sur la nature des substances organiques susceptibles de migrer et de fixer les métaux libérés par l'altération. Ceci a amené les scientifiques à proposer plusieurs modèles conceptuels de formation des podzols.

D'après Petersen (1984), de Coninck (1980) et Buurman (1987), les acides organiques à faible poids moléculaire sont des agents de transport du Fe et de l'Al sous forme complexée. Ces complexes organo-métalliques peuvent être immobilisés en profondeur (1) au niveau de discontinuités lithologiques, (2) par la diminution du rapport C/(Al+Fe) au fur et à mesure que les complexes migrent à travers le profil, ce qui conduit à la saturation des sites d'échange de la matière organique, à la neutralisation de leurs charges négatives et à la précipitation des complexes, (3) après la biodégradation de certains complexes organo-métalliques, ce qui libère des cations métalliques qui peuvent saturer d'autres complexes, les faisant moins biodégradables, ou précipiter sous forme inorganique, ou (4) par adsorption des substances organiques à la surface des imogolites dans les horizons spodiques, suivant la diminution de la capacité complexante des groupements carboxyliques après la diminution du pH en profondeur.

D'après Farmer (1980), Anderson et al., (1982) et Farmer (1987), les cations Al et Fe libérés en surface par l'altérations des phases argileuses forment des gels de haut poids moléculaires (formation en particulier de proto-imogolites). Ces gels migrent en profondeur et s'accumulent dans les horizons spodiques sous forme de ferrihydrites et/ou de produits allophaniques (surtout imogolite). La matière organique (principalement les acides fulviques) migre en profondeur et s'adsorbe à la surface des imogolites.

D'après Ugolini & Dahlgren (1987) et Lundström (1993), l'imogolite se forme dans les horizons spodiques après hydrolyse des minéraux argileux dans un milieu à forte pCO_2. Ces imogolites adsorbent des complexes organo-métalliques (acides fulviques + métaux) qui migrent depuis la surface.

1.6. Conditions de formation et répartition géographique

Les conditions propices à la migration et accumulation de complexes organo-métalliques dans les sols sableux des surfaces continentales et de ce fait à la formation de podzols sont grandement favorisées par des climats froids et humides, par des environnements de hautes montagnes, par des matériaux parentaux sableux et des couverts végétaux acides (e.g.

conifères et landes) (FAO, 1998). Les Podzols peuvent se former sur n'importe quel type de matériaux parentaux (Buurman, 1984). Toutefois, les sédiments sableux sont très propices à la formation de ces sols lorsque les autres conditions du milieu s'y prêtent (Pedro, 1987). Ils peuvent également se développer à partir d'autres types de sols qui ont été au préalable appauvris en éléments fins argileux (Turenne, 1977; Lucas *et al.,* 1989). L'influence de systèmes de nappes semble également être un élément prépondérant dans l'accumulation des matières organiques et la mise en place de ces sols.

Les podzols sont les sols zonaux des régions boréales, où ils sont communément associés aux dépôts morainiques des glaciers et aux forets à *Taïga* (Buurman, 1984; Pedro, 1987). Bien que la podzolisation des sols affecte de très grandes superficies dans cette partie émergée des surfaces continentales, ce processus n'est pas limité à ces régions froides et humides. En effet, il est bien connu que ce processus est actif dans toutes les régions humides de la planète (FAO, 1998), plus particulièrement dans les régions tempérées (e.g. Buurman, 1984 ; Righi, 1987), mais aussi dans les régions tropicales (Klinge, 1965; Schwartz, 1987; Bravard & Righi, 1990; Dubroeucq & Volkoff, 1998; Thomas, 1999), où de nombreux exemples de podzols géants ont été décrits (e.g. Klinge, 1965). Les podzols tempérés et tropicaux ont été qualifiés d'intrazonaux par Buurman (1984) et de podzols secondaires par Duchaufour (1982).

Les Podzols des régions tropicales ne figurent pas sur la plupart des cartes pédologiques établis à l'échelle du globe, alors qu'ils semblent occuper des superficies importantes dans les zones les plus pluvieuses de cette partie de la planète (e.g. Amazonie, Afrique centrale et Indonésie). Ces sols, relativement peu connus dans ces régions, n'ont entre autres été décrits qu'assez récemment à partir des années 1960. Ils se forment sur des matériaux beaucoup plus altérés et souvent plus profonds. Ils présentent de ce fait une minéralogie plus simple que celle des podzols boréaux et tempérés. En particulier, les horizons éluviaux (AE et E) de ces podzols sont constitués presque exclusivement de quartz et de quelques minéraux lourds, résistants à l'altération (zircon, rutile, anatase…). Dans les horizons spodiques et à la bordure des aires podzoliques, les matières organiques sont généralement associées aux minéraux secondaires les plus communément rencontrés dans la zone tropicale (i.e. kaolinite, gibbsite et goethite) (Turenne, 1977; Schwartz, 1987, 1988; Lucas *et al.,* 1989; Bravard & Righi, 1990; Dubroeucq & Volkoff, 1998; Nascimento *et al.,* 2004). Comme l'ont souligné Nascimento et al. (2004), la présence de composés allophaniques (imogolite, allophane) dans les horizons spodiques des podzols tropicaux n'a encore jamais été démontrée, probablement du aux

faibles quantités des cations présents dans les nappes perchées de ces podzols hydromorphes (Si, Al et Fe), ainsi qu'à la forte lixiviation et acidification de ces sols.

CAPÍTULO 2. SOLOS E PROCESSOS MAIORES DE ALTERAÇÃO E PEDOGÊNESE NO ALTO RIO NEGRO

2.1. Histoire géodynamique du bassin et principaux ensembles structuraux

Situé sous les tropiques, le bassin forestier amazonien a focalisé l'attention de la communauté scientifique brésilienne et internationale par la diversité des processus mis en jeu et des facteurs qui ont pu contrôler la mise en place de ses principaux ensembles structuraux. Ces facteurs sont étroitement associés à la géodynamique de la plaque sud américaine et les processus à l'altération, l'érosion et la déformation (flexure et fracture) de cette plaque. La formation du graben amazonien a, entre autres, été reliée à l'érosion des socles brésilien et guyanais et à une sédimentation massive dans la partie centrale et ouest du bassin à une époque où les écoulements se faisaient vers le Pacifique (Fig. 3a). La majeure partie des sédiments accumulés dans ce bassin correspond ainsi de nos jours aux vastes pénéplaines à faible gradient topographique du haut bassin amazonien. La subduction de la plaque de Nazca a initié au Tertiaire la formation de la chaîne montagneuse des Andes sur la bordure Ouest du bassin. La surrection de cette chaîne, toujours actuelle, a joué un rôle déterminant sur le climat, l'érosion et changé de façon irréversible le sens des écoulements des eaux dans le bassin (vers l'Atlantique). Les changements climatiques et les variations des niveaux de base au Quaternaire ont favorisé l'incision des pénéplaines et de ce fait formé les bas plateaux qui dominent le modelé du bassin. Le basculement définitif du réseau hydrographique au Pliocène (~ 2,5 Ma) a contribué à l'individualisation de chenaux fossiles et de vastes étendues ennoyées dans les sédiments du haut bassin amazonien (Campbell ***et al.,*** 2006, Fritsch ***et al.,***

2007), dans une région soumise alors à de forts gradients pluviométriques (1,5 m/an à l'Est, jusqu'à 6 m/an au Nord Ouest).

L'histoire géodynamique de ce bassin est ainsi à l'origine de la mise en place de ses principales formations sédimentaires. Les formations les plus anciennes, issues de l'érosion des socles brésilien et guyanais, affleurent de nos jours au nord et au sud du graben central (Formations Prosperança et Trombetas), lui-même comblé par une puissante formation Crétacé (Formation Alter do Chão). Des sédiments plus récents ont recouvert ces dépôts dans le haut bassin amazonien. Ils correspondent à l'une des plus vastes formations Tertiaires de la planète (Fig. 3a). Des travaux récents (Campbell *et al.,* 2006) ont révélé deux grands cycles sédimentaires pan-américains au Tertiaire, séparés par une longue période d'aplanissement qui a tronqué toutes les structures géologiques exposées à la surface ("*the Ucayali Peneplain*"). Ces cycles, reliés à la surrection des Andes, sont associés à deux événements tectoniques majeurs: Quechua I et Quechua II. Le premier événement tectonique (Quechua I) s'est achevé approximativement au Miocène moyen. Il a contribué à la mise en place des épais sédiments de la Formation Solimões. Le second événement (Quechua II) est relié à la surrection définitive des Andes (~ 9,5 Ma) qui a définitivement obturé les écoulements vers le Pacifique. En initiant la formation d'un méga-lac dans la partie centrale et aval du haut bassin amazonien, il marque le début de l'ultime sédimentation Tertiaire (Formaton Içá). Cette sédimentation, essentiellement attribuée à l'érosion des Andes, s'est achevée vers 2,5 Ma avec la naissance du réseau hydrographique actuel, qui a pu explorer les anciens axes de drainage ou en créer de nouveaux en incisant de ce fait profondément les vastes plaines sédimentaires du bassin (Fig. 6).

L'observation de la Figure 3 montre que la distribution actuelle des sols se cale grosso modo sur ces structures géologiques et sédimentaires (N.B. la Formaton Içá, identifiée en 1981 par le DNPM, n'a pas été représentée sur la Fig. 3a, elle correspond toutefois à l'extension des latérites à sols hydromorphes de la Fig. 3b, cf aussi Fritsch *et al.,* 2007). On voit en particulier que les latérites rouges les mieux drainées (en rouge dans la Fig. 3b) se sont essentiellement développées au Nord et au Sud sur les roches cristallines des socles guyanais et brésilien. A l'inverse, les autres sols qui font apparaître soit une tendance plus ou moins affirmée au jaunissement et à l'appauvrissement de la partie supérieure des latérites, soit une tendance plus affirmée à l'hydromorphie et à la podzolisation se développent de préférence sur les formations sédimentaires de ce bassin. Les formations podzoliques (en gris ou noir sur la Fig. 3b) semble néanmoins échapper à cette règle puisqu'on les retrouve de part et d'autre de la

limite entre formations sédimentaires au Sud et cristallines au Nord, dans les zones les plus pluvieuses du bassin. Comme nous le verrons dans ce mémoire, les sols hydromorphes à Gleys ou à Podzols s'observent soit dans les dépressions des bas plateaux amazoniens (cas très fréquents de certaines unités de paysages) soit en positions plus basses, sur les bas de versants et les dépôts alluviaux (sableux ou argileux) du Quaternaire. Les premiers systèmes sont partiellement confinés (drainés par un réseau épars de petits ruisseaux) tandis que les seconds sont ouverts et directement connectés aux principales rivières du bassin. A ces systèmes peuvent être reliées des séquences ordonnées de sols qui partiront soit du rebord vers le centre des plateaux (cas des plateaux à dépressions) soit de l'amont vers l'aval sur les versants du rebord de ces plateaux.

2.2. Les grandes catégories de sols, de végétation et de régimes hydriques

Les sols du bassin Amazonien peuvent être regroupés dans deux grandes catégories suivant la nature des processus d'altération mis en jeu et les régimes hydriques qui leurs sont associés. La première catégorie de sols correspond aux latérites, formations également connues sous les termes de sols ferrallitiques, de Latosols, d'Oxisols ou de Ferralsols. Ces formations occupent généralement les positions hautes les mieux drainées des paysages et sont reliées à des écoulements libres verticaux. Ces écoulements sont propices à une horizonation des sols, et donc à un développement vertical des processus d'altération. Le processus majeur associé à la formation de ces sols argileux et bien structurés est la latéritisation (Melfi & Pedro, 1977; Fanning & Fanning, 1989: Fritsch *et al.*, 2002, 2005). La deuxième catégorie de sols se situe en général dans les zones basses ou déprimées des paysages. Il est de ce fait étroitement lié à des engorgements permanents ou provisoires contrôlés par les apports pluviométriques et la capacité de ces sols à exporter l'eau au réseau hydrographique. L'altération et la pédogenèse sont alors contrôlées par la dynamique des nappes. Les écoulements d'eau et les exportations de matières sont essentiellement latéraux. Les Gleys et les Podzols sont de bons exemples de sols hydromorphes. Ils peuvent se développer verticalement à partir de matériaux sous-jacents, mais aussi latéralement à partir des formations latéritiques amont (Nascimento *et al.*, 2004). En accord avec Fanning & Fanning (1989), cela suggère que des sols puissent se former dans un premier temps (*soil forming processes*) puis se transformer ou se dégrader dans un second temps (*soil change processes*). Ce concept nouveau permet ainsi d'introduire la notion d'équilibre ou déséquilibre géodynamique pour les formations latéritiques et également de systèmes de transformation (Boulet *et al.*, 1982) ou transformants (Fritsch *et al.*,

1986). Dans les paysages latéritiques des régions humides du bassin amazonien, la pédogenèse semble ainsi favoriser l'exportation des éléments préalablement accumulés lors d'une phase d'intense latéritisation.

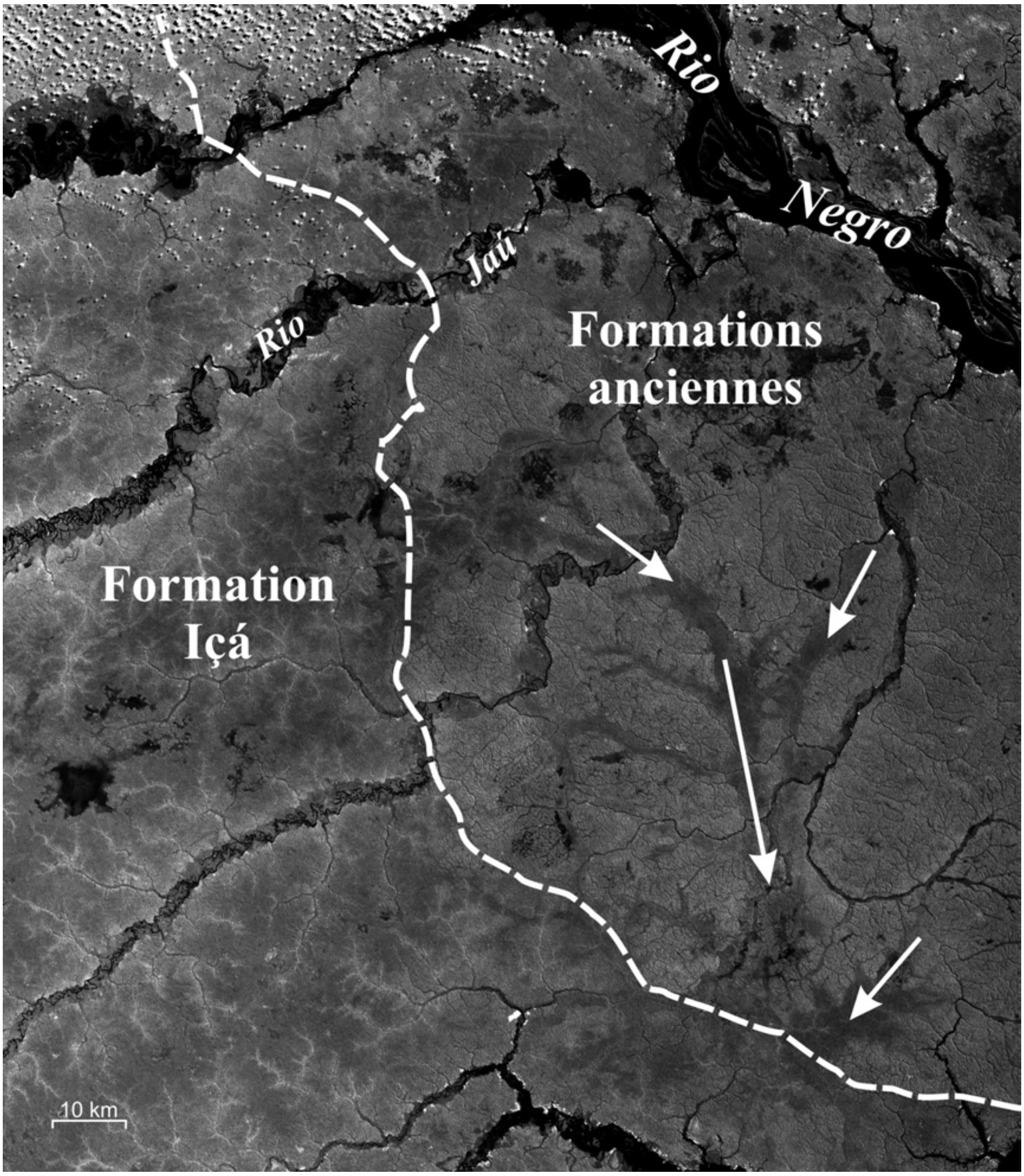


Figure 6. *Image Landsat d'un reseau fluvial fossile (zone foncée sous les fleches) installé sur les formations géologiques anciennes (Prosperança, Trombetas et Alter do Chão). Ce reseau est localement recoupé par le réseau de drainage actuel des bas plateaux de la région du Jaú. Noter des directions opposées pour les écoulements suggérant que les paléo chenals puissent être antérieurs à l'installation du réseau de drainage moderne du fleuve Amazone).*

La distribution de la végétation reflète très généralement cette distinct entre ces deux grandes catégories de sols (Fig. 2a). Par ailleurs, le type de régime climatique et de sol formé en

environnement hydromorphe semble également avoir une incidence notable sur le port du couvert végétal. Ainsi, les sols latéritiques bien-drainés (Ferralsols et Acrisols) soutiennent très généralement la forêt sempervirente (*Floresta de Terra Firme*) (Silva *et al.,* 1977). Sur les sols périodiquement engorgés (e.g. Gleys ou Podzols hydromorphes) se développent des couverts végétaux plus bas et ouverts que la forêt. Dans les podzols hydromorphes de la partie centrale de certains plateaux (cas par exemple du site (3) du Jaú, Nascimento *et al.,* 2004), la forêt laisse place à une végétation arbustive dense à la bordure des dépressions à podzols (*Campinarana*) puis à une savane arbustive ouverte (*Campina*) dans la partie saisonnièrement ennoyée de ces dépressions. Ces couverts arbustifs témoignent ainsi de stress hydriques plus marqués à l'aval de ces dépressions (Anderson, 1982), avec des périodes d'ultra-dessiccation en saisons sèches (faible capacité de rétention en eau du sable) et d'engorgements prolongés en saisons pluvieuses. Dans des régions plus pluvieuses à paysages plus fortement podzolisés mais également incisés par le réseau hydrographique (cas du site (4) de São Gabriel da Cachoeira), une forêt arborée plus haute, mais plus claire que la forêt sempervirente peut alors coloniser les aires podzoliques (*Caatinga*) (Fig. 2a). Ces distributions de végétations (Magnago *et al.,* 1978; Chauvel *et al.,* 1987) semblent ainsi être plus attribuables à des régimes hydriques contrastés entre latérites et podzols, voire même entre podzols hydromorphes et podzols drainés, qu'à des oscillations climatiques Quaternaires comme cela est généralement invoqué dans la littérature (Gouveia *et al.*, 1997).

2.3. Les latérites (Ferralsols) et la latéritisation

La latéritisation correspond à l'altération zonale des régions intertropicales humides ou à saisons contrastées du globe. Les latérites meubles ou indurées (e.g. cuirasses) sont les résidus de cette altération (Melfi & Pedro 1977, Fanning & Fanning 1989). Dans ces régions, les conditions de drainage ouvert à semi-ouvert, les températures élevées et les pHs modérément acides sont propices à une exportation totale des bases, partielle de la silice et une accumulation résiduelle du fer et de l'aluminium dans les minéraux secondaires du sol (essentiellement kaolinite, oxydes de Fe et d'Al) (Robinson 1949; Melfi & Pedro, 1977). Des éléments en trace (e.g. Zr, Ti, Th), présents dans des phases minérales peu altérables (e.g. zircon, oxydes de Ti ou de Th) (Balan *et al.,* 2001; Maurin *et al.*, 2005) ont également tendance à s'accumuler de façon relative dans ces profiles d'altération. Ils sont souvent utilisés comme invariants pour les calculs des bilans de masse (Brimhall & Dietrich 1987; Chadwick *et al.,* 1990). Les latérites meubles présentent des horizons organiques de type

mull. Ils sont fréquemment argileux et présentent verticalement de faibles gradients texturaux. Les oxydes de Fe intimement liés aux argiles forment avec ces derniers des structures polyédriques ou micro-agrégées stables (pseudo-particules, Beaudou & Chatelin, 1972) qui rendent les matrices poreuses et perméables.

Des travaux récemment engagés sur des latérites meubles de la zone intertropicale humide d'Amazonie ont également montré que les accumulations résiduelles de matières étaient aussi reliées à une dissolution ménagée des quartz et à des mécanismes de dissolution/recristallisation affectant les principales phases minérales secondaires de ces sols: la kaolinite (Balan *et al.,* 2005) et les oxydes de fer (Fritsch *et al.,* 2005). Ces transformations minéralogiques sont appréhendées sur le terrain par des variations progressives de texture et de couleur. Les variations texturales sont attribuées à une diminution progressive de la taille des particules de kaolinite de la base vers le sommet des profils latéritiques. Elles sont particulièrement marquées en profondeur à la transition entre les altérites et les sols. La diminution de la taille de ces particules a été reliée à un accroissement du désordre cristallin des kaolinites, lui-même attribué à des fautes d'empilement des feuillets de ce minéral (Balan *et al.,* 1999). Ces variations texturales ne peuvent s'expliquer que par des mécanismes de dissolution/recristallisation propices au remplacement d'anciennes populations de kaolinite de grande taille et dépourvu de fautes d'empilement par de nouvelles populations de kaolinite plus petites et fortement désordonnées. Les variations colorimétriques sont attribuées au jaunissement progressif des latérites rouges, particulièrement marquées dans la partie supérieure des profils d'altération. Ces changements, qui peuvent se faire sans perte des teneurs en fer, ont été attribués à la dissolution d'oxydes de fer faiblement substitués en aluminium (hematite et goethite) suivie par la recristallisation d'oxy-hydroxydes plus fortement substitués (goethite alumineuse) (Fritsch *et al.,* 2005). Lorsque l'accumulation d'aluminium dans les structures des oxyhydroxydes de fer est achevée (maximum de 33%), des hydroxydes d'aluminium (gibbsite) sont alors susceptibles d'être produits. Ces transformations témoignent d'une activité en aluminium et en eau plus élevée et, à l'opposé, d'une activité en silicium plus faible dans la partie supérieure de ces profils. Ces conditions d'altération qui restent propices à la dissolution des kaolinites ne sont par contre plus favorables à la recristallisation de nouvelles générations de phyllosilicates. Elles favorisent à l'opposé le piégeage de l'aluminium dans des phases minérales plus hydroxylées (goethite alumineuse puis gibbsite). Ces dernières témoignent d'un début de mobilité de l'aluminium dans ces profils d'altération.

2.4. Les latérites (Acrisols) et l'appauvrissement

Les latérites, précédemment décrites (Ferralsols), sont susceptibles de s'appauvrir en éléments fins et d'acquérir de ce fait des textures de plus en plus sableuses. L'appauvrissement en éléments fins peut se faire soit directement lors de l'altération de la roche (Wesemael *et al.,* 1995) soit par transformation latérale d'un autre sol (des latérites par exemple). Il donne naissance à des sols qui ont reçu différents qualificatifs: « *sandy bleached brown loam* » (Klinge, 1965), « sols ferrallitiques fortement désaturés, lessivés, intergrades » (Turenne, 1977), « sols intermédiaires ferrallitiques lessivés » (Lucas *et al.,* 1988), Ultisols (Bravard & Righi, 1990) ou Acrisols (Nascimento *et al.,* 2004). Ces sols présentent généralement des horizons organiques de type mull et des gradients texturaux avec ou sans évidence de transport particulaire, en particulier des revêtements argileux (cutanes d'illuviation) dans des horizons Bt plus profonds ou situés plus à l'aval dans les paysages. Deux processus majeurs sont généralement invoqués dans la littérature pour expliquer ces pertes de matières: (i) la lixiviation associée à des dissolutions de minéraux et au transport d'ions en solution (Plaisance & Cailleux, 1958) et (2) le lessivage attribué au transport de particules ou colloïdes en suspension (Aubert, 1954; Bocquier, 1971).

La lixiviation peut être relié au processus de latéritisation tel qu'il a été décrit dans le précédent paragraphe, dans la mesure ou les pertes en éléments dissous peuvent être reliées à une nette prédominance des dissolutions par rapport aux recristallisations de minéraux secondaires. Ces dissolutions seraient sélectives et affecteraient d'abord les oxydes de fer puis les kaolinites. Dans les latérites meubles, les pertes de matières associées à une remobilisation du fer sont souvent minimes. Elles ont néanmoins une répercussion importante sur la structuration et perméabilité du sol. En effet, le rôle agrégeant et stabilisant du fer (surtout hématite) sur la fraction fine du sol est reconnu depuis longtemps (Gombeer & D'Hoore, 1971; Van Ranst & De Coninck, 2002). Son exportation est généralement associée à une dissolution sélective des hématites et à un jaunissement du sol (Fritsch *et al.,* 1989; Peterschmitt *et al.,* 1996). Ce processus conduit à la rupture des liaisons fer-argile, à la destruction des agrégats du sol et à la prise en masse des matrices (Chauvel *et al.,* 1977; Fritsch *et al.,* 1989). La dissolution des kaolinites est un processus beaucoup plus lent qui s'opère vraisemblablement sur des temps géologiques (Balan *et al.,* 2005). Un autre processus est parfois invoqué pour expliquer les pertes importantes de minéraux argileux : La ferrolyse (Brinkman, 1970). Ce processus opère en deux grandes étapes: (i) le Fe^{2+} remplace d'abord des cations échangeables des argiles, qui sont lixiviés (phase réductrice), (ii) ce Fe^{2+} est

ensuite oxydé en Fe^{3+} (phase oxydante avec formation d'hydroxydes), et les protons H^+ occupent leur place dans les argiles. Cet environnement acide favorise la dissolution partielle de ces silicates (Brinkman, 1970; Van Breemen, 1985).

Les pertes en éléments fins entraînent une modification du type d'assemblage (de compact à granulaire) propice au développement d'une porosité grossière (Fritsch *et al.,* 1989) et de ce fait au transport de particules fines lors d'écoulements gravitaires (Fritsch *et al.,* 1989; Bravard & Righi 1990; Lucas *et al.,* 1996). Les pertes de matières semblent ainsi se faire en deux étapes. La première étape est attribuée à l'altération ou lixiviation des matériaux (par dissolutions sélectives et détachement des particules). La seconde étape correspond au soutirage ou lessivage des particules fines d'un horizon ou d'un ensemble d'horizons. Ce lessivage peut être mis en évidence soit par des mesures d'éléments en suspension dans les eaux de percolation soit par la reconnaissance de cutanes d'illuviation dans les profils d'altération. Il peut aboutir à l'individualisation de compartiments éluviés (pertes relatives) et illuviés (accumulations absolues) qui peuvent être soit superposés soit distribués latéralement en accord avec des écoulements hydriques latéraux dominants (Bocquier, 1971; Boulet, 1974; Fritsch *et al.,* 1990a; 1990b; Valentin & Fritsch, 1990). Signalons enfin dans certains paysages de savanes, la contribution non négligeable des remontées biologiques de terre et de l'érosion sélective en surface par ruissellement (Fauck, 1972; Fritsch *et al.,* 2007) dans l'appauvrissement des horizons de surface. Ces horizons sableux ne peuvent plus de ce fait contribuer à la reconstruction des profils latéritiques par la base (Lucas *et al.,* 1996).

La contribution respective des processus de lixiviation et de lessivage dans ces pertes de matière reste toutefois délicate à établir. Des tentatives ont été réalisées en utilisant des éléments considérés comme peu mobiles dans les profils d'altération (e.g. Zr, Ti et Th) et en les comparant aux principaux éléments (Fe et Al) présents dans les principales phases minérales de ces sols : oxydes de fer et kaolinites (Lucas *et al.,* 1987, 1996; Bravard & Righi, 1989, 1990). Ainsi une plus grande perte de Fe par rapport à Al et une bonne corrélation de ce dernier élément avec Ti indiquerait une dissolution sélective des oxydes de fer. Par contre, des pertes des trois éléments (Fe, Al et Ti) dans des rapports qui restent constants pris deux à deux indiquerait plutôt un lessivage (Bravard & Righi, 1990).

Les processus de lixiviation et lessivage, impliqués dans la perte en éléments fins peuvent s'observer dans la partie supérieure ou inférieure des profils d'altération, ou encore les deux à la fois. Ils sont identifiés soit en milieu non saturé (dans la partie supérieure de certains profils latéritiques) soit en milieu saturé (dans la partie inférieure de ces profils) et être associés à des

systèmes de nappe. Cela suggère de ce fait que l'hydromorphie prolongée des latérites (ou forte oxydo-réduction) n'est pas forcement une étape préalable à leur appauvrissement.

Les facteurs environnementaux invoqués pour expliquer ces pertes de matières restent encore incertains et parfois contradictoires. Ainsi en régions tropicales à saisons contrastées, elles ont été attribuées principalement à l'ultra-dissecation des sols (Chauvel *et al.,* 1977; Chauvel & Pedro, 1978). Sous conditions de très faible humidité du sol, les films d'eau deviennent polarisés, les taux de dissociation s'élèvent (Mortland, 1968) et les pH aux interfaces s'abaissent (ordre de 2). Ces conditions permettraient alors la mobilisation du fer des sites d'échange des argiles, même en milieu oxydant (Chauvel & Pedro, 1978). En régions tropicales humides, ces pertes de matières ont, à l'inverse, été attribuées à une plus forte hydratation du sol (climats ou pédoclimats plus humides), à des mécanismes d'auto-développement et au vieillissement des latérites (Fritsch *et al.,* 1989, 2005).

2.5. Les sols hydromorphes (Gleysols) et l'oxydo-réduction

Les sols de ces environnements sont associés à des systèmes de nappe. Ce sont des sols intrazonaux et leur distribution relative dans les paysages est de ce fait commandé par le relief et la capacité des nappes à alimenter en eau mais aussi en matériel dissous et particulaire les rivières. En Amazonie, ils occupent de ce fait systématiquement les bas de versants des rebords des plateaux et les plaines alluviales. On les trouve également dans les dépressions de certains plateaux, plus particulièrement dans les nombreuses dépressions anastomosées de la Formation Içá (Fritsch *et al.,* 2007).

Les sols de ces environnements ont généralement des teneurs en argile assez élevées et l'accumulation d'eau va d'une part altéré les flux du cycle du carbone entre lithosphère, biosphère, atmosphère et hydrosphère, et d'autre part favoriser le développement de conditions réductrices propices à la mobilité de certains éléments (en particulier Fe). En milieu saturé et anoxique, la minéralisation réduite des matières organiques va favoriser leur accumulation dans la partie supérieure des sols, ces accumulations de matières organiques pouvant aboutir à la formation d'Histosols en cas de saturation hydrique permanente jusqu'en surface (Fanning & Fanning, 1989). D'autre part, les saturations hydriques temporaires ou permanentes de ces sols sont propices au développement d'une faune microbienne adaptée aux conditions oxydo-réductices qui règnent dans ces sols (Duchaufour, 1982).

En période d'engorgement, le développement de conditions réductrices est propice sous l'action de bactéries à la consommation de l'oxygène de l'eau, puis à la réduction en chaîne de composés minéraux, les plus connus étant les nitrates, les oxydes de Mn, les oxydes de Fe et les sulfates. En milieu tropical où les oxydes de fer sont largement prédominants, cela conduit progressivement au jaunissement et blanchiment des latérites rouges (Fritsch *et al.,* 1989; Peterschmitt *et al.,* 1996). Ce jaunissement et cet éclaircissement des matrices latéritiques constituent très certainement l'un des processus majeurs de la zone intertropicale. Ils ont été reliés à une dissolution préférentielle des hématites, généralement moins substituées en Al, dans le pool des oxydes de fer souvent dominé par la goethite (Jeanroy et al., 1991; Bousserrhine et al., 1999; Torrent *et al.,* 1987; Peterschmitt *et al.,* 1996). Ces dissolutions sélectives sont majoritairement guidées par la taille et les taux de substitution en Al dans les sites octahédriques de ces minéraux. Ils s'expriment de ce fait différemment suivant qu'on se situe dans les altérites ou dans les sols qui les surmontent au sein des profils d'altération.

En période de rabattement des nappes, l'oxygénation temporaire et parfois localisée de ces sols est propice aux re-précipitations des éléments préalablement dissous. Ces re-précipitations de minéraux mal cristallisés (ferrihydrite) ou mieux cristallisés (lepidocrocite, goethite, hématite…) peut dès lors conduire à l'individualisation de taches, de nodules ou concrétions, de raies ferrugineuses ou d'horizons indurés (e.g. plinthites) (Duchaufour, 1982; Fanning & Fanning, 1989; Fritsch *et al.,* 2002, 2007).

Dans les régions tropicales humides, ces re-mobilisations de matières sous l'action des nappes restent limitées puisqu'elles sont essentiellement attribuées à la dissolution des oxydes de fer pris au sens large, et qu'elles préservent les minéraux argileux (kaolinite) généralement très dominant dans les fractions fines de ces sols (Fritsch *et al.,* 2002). Elles aboutissent généralement à la formation de sols à colouration hétérogène en cas d'engorgements provisoires (horizon diagnostique: pseudogleys) ou à des sols entièrement blanchis en cas d'engorgements permanents (horizon diagnostique: gleys) et lorsque les conditions réductrices sont maintenues dans les sols (Fanning & Fanning, 1989). A l'échelle des paysages et comme dans le cas de l'appauvrissement, la redistribution du fer peut aboutir à l'individualisation de compartiments réduits (pertes relatives) et indurés (accumulations absolues) qui peuvent être soit superposés et déconnectés du réseau hydrographique (Fritsch *et al.,* 2002), soit distribués latéralement et reliés au réseau hydrographique (Fritsch *et al.,* 2007). Dans ce dernier cas, des transitions ou structures en "double langue" ont pu être

identifiées entre les compartiments latéritiques les mieux drainés de l'amont et les systèmes hydromorphes aval. De telles structures témoignent d'écoulements hydriques latéraux dominants en accord avec la fluctuation de systèmes de nappe (Fritsch ***et al.***, 2007).

2.6. Les podzols hydromorphes et la podzolisation

Comme les Gleysols, les Podzols hydromorphes du bassin amazonien sont associés à des systèmes de nappe. Ils correspondent de ce fait à des sols intrazonaux et leur distribution relative dans les paysages est commandé par le relief et la capacité de ces nappes à exporter les éléments dissous et particulaire aux rivières. Ils occupent sensiblement les mêmes positions topographiques que les Gleysols. Néanmoins et comme nous le soulignons dans cette thèse, la mise place de ces sols nécessite soit des matériaux parentaux à texture sableuse soit des formations latéritiques ayant au préalable perdues une grande partie de leurs constituants fins argileux par appauvrissement. En effet, la migration verticale et latérale des produits de décomposition des matières organiques n'est vraiment efficace que lorsque la porosité du sol devient suffisamment élevée, en dessous d'un seuil de teneur en argile très faible de l'ordre de 2 à 3% (Bravard & Righi, 1989). Dans la mesure où cet appauvrissement des latérites en éléments fins affecte essentiellement les parties déprimées des vastes pénéplaines du bassin amazonien, des podzols d'extension très variable s'observent essentiellement dans les dépressions de ces pénéplaines, qui correspondent de nos jours aux bas plateaux incisés par le réseau hydrographique du fleuve Amazone (Nascimento *et al.*, 2004). Toutefois des podzols, sans doute plus récents, s'observent également sur les incisions (Lucas *et al.*,1988, 1996) et dépôts alluviaux de ce fleuve et de ses tributaires.

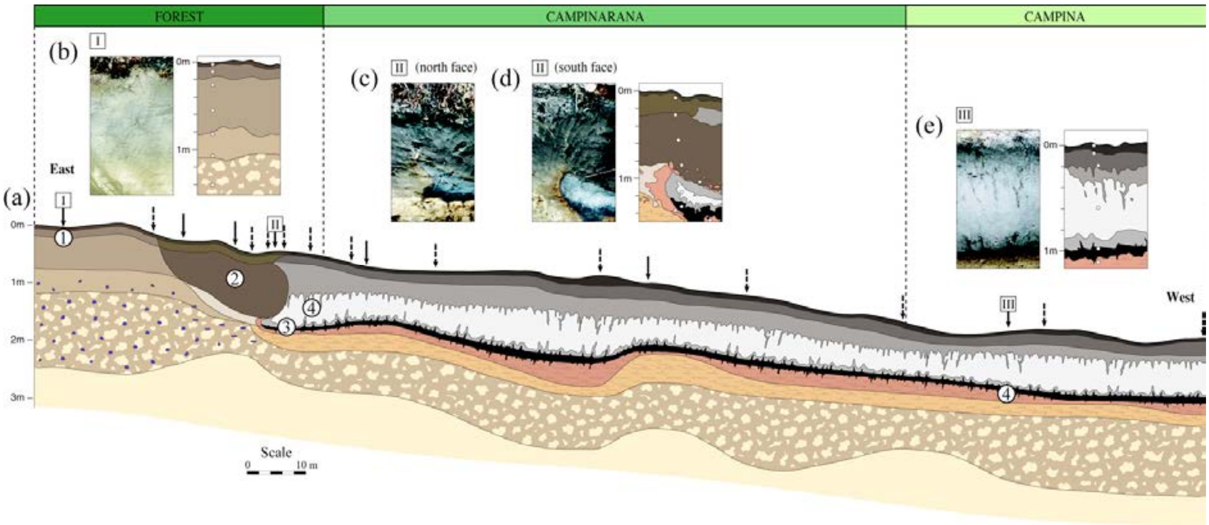


Figure 7*. Séquence de sols étudiée au Jaú (site 3) illustrant la transition latérale entre les latérites (à gauche) et les podzols des dépressions des plateaux (à droite) (d'après Nascimento et al., 2004).*

Dans les dépressions des bas plateaux où les podzols hydromorphes commencent à apparaître (site (3) du Jaú), la caractérisation minéralogique et structurale de séquences ordonnées de sols (Fig. 7) a permis de mieux définir les deux grandes étapes dans la podzolisation des latérites (Nascimento *et al.,* 2004). La première étape marque l'apparition à la bordure de la dépression de podzols faiblement différenciés (ou sols crypto-podzoliques). Ces podzols comprennent des horizons humifères A de type Mor surmontant des horizons spodiques, peu différenciés de type Bhs. La matière organique imprègne de ce fait profondément (sur plus d'1m) les latérites jaunes, appauvries de la bordure de ces dépressions, qui contiennent essentiellement du quartz mais aussi des minéraux argileux résiduels (kaolinite, gibbsite et goethite). Ces substances organiques assurent l'altération de ces minéraux argileux et contribuent à la formation et au transfert vertical de complexes organo-métalliques (principalement à base de Al mais aussi de Fe). La deuxième étape marque la quasi-disparition de ces minéraux argileux dans les horizons AE et E de podzols mieux différenciés et l'accumulation à plus grande profondeur d'une seconde génération de complexes organiques dans les deux horizons spodiques de ces podzols (Bh et Bs). Une étude hydrodynamique et géochimique le long de ces différentiations pédologiques a montré que la seconde étape était étroitement liée au développement de conditions réductrices et acides au sein d'une nappe perchée qui alimente en saisons pluvieuses les ruisseaux à l'aval des dépressions (Nascimento *et al.,* 2008).

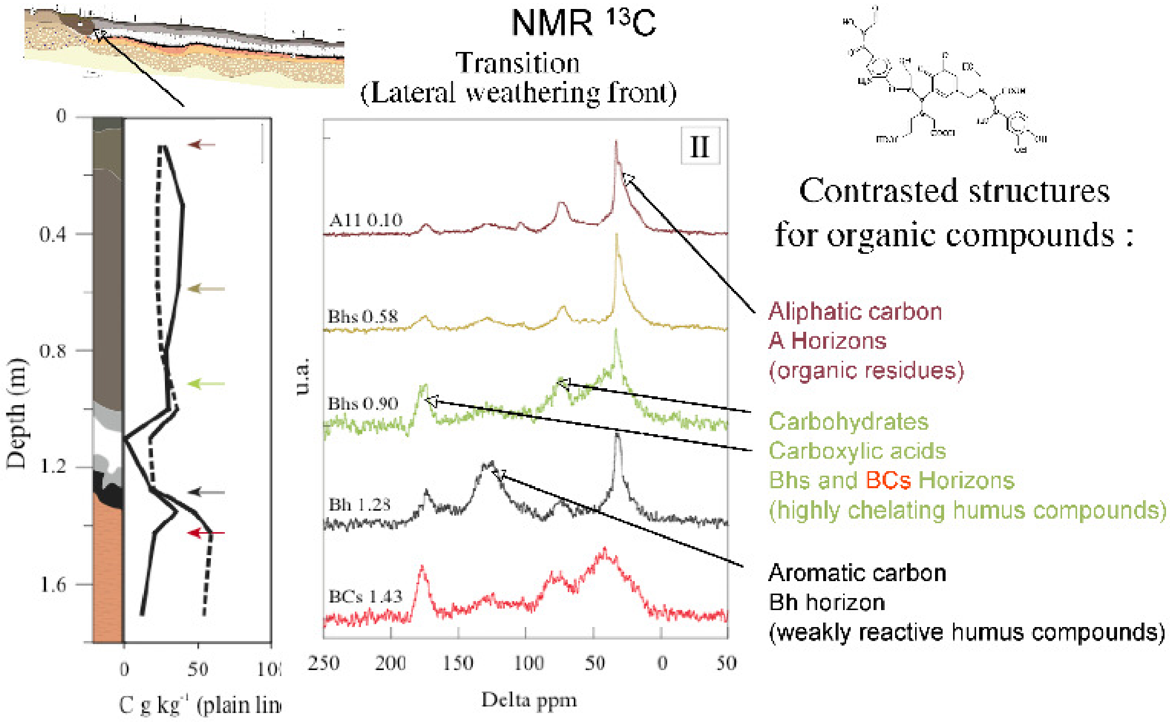


Figure 8*. Spectres RMN des matières organiques dans les horizons éluviés (A) et illuviés (Bhs, BCs et Bh) des podzols à la bordure de la dépression de la séquence du Jaú (d'après Bardy et al., 2008).*

La caractérisation microscopique et spectroscopique (RMN) des matières organiques de ces podzols a par ailleurs révélé des groupements fonctionnels dont l'abondance relative variait de façon significative suivant la nature des principaux composés organiques reconnus dans les horizons identifiés le long d'une séquence de sols (Fig. 8) (Bardy *et al.*, 2008). Ainsi les horizons de surface, éluviés, des podzols (A et AE) à nombreux résidus végétaux présentent essentiellement des groupements aliphatiques sur spectres RMN. Des matières organiques très fines formant des revêtements bruns dans les horizons spodiques Bhs des podzols faiblement différenciés, mais aussi plus en profondeur dans les horizons Bs de podzols mieux différenciés, sont caractérisés essentiellement par des groupements carboxyliques, dont l'aptitude à complexer les métaux est unanimement reconnue. Enfin, les revêtements organiques noirs et plus grossiers qui colmatent la base des horizons sableux de ces podzols et forment des horizons Bh sont essentiellement caractérisés par des groupements aromatiques. Les matières organiques qui alimentent les eaux noires des podzols en colloïdes organiques (Allard *et al.*, 2004, Fritsch *et al.*, 2009) s'observent sous forme de « boulettes », dispersées et peu abondantes dans les horizons de surface et en remplissage entre les quartz ou en

revêtements sur ces derniers dans les horizons Bh (Bardy *et al.,* 2008). Ces différenciations verticales témoignent ainsi d'un fractionnement physique des matières organiques lors de leur migration verticale dans les profiles d'altération. Les éléments les plus fins migrent plus en profondeur ou à la périphérie des aires podzoliques dans des horizons moins poreux (horizons Bhs et Bs) et les plus grossiers tapissent la bordure des réservoirs sableux de ces podzols (horizons Bh) (Duchaufour, 1972). L'aptitude de ces matières à complexer les métaux a été révélée dans un premier temps par des attaques chimiques sélectives (Nascimento *et al.,* 2004). Elle a été ultérieurement confirmée par des approches spectroscopiques à la fois pour l'aluminium qui est abondamment complexé aux matières organiques dans ces environnements (Bardy *et al.,* 2007) et pour le fer qui l'est beaucoup moins du faite des conditions réductrices qui prévalents dans ces podzols hydromorphes (Fritsch *et al.,* 2009). Ces travaux ont également montré qu'au fractionnement physique des substances organiques dans ces podzols pouvait être relié une séparation des formes complexées de l'aluminium et de celles du fer, les complexes alumineux s'accumulant plus en profondeur (Bs) ou plus à la périphérie dans les organisations latéritiques encaissantes (Bhs) que les complexes ferriques qui tapissent la bordure des réservoirs sableux (Bh). L'ensemble de ces travaux montre également que le développement de conditions très acides ($pH < 3.5$) dans les réservoirs sableux de ces podzols est propice à la remobilisation des métaux, principalement de l'aluminium, en accord avec les travaux de Jansen et al. (2003). Ces podzols seraient de ce fait des pièges à métaux dans les fronts latéraux de podzolisation et à l'inverse une source de métaux pour les rivières, à proximité des incisions qui drainent les dépressions de ces podzols (Allard et al., 2004; Benedetti *et al.*, 2003a, 2003b; Nascimento *et al.,* 2004; Bardy *et al.,* 2007; Fritsch *et al.,* 2009).

L'étude de la dynamique et composition chimique des nappes qui drainent ces associations de sols montre par ailleurs que la recharge rapide de la nappe perchée dans les réservoirs sableux de ces podzols est susceptible de créer des gradients de charge inverses à la topographie des dépressions et de contribuer ainsi à la recharge de la nappe phréatique profonde des latérites, à la bordure des aires podzolisées (Nascimento *et al.,* 2008). La mobilisation des éléments chimiques a lieu essentiellement à l'amont, dans le nappe phréatique des latérites (pour Fe), mais aussi dans les fronts de podzolisation lors de la recharge de la nappe perchée (à la fois pour Fe et Al) (Fig. 9). Cette nappe, chargée en matière organique dissoute et colloïdale, est donc susceptible de contribuer à la formation des complexes organiques, puis à leur accumulation dans les organisations périphériques, encaissantes lors du rabattement de cette

nappe. La forte baisse des teneurs en silice dissoute et en métaux (Fe et Al) dans la nappe perchée des horizons sableux des podzols (Fig. 9) témoigne enfin d'un temps de résidence court des eaux noires qui drainent les aires podzoliques (Bravard & Righi, 1989; Lucas *et al.*, 1996; Patel-Sorrentino *et al.*, 2007).

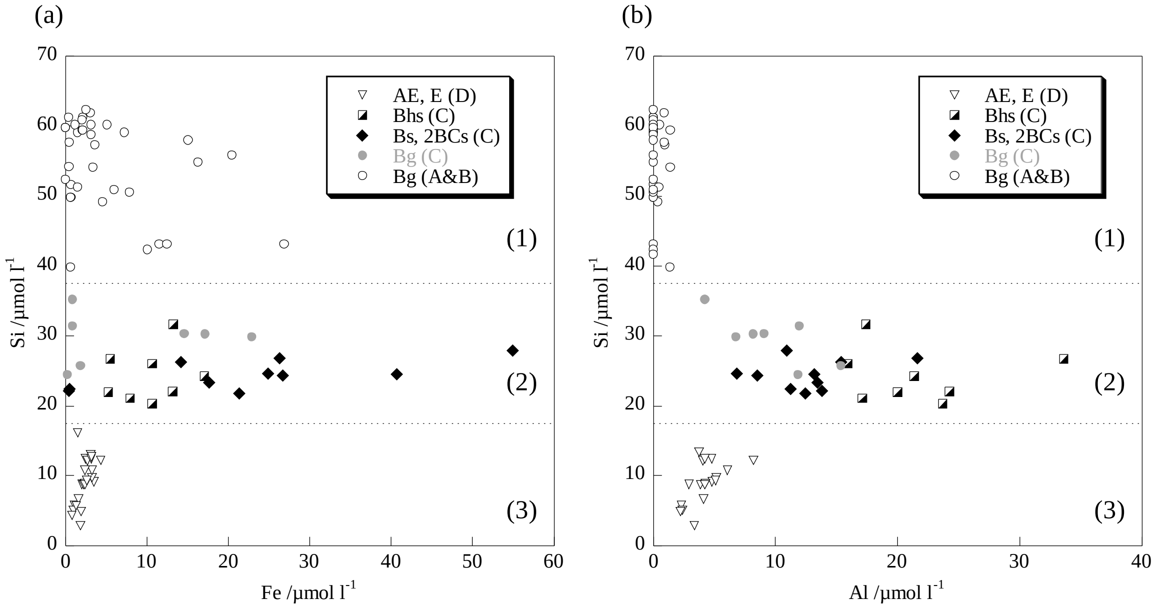


Figure 9*. Composition géochimique des eaux (Si, Al, Fe) dans les trois compartiments majeurs de la séquence du Jau : (1) à l'amont dans la nappe phréatique des latérites, (2) dans les fronts latéraux de podzolisation et (3) dans la nappe perchée des podzols de l'aval.*

Figure 10*. Front latéral de podzolisation en forme de double langue dans la séquence du Curicuriari (site 4): Latérites jaunes appauvris (à gauche) et podzols évolués (à droite).*

Les structures pédologiques mise en place dans les dépressions de ces plateaux reflètent dès lors la dynamique évolutive de ces systèmes. Les travaux entrepris par Nascimento et al. (2004) au Jaú et ceux que nous avons entrepris à São Gabriel da Cachoeira montrent que le développement vertical des podzols est arrêté dès qu'une discontinuité texturale ou structurale est rencontrée (une dalle rocheuse ou une altérite). Ces podzols ne peuvent donc plus se développer que latéralement, ce qui aboutit par soutirage à un agrandissement de la taille des dépressions. Latéralement, la transition entre latérite et podzols présente une forme en "double langue" qui a systématiquement été observée dans le haut bassin amazonien (Fig. 10). Cette structure peut être reliée à la dynamique des nappes perchées de ces podzols (Nascimento *et al.,* 2008). La langue inférieure est attribuée aux périodes de rabattement des nappes et plus particulièrement au soutirage généré par les écoulements latéraux de la nappe phréatique amont des latérites dans les systèmes podzoliques. La langue supérieure est associée aux fluctuations de la nappe perchée au voisinage de la surface topographique et à la bordure des aires podzoliques lors d'épisodes particulièrement pluvieux en saisons humides.

2.7. Processus d'altération et d'érosion, relations avec la morphogenèse

Deux grands types de processus peuvent être invoqués pour expliquer l'évolution des modelés sur les surfaces continentales: (i) des processus érosifs associés aux écoulements superficiels et aux transports de matières en surface (ruissellement en nappe ou concentré avec décapage ou incision des versants et dépôts dans les zones planes aval), et (ii) des processus érosifs associés à l'altération, aux écoulements internes et au transport d'éléments en solution (lixiviation) ou au transfert de particules en suspension dans les horizons poreux du sol (lessivage ou éluviation). Les premiers processus (érosion essentiellement physique) ont généralement été privilégiés dans de nombreuses études géomorphologiques au détriment des seconds (érosion principalement chimique) pour expliquer la mise en place des paysages. En particulier des épisodes d'érosion physique intense en climats secs seraient propices à la mise en place de surfaces d'aplanissement ou de pénéplaines (King, 1953). Ces surfaces pourraient être ultérieurement incisées en période plus humides et par abaissement des niveaux de base locaux, aboutissant ainsi à des inversions de relief. En particulier et comme cela semble être le cas pour le bassin amazonien, des plateaux pourraient ainsi résulter de l'incision d'immenses surfaces d'érosion et de sédimentation, marquant ainsi d'anciennes positions basses du bassin.

D’autres travaux ont néanmoins montré que l’érosion chimique des couvertures d’altération par soutirage interne (véritable fonte géochimique) et exportation au réseau hydrographique de matières en solution et ou en suspension pouvaient former des dépressions en surface (dolines en milieu karstique), des décrochements sur les versants et également de vastes zones déprimées ou plaines dans les paysages (Trescases, 1975; Millot, 1983; Lucas *et al.*, 1988; Dubroeucq & Volkoff, 1998). Dans les régions arides d’Afrique de l’Ouest, des processus d’éluviation (pertes) et d’illuviation (gains), associés à des systèmes de nappe, se relayent latéralement sur de vastes zones aplanies (Bocquier, 1971; Boulet, 1974). Comme nous le verrons par la suite dans ce mémoire, il sera parfois difficile de déterminer l’origine de certaines facettes des paysages du bassin amazonien (e.g. dépressions et vastes chenaux anastomosés des bas plateaux). Ces facettes pourront soit marquer d’anciennes structures sédimentaires (chenaux fluvio-lacustres) soit résulter d’une véritable fonte géochimique des latérites avec comme stade ultime l’individualisation de podzols dans les zones déprimées des paysages, soit encore résulter d’une combinaison de ces deux types de processus (a “t*wo stage process*”, e.g. Wayland, 1934; Linton, 1955; Budel, 1957; Planchon et al.,1987).

CAPITULO 3. O EMPOBRECIMENTO DOS SOLOS LATERÍTICOS: UMA ETAPA PRÉVIA À PODZOLIZAÇÃO

Résumé

Le chapitre traite de l'appauvrissement des latérites comme étape préalable à la podzolisation. Cette étude a été réalisée dans la région de São Gabriel da Cachoeira à la bordure des aires fortement podzolisées du bassin versant du Curicuriari. Cinq profils latéritiques ont été sélectionnés depuis la bordure d'un plateau disséqué vers la partie centrale d'une dépression à podzols hydromorphes. Sur un transect de 1,6 km de long, les cinq profils (P1 à P5) illustrent les pertes graduelles en minéraux argileux qui s'observent essentiellement dans la partie supérieure des profils d'altération. Le profil P5 est situé 5m en amont de la dépression à podzols. Des caractérisations pétrographiques, minéralogiques (DRX, IRTF et DRS) et géochimiques, elles-mêmes couplées à des calculs des fonctions de transfert (éléments majeurs et en trace), ont permis de révéler les principales étapes dans la perte sélective de matières et la différenciation verticale et latérale des profils latéritiques.

Les profils d'altération, développés sur des granites à corps mafiques de la formation Uaupés, appartiennent à la surface d'aplanissement *Ucayali*. La latéritisation a généré une exportation totale des bases et partielle de la silice à la base de ces profils d'altération, et à une accumulation résiduelle du fer et de l'aluminium dans les principaux minéraux secondaires de

ces sols (kaolinite, gibbsite, hématite et goethite). La gibbsite, généralement présente en faibles quantités au sein de ces profils, est toutefois très abondante dans le profil sommital le plus rouge (P1), probablement due aux excellentes conditions de drainage régnant dans cette partie du paysage. Une altération plus ménagée des minéraux métamorphiques ou corps mafiques (illite, épidote, biotite, titanite, apatite, allanite, magnetite) dans les saprolites permet de différencier le manteau d'altération de l'épaisse couverture de sols (2.3 m) qui le surmonte.

Les différentiations latérales très progressives et l'absence de structures lithologiques d'origine sédimentaire sont en faveur d'une perte de matière par érosion interne des couvertures d'altération (lixiviation et lessivage). Ces différenciations latérales, qui affectent séparément le compartiment sol et le manteau d'altération, se rejoignent à l'aval (P5). Dans les sols, un net jaunissement, associé à des pertes ménagées de matières, est tout d'abord observé de P1 à P2. Cette première étape dans la différenciation latérale de ces sols est attribuée à une dissolution sélective des hématites dans le pool des oxydes de fer. Elle traduit une plus grande hydratation des matériaux et de ce fait un pédoclimat plus humide. Une perte très progressive de minéraux fins argileux, associée au développement d'une porosité d'assemblage inter-quartz, est ensuite constatée entre P2 et P5. L'absence de revêtements argileux et des pertes de matières à rapport Al/Fe sensiblement constant d'un profil à l'autre suggèrent une altération conjointe des kaolinites et oxydes de fer (essentiellement de goethite) lors de la fonte géochimique. Un léger accroissement du rapport Al/Fe de la base vers le sommet de ces sols suggère néanmoins une plus grande dissolution de goethites. Dans le manteau d'altération, des pertes brutales en fer sans variations texturales majeures et ordonnées le long de la séquence (nette accroissement du rapport Al/Fe) sont reliées au blanchiment d'altérites rouges sous l'action d'une nappe phréatique. Ce blanchiment et ces pertes en fer sont localisés à l'amont (P2 et P3) et généralisés à l'aval (P4 et P5). Enfin, la partie supérieure blanchie du réservoir de nappe s'appauvrit brutalement à l'aval de ce transect (P5). Les pertes ultimes d'éléments fines dans ce réservoir affectent également les éléments en trace (Zr), témoignant de ce faite de transport particulaire (zircon) en milieu saturé.

En conclusion, cette étude montre que les pertes de matières s'expriment différemment suivant qu'on se situe au voisinage de la surface dans les sols en milieu non-saturé, mais à hydratation saisonnière croissante vers l'aval, ou plus en profondeur en milieu saturé dans le manteau d'altération. Ainsi, des processus lents de dissolution sélective et de lixiviation prédominent dans les sols. A l'inverse dans le manteau d'altération, les pertes de fer puis de

minéraux argileux sont brutales et nettement dissociées latéralement dans le réservoir de la nappe phréatique. Lorsque le milieu devient suffisamment poreux, les pertes ultimes d'éléments fins lors d'écoulements latéraux de nappe pourraient en grande partie se faire sous forme particulaire. Les pertes de matières en surface et en profondeur aboutissent à l'individualisation en bordure des dépressions d'un compartiment sableux dont la transition latérale présente une forme caractéristique en "double langue". Comme nous le verrons dans le second article, cette nouvelle structure sera exploitée ultérieurement par la podzolisation. L'étude souligne également que les re-mobilisations de matières attribuées à une ultime évolution podzolisante resteront minimes par rapport à celles résultantes d'un appauvrissement préalable des latérites.

3.1. Introduction

The weathering of rocks in tropical regions leads to the intense leaching of base cations and silica. In high elevated and freely drained environments of the landscapes, this kind of weathering, also known as lateritisation (Kronberg & Melfi, 1987; Fanning & Fanning, 1989), leads to the residual accumulation of the less mobile Al and Fe in secondary minerals, predominantly kaolinite, Al- and Fe-oxides (mainly gibbsite, hematite and goethite), and the formation of thick clayey regoliths comprising both soils and saprolites (Ségalen, 1966; Nahon, 1991; Tardy, 1993; Fritsch et al., 2002).

Weathering of granitic rock basements may also lead to the residual accumulation of metallic trace elements (MTE) such as Zr, Ti and Th, which are frequently used as invariants in the assessment of losses or gains of more mobile chemical elements (Brimhall *et al.*, 1991; Braun et al., 1993). The commonly weak mobility of Zr in regoliths derived from granites is mainly due to its incorporation in zircon, a highly resistant primary mineral to chemical weathering with dominant silt and fine sand particle sizes (Braun et al., 1993; 2005; Balan *et al.*, 2001; Maurin, 2005; Taboada et al., 2006). The mobility of Ti and Th is also low in lateritic soils as they are incorporated in stable secondary minerals of smaller particle sizes (mostly anatase and thorianite) (Fritsch et al., 2005). However, the mobility of both MTE may be enhanced at depth in saprolites, depending on the nature of the parent host minerals. In particular, the weathering of titanite, rutile and ilmenite into anatase (Middelburg et al., 1988; Cornu et al., 1999) may contribute to significant losses of Ti.

The upward accumulation of clay minerals in loose laterites has been related to major crystallographic changes in kaolinites and Fe-oxides. In particular, the gradual transition from saprolite to soil is mostly due to decreasing size and increasing disorder of kaolinites (Balan et al., 2005). The upward yellowing of red laterites has been related to increasing proportion of goethite and Al substitution rates in the pool of Fe-oxides (i.e. in both hematite and goethite) (Fritsch et al., 2005). Such crystallographic trends illustrate changing weathering conditions in soil horizons that have been attributed to soil aging and longer wetting periods in the upper part of the soils. They also reveal cyclic dissolution and crystallization reactions that concern both kinds of minerals (i.e. kaolinites and Fe-oxides). These mechanisms increase the specific area and reactivity of the soil minerals and favor the aggregation of the soils. However, the upward yellowing of soils has also been related to clay depletion and soil structure breakdown (Fritsch et al., 1989; 2005).

In the Rio Negro watershed of the upper Amazon Basin, lateritic soils are widely and closely associated with waterlogged Podzols. Red clayey lateritic soils (Ferralsols) are commonly found at the margin of strongly dissected low elevation plateaus that belong to the pan American *Ucayali* peneplain (Campbell et al., 2006). By contrast, podzols are commonly found in poorly drained depressions of the central parts of the plateaus. Podzol formation results from the downward and downslope migration of organic acids (Pedro, 1987) in highly porous sandy materials during the lowering of perched groundwaters (Bravard and Righi, 1990; Nascimento et al., 2004). The accumulation of the organic acids at the periphery of the podzolic areas enables to sustain the perched groundwater. It also promotes the weathering of clay minerals and the formation of organo-metallic complexes (Lundström et al., 2000, Nascimento et al., 2004). Accordingly, the dominant Al and Fe previously incorporated in mineral phases of the lateritic environments become predominantly bound to organic matter in waterlogged podzols (Bardy et al., 2007; Fritsch et al., 2009). The high porosity of the sandy horizons of podzols explains the short residence time of water (Nascimento et al., 2008) and fast lateral fluxes in perched groundwater (Lucas et al., 1996) that enhanced the lixiviation and acidification of the soils. In these highly reduced, acidic and organic-rich environments, the heavy minerals such as Ti-oxides and zircon may be partly dissolved, and the metal cations released in solutions be exported in black surface waters (Colin et al., 1993; Oliva et al., 1999; Braun et al., 2005). The interstices managed by the quartz sands of these podzols may also promote the physical transport in perched groundwater of clay and silt size

particles, comprising therefore kaolinite, thorianite, Ti-oxides and to some extent zircon (Nascimento et al., 2004).

Red clayey laterites (Ferralsols) and waterlogged podzols belong to two end-members of soil catena on the low elevation plateaus of the Rio Negro watershed. A transition zone between these two end-members comprises yellow clay-depleted laterites (Acrisols) that can extend on several hundred meters on the plateaus. Soil catena studies have shown that podzolic areas can increase in size and form at the expenses of their surrounding clay-depleted laterites (Turenne, 1977; Chauvel et al., 1978; Lucas et al., 1987; Bravard and Righi, 1990; Nascimento et al., 2004). This kind of soil dynamics then suggests that yellowish clay-depleted laterites could in the same manner be formed laterally from better-drained laterites exhibiting heavier texture and redder colours. Pre-existing weathering processes associated with drastic colorimeric and textural changes seem therefore necessary to form waterlogged podzols on the plateaus. Such processes that enhance the chemical and physical erosion of laterites still remain poorly understood. Moreover, the hydraulic regime contributing to greater erosion and the compartments of the regoliths where they are acting need to be better defined. On this regards, Bravard and Righi (1990) and Nascimernto et al. (2004) point out that tropical podzols commonly form in poorly drained areas. This suggests that reducing conditions that promote yellowing and bleaching in laterites (Chauvel et al., 1977; Peterschmitt et al., 1996) could be one of the major soil change processes promoting the formation of podzols, the second one being associated to clay depletion. Fe could therefore be mobilized before Al in the transition zone between red clayey laterites and waterlogged podzols. At least, the removal and the transfer of matters that play a major role in the vertical and lateral differentiation of regoliths (Simonson, 1959), may be assigned to two major mechanisms (Fanning & Fanning, 1989): (i) solution transport (lixiviation or chemical erosion) and (ii) particulate or suspension transport (eluviation or mechanical erosion). Solution transport and redistribution of major and trace elements by chemical erosion are mostly controlled by hydrological regimes and weathering conditions (e.g. Eh, pH) (Van der Weijden and Van der Weijden, 1995; Grybos et al., 2007). Particulate transport depends on pore size, dispersion/flocculation properties and the existence of hydraulic gradients (Soil Survey Staff, 1975). This suggests that chemical erosion and solution transport might prevail in the transition zone, whereas particulate transport could be also involved close to the podzolic areas due to greater development in soil matrix of macro-voids between adjacent quartz grains.

Structural, geochemical and mineralogical (XRD, FTIR et DRS) investigations were performed in five profiles (P1 to P5), located along a 1.6km long transect from the margin of a dissected plateau to the border of a huge depression containing waterlogged Podzols. The profiles illustrate vertical and lateral differentiations associated with the formation of reddish clayey laterites (Ferralsols) at the margin of the plateau and their lateral transformation into yellowish clay depleted laterites (Acrisols) towards the depression. Lateral differentiations in the field are mostly assigned to colorimeric and textural changes in both soils and saprolites The aims of this work are to reveal (i) the sequence of major weathering processes that generates losses of clay minerals and therefore promote the podzolisation of lateritic landscapes, (ii) the general hydric regimes that enhanced the chemical and physical erosion of the regoliths and (iii) the places in the landscapes where these weathering processes and hydraulic regimes are acting.

3.2. Environmental setting

The transect with its five profiles is located near São Gabriel da Cachoeira (0^o 15’ 50”S; 67^o 03’ 10”W) in the upper Negro River watershed (see star in Fig. 1). It belongs to the *Ucayali* peneplain, formed during an intense erosion phase of the mid Miocene (Campbell et al., 2006) that corresponds nowadays to the low elevation and dissected plateaus of the upper Amazon basin (about 90m above mean sea level, or 15m above mean river level at São Gabriel da Cachoeira). This transect is also located at the margin of a huge podzolised and inundated peneplain that covers 95% of the Curicuriari subcatchment in the West.

The vegetation of the region is in agreement with the soil distribution. The evergreen Amazonian forest covers the lateritic soils of the plateaus (*Terra Firme*), whereas a lower and more open forest with thin tree trunks (*Caatinga*) is growing on the hydromorphic Podzols of the depressions and peneplains (Silva et al., 1977). The mean annual temperature in that region is 25^oC and the rainfall is about 3000 mm per year with two maxima, on January (289 mm) and April (339 mm), and two minima, on February (282 mm) and August (124 mm) (Costa et al., 1977).

Soils in the region of São Gabriel da Cachoeira are formed on (titanite)-(amphibole)-biotite-granites and gneisses, with similar composition, of the western part of the Guyana Shield. They yielded 1518 +/- 25 Ma age by the ID TIMS U/Pb (zircon) method (Santos et al., 2000)

and younger thermotectonic event, related to Grenville orogeny, has been affect these granites at 1200 +/- 100 Ma (K'Mudku episode).

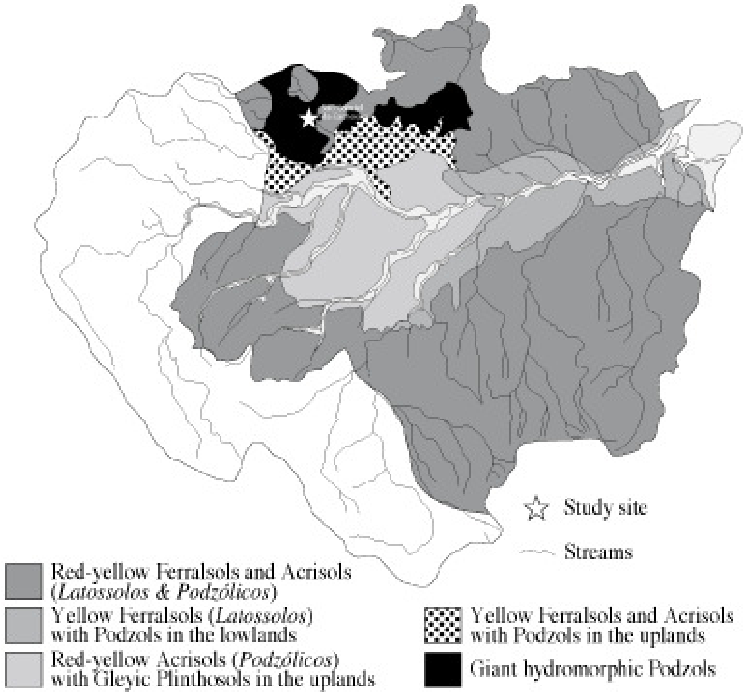


***Figure 1**. Broad scale soil map of the Brazilian Amazon basin (reduced and simplified from RadamBrazil maps at 1:2.500.000) showing the site location (star) at the margin of a highly podzolised region of the Rio Negro watershed.*

Granitoid rocks of the region comprise mafic-bearing granitic bodies locally sheared and mineralized and are crosscut by pegmatite or quartz veins (Fernandes et al., 1977, CPRM, 2006). Two major structural lineaments were recognized in that region: a dominant NE-SW to ENE-WSW lineament and a secondary NW-SE one. In the low course of Curicuriari River, the rock basement belongs to two granitic suites: (i) the syenogranites to alkali-feldspar granites of the Curicuriari Suite and (ii) the monzogranites to quartz-monzonites of the Uaupés Suite (Almeida, 2005, CPRM, 2006). Profiles of the transect have formed on the quartz-monzonite and monzogranite of the Uaupés Suite that contain less quartz (15%) and alkali-feldspar (30%) than that of the Curicuriari Suite (42 and 50%, respectively) and much more plagioclase (44% versus 5%) and mafic minerals (11% versus 3%).

Table 1 : Analytical data from electron microprobe analyses (wt% oxides) of major minerals identified in the granite

Minéral	SiO_2	Al_2O_3	FeO	K_2O	Na_2O	CaO	MgO	MnO	TiO_2	P_2O_5	La_2O_3	Ce_2O_3	ZrO_2	LOI	Total
Microcline	64.62	18.63	0.14	15.99	0.49	-	-	-	-	-	-	-	-		100.4
(σ, n=10)	(0.45)	(0.14)	(0.06)	(0.26)	(0.13)	-	-	-	-	-	-	-	-		
Anorthite	60.83	25.34	0.10	0.10	7.76	6.46	-	-	-	-	-	-	-		100,6
(σ, n=10)	(0.89)	(0.52)	(0.11)	(0.03)	(0.28)	(0.60)	-	-	-	-	-	-	-		
Albite	66.29	21.21	0.27	0.17	9.93	1.82	-	-	-	-	-	-	-		99,7
(σ, n=15)	(2.23)	(1.44)	(0.29)	(0.19)	(0.85)	(0.60)			-	-	-	-	-		
Biotite	39.13	16.52	20.04	9.16	-	-	8.61	0.59	1.61	-	-	-	-		95.7
(σ, n=15)	(2.00)	(0.37)	(1.13)	(0.31)	-	-	(0.81)	(0.08)	(0.20)	-	-	-	-		
Amphibole	41.97	9.98	21.07	1.32	1.17	11.28	7.88	0.93	0.80	-	-	-	-		96.5
(σ, n=15)	(0.41)	(0.05)	(0.26)	(0.02)	(0.03)	(0.16)	(0.28)	(0.05)	(0.09)	-	-	-	-		
Titanite	30.34	2.15	1.73	-	-	26.88	-	0.18	34.80	-	-	-	-		96.1
(σ, n=15)	(0.39)	(0.21)	(0.48)	-	-	(1.19)	-	(0.05)	(0.65)	-	-	-	-		
Apatite	0.47	-	0.10	-	-	54.19	-	0.08	-	40.88	0.18	0.39	-		96.3
(σ, n=15)	(0.20)	-	(0.10)		-	(0.50)	-	(0.03)	-	(1.20)	(0.10)	(0.18)	-		
Allanite	31.13	13.79	14.51	0.07	0.31	11.42	0.25	0.54	1.02	0.10	4.54	8.16	-		86.0
(σ, n=15)	(1.07)	(0.81)	(1.99)	(0.03)	(0.13)	(1.19)	(0.07)	(0.12)	(0.39)	(0.06)	(0.73)	(0.65)	-		
Garnet	38.05	23.32	11.95	0.09	-	22.33	0.11	0.48	0.10	-	0.03	0.08	-		96.7
(σ, n=15)	0.65)	(0.28)	(0.29)	(0.12)	-	(0.43)	(0.14)	(0.02)	(0.01)	-	(0.01)	(0.04)	-		

In the bedrock of the profiles, the alkali-feldspar corresponds to perthitic microcline with Tartan type twinning, which locally encloses quartz and plagioclases inclusions. The plagioclase show two generations and common polysynthetic twinning. Indeed, phenocrystals of plagioclase (2nd generation), highly saussuritized, exhibit sericite, epidote and smaller plagioclase inclusions (1st generation). The centrimetric mafic clots, which give to the rock its characteristic speckled aspect, mostly consist of biotite and amphibole (8%) and accessory minerals, such as apatite, allanite, zircon and opaque minerals (mostly magnetite and also locally pyrite) commonly surrounded by titanite. Allanite crystals are locally surrounding epidote and often aggregated with titanites. When apatite and allanite crystals appear as inclusions within biotite crystals, they often display a thin fringe of radiation-induced defects in the phyllosilicate (pleocroic haloes). The crystal chemistry of most of the major and accessory minerals on thin sections is given in table 1. It has permitted to identify the main mineral carriers for trace elements in rocks, saprolites and soils (e.g. mostly titanite and rutile for Ti, apatite for P and Ca, allanite for light rare earth element (La, Ce) and zircon for Zr).

3.3. Materials and methods

Soil survey, soil description and sampling

We used 2005 Ikonos satellite images to map the main geomorphologic and pedological units at the transition between the huge podzolized and waterlogged peneplain of the Curicuriari watershed and their lateritic counterpart at the border of the Guianense shield, in the western part of the watershed (Fig. 2a). Field surveys under forest were carried out in selected areas to

control map unit demarcations and to obtain precise topographic data using Topcon Hiper GPSs with a pair of Paulin Altimeters. Satellite images together with topographic GPS and altimeter data allowed building up a block-diagram for the investigation region using 3D design softwares (black insert in Fig. 2a and Fig. 2b). The site selected for this study belongs to the *Ucayali* Peneplain (Campbell et al., 2006) at the margin of the low elevated lateritic plateaus, just before reaching the huge podzolic and inundated peneplain of the region. It corresponds to a 1.6 km long transect on the edge of an incised plateau. The transect starts on the right bank of the Curicuriari river with red clayey laterites and ends up 5m before reaching the margin of a large podzolized depression (white dashed line in Fig. 2a,b). Along the transect, topographic survey was made at 7 m intervals and 27 soil augerings allowed the selection of 5 pits (from P1 to P5 in Fig. 2c) for soil sampling and investigations. Soil pits are located on hill-top positions at a water divide in the dissected plateau to minimize the contribution of colluvial deposits. Soil description was done according to ISRIC-FAO (1994). 121 samples from the 5 pits and 4 samples from rock outcrops were collected for chemical, physical and mineralogical investigation. 32 undisturbed samples of rocks, saprolites and soil horizons were also collected in cardboard boxes. They were impregnated with resin, cut and grounded for the elaboration of thin sections. The latter were observed under plain-polarized light (PPL) and cross-polarized light (CPL) using a microscope.

Chemical and physical analyses

Air-dried soil samples were sieved through a 2-mm screen. Particle-size distribution was determined by sieving (sand fractions) and pipetting (clay and silt fractions) after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. pH was measured both in water and in 1 M KCL (soil:solution; 1:2.5). Organic C and N contents were determined using a Carmograph LECO CHN analyser. Total chemical composition was performed on pulverized samples (150 mesh) at Actlabs Ltd (Canada); major elements by inductively coupled plasma atomic emission spectrometry, and trace elements by inductively coupled plasma atomic mass spectrometry.

Electron Punctual Microprobe Analyses (EPMA) were carried out on thin sections to determine the chemical composition of parent material minerals using a CAMECA SX50 equipped with four Wavelength Dispersive Spectrometers (WDS) and operating at 15 kV and 30 nA at the Centre d’Analyse des Minéraux de PARIS (CAMPARIS, Université Pierre et Marie Curie, Paris, France).

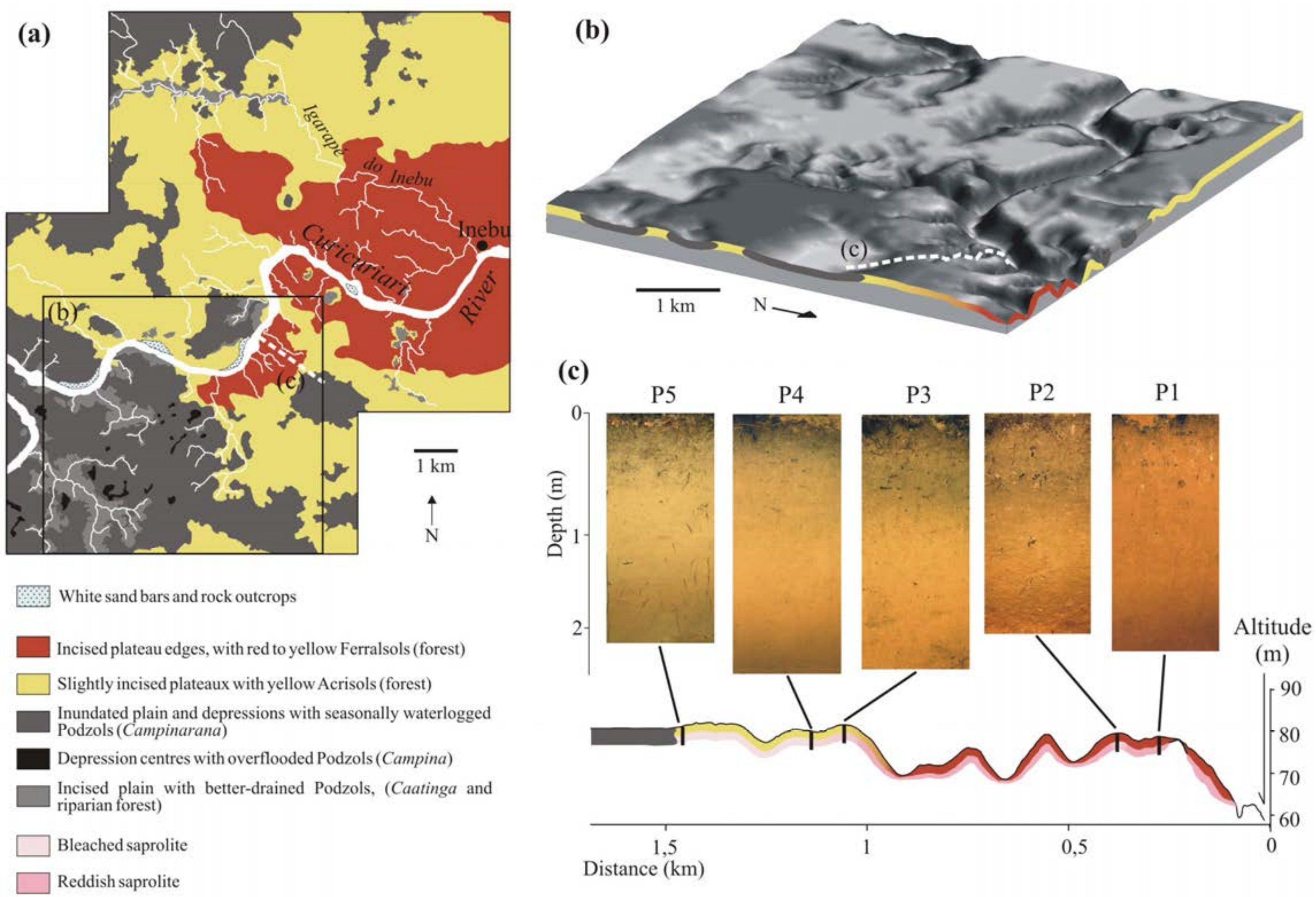


***Figure 2**: (a) Regional map of major soil landform units with their vegetation in the lower course of the Curicuriari watershed at the transition between podzols and laterites, which also shows the localisation of the transect (white dashed line), (b) 3D representation of the same area (see black rectangle insert in (a) for location of the selected zone), (c) soil transect with the position of the five selected profiles (from P1 to P5) and photographs of their upper parts (soils).*

Total chemical analyses and the mass-balance approach (Brimhall et al., 1991, Chadwick et al., 1990) were used to assess the relative losses or gains of chemical elements in the 5 profiles as compared to their underlying bedrock. This approach requires the selection of a chemical element, considered as immobile during weathering processes. In our investigation site, the element used as an invariant (suffix *i*) to assess the mobility of other elements (suffix *j*) in saprolites and soils is Zr. Indeed, Zr is present in zircon in the granitic rocks and their overlying weathered products, i.e. in an accessory mineral known for its high resistance to chemical weathering. The iso-element approach of Brimhall et al. (1991) requires the selection of a protore (suffix *p*), considered as chemically homogeneous and representative of the parent material for the overlying weathered (suffix *w*) saprolite and soil layers (average of the four rock samples). The relative loss or gain of a chemical element (*j*) in the investigated profiles were then determined from the mass balance factor ($_{j,w}$) according to the following equation (Chadwick et al., 1990):

$$_{j,w} = \frac{C_{j,w}/C_{i,w}}{C_{j,p}/C_{i,p}} - 1$$

In this equation, the mass balance factor is expressed independently of the volumetric strain (ε), related either to soil swelling or expansion (positive ε values) or soil shrinkage or collapse (negative ε values) during weathering processes. This mass balance factor corresponds to concentration ratios between a chemical element (*j*) and the chemical invariant (*i*) in a considered weathered material (*w*), as compared to its corresponding parent material (*p*), minus 1. The ratio of both elements in the protore (*p*) is a reference and thus assimilated to a constant. A mass balance factor smaller than 1 will then refers to a loss of chemical element (*j*), which is completed at $_{j,w}$ = O, whereas a mass balance factor greater than 1 will reveal a gain of the same element.

X-Ray diffraction and spectroscopic analyses

The mineralogical composition of clay and bulk samples was assessed by powder X Ray Diffraction (XRD) with a PHILLIPS PW 1730 using Co K radiation and operating at 40 kV and 30 mA at the Institut de Minéralogie et Physique des Milieux Condensés (IMPMC, Paris, France). XRD traces were collected for 2 angles ranging from 5 to 120° with a 0.02° steps and a counting time of 400s per step. Grounded powder samples (± 30 m) were prepared according to the technique of the "back pack-mounted slide” (Bish and Reynolds, 1989).

Identification of the mineral phases was carried out by comparing the experimental XRD traces with those from the mineral references of the ICDD data set.

FTIR spectroscopy was performed in the transmission mode using a Nicolet Magna 560 IR Spectrometer. One mg of oven-dried sample was mixed with 300 mg KBr and pressed at 10 $t.cm^{-2}$ to form a KBr disc. KBr discs were heated at 105°C overnight to remove absorbed water. Spectra were run in the 250 to 4000 cm^{-1} range with a 2 cm^{-1} resolution and normalized with sample exact weight.

Diffuse reflectance spectroscopy (DRS) was performed on bulk samples using a Cary 5G (US-VIS-NIR) spectrophotometer with a 100 mm-diameter integrating sphere coated with Halon (Labsphere, Inc., USA). Samples were gently ground (breakdown of the aggregates), overnight oven dried at 60° and filled into a 27 mm diameter and 2 mm thick hole of an Al holder without packing to minimize preferential orientation and specular reflection. An optically treated silica slide was used to cover the sample holder. Reflectance R was measured relative to a Halon standard. The spectra were run in the 200 to 2500 nm range with a 1 nm increment. The wavelength-dependent reflectance function was transformed into Kubelka-Munk remission functions by $f(R) = (1 - R)^2 / 2R$, which is proportional to the absorber concentration. The curves were smoothed using a cubic spline fitting procedure then the second derivatives were calculated (Malengreau et al., 1996). The nature and relative proportion of Fe-oxides (mostly goethite and hematite) were determined from the position and intensity of the optical transitions on the second-derivative curves calculated from f(R) (Kosmas et al., 1984).

Soil colour was quantified from the reflectance curves in the visible range (from 360 to 830 nm). The CIE tristimulus values (X, Y, Z) were computed from the spectral reflectance and energy of the light source for each wavelength using the colour matching functions of the CIE standard illuminant C (Wyszecki & Stiles, 1982). Tristimulus values were converted into colour units (x, y and Y%) of the CIE System (1931) and in those of the Helmholtz coordinates (L_d and P_e). They were ultimately plotted in the colour diagram of the visible range. In this diagram, the dominant wavelength (L_d) is the slope between the white light source and a given dot, and is related to the tint of the sample. The excitation purity (P_e) is equivalent to the chroma of the Munsell colour chart. It is scaled between 0 % for a colourless sample and 100 % for a pure colour monitored at the output of a monochromator (Bedidi et al., 1992).

3.4. Results

3.4.1. Vertical and lateral soil differentiation along the transect

Two sets of horizons are distinguished in the 5 soil profiles: (i) an approximately 2.3m thick soil cover (solum), strongly weathered and relatively homogeneous showing gradual changes of colour, texture and structure towards the depression and (ii) an underlying saprolite, slightly heterogeneous, less weathered and massive, which display abrupt changes of colour and then of texture towards the depression.

In the freely drained environment of the margin of the dissected plateau (P1), the regolith is clayey and intensively coloured by Fe-oxides. The thick massive saprolite (BC and C horizons) inherited from the weathering of granites of the Uaupés Suite (reached at 5m deep in P1) is clay loam to sandy clay loam and dominantly red. It exhibits slightly darker colours at the bottom of the saprolite due to the weathering of centrimetric mafic bodies of the granites. The transition with the overlying soil cover is progressive and mainly associated with (i) heavier sandy clay textures (decrease of the silt size fraction, predominantly made of clay minerals, and increase of the fine sand fraction with dominant quartz), (ii) more yellowish colours (yellowish red soils) likely due to greater amounts of goethite, and (iii) the development soil aggregates in B-horizons (mostly medium to fine blocky aggregates, with micropeds of biological origin). Towards the soil surface, the soil impregnated by the organic matter turns yellowish brown and becomes clay-depleted. Such changes thus mark at about 0.4m deep the second major transition between topsoil A-horizons and subsoil B-horizons. From the edge of the plateau (P1) to the margin of the podzolic area (5m upslope of latter in P5), the following morphological changes are reported (Fig. 2c).

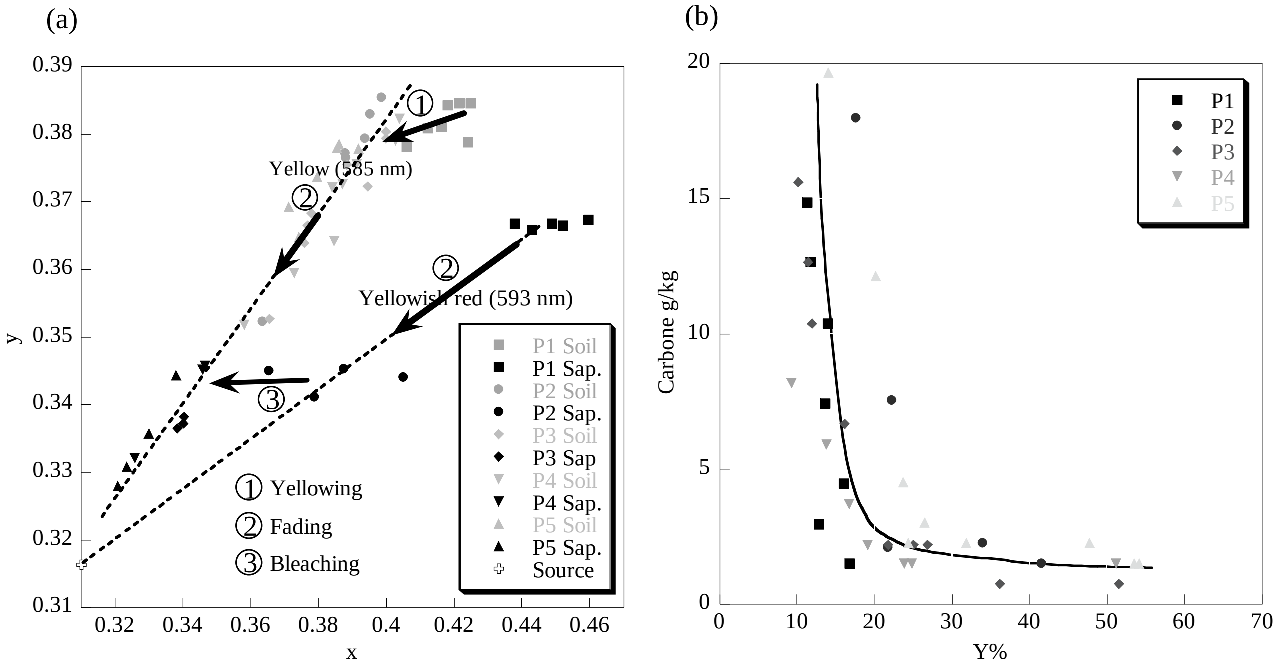


Figure 3*. (a) x and y values of the CIE System (1931) for soil (grey symbols) and saprolitic (black symbols) samples of the five profiles (P1 to P5) plotted in the visible colorimeric diagram, slope and distance from the CIE standard illuminant C (source: white cross) are used to calculate the dominant wavelength (L_d) and the excitation purity (P_e), respectively for each sample (Helmholtz coordinates), (b) Y% value of the CIE System (1931) versus total carbon content.*

In the upper soil cover, lateral changes are progressive but also slightly dissociated in space for colour and texture. From P1 to P2 and within the 2m thick B-horizons, soil colour grades from reddish-yellow to yellow whereas the soil texture remains almost unchanged (sandy clay). Such a soil yellowing is revealed on a colour diagram by a slight decrease of the dominant wavelength (L_d) that reaches an average value of 585nm in P2 (arrow 1 in Fig. 3a). Change of texture occurs later on and range from sandy clay in P1 and P2, to sandy clay loam in P3, sandy loam in P4 and loamy sand in P5 (Fig. 4a). This regular decrease of clay particles from P2 to P5 occurs without significant change of tint in B-horizons, but is closely associated with fader soil colours. On the colour diagram, this second colorimeric trend is related to equivalent dominant wavelength (average L_d of 585 nm) but to smaller values for excitation purity (P_e) (arrow 2 in Fig. 3a).

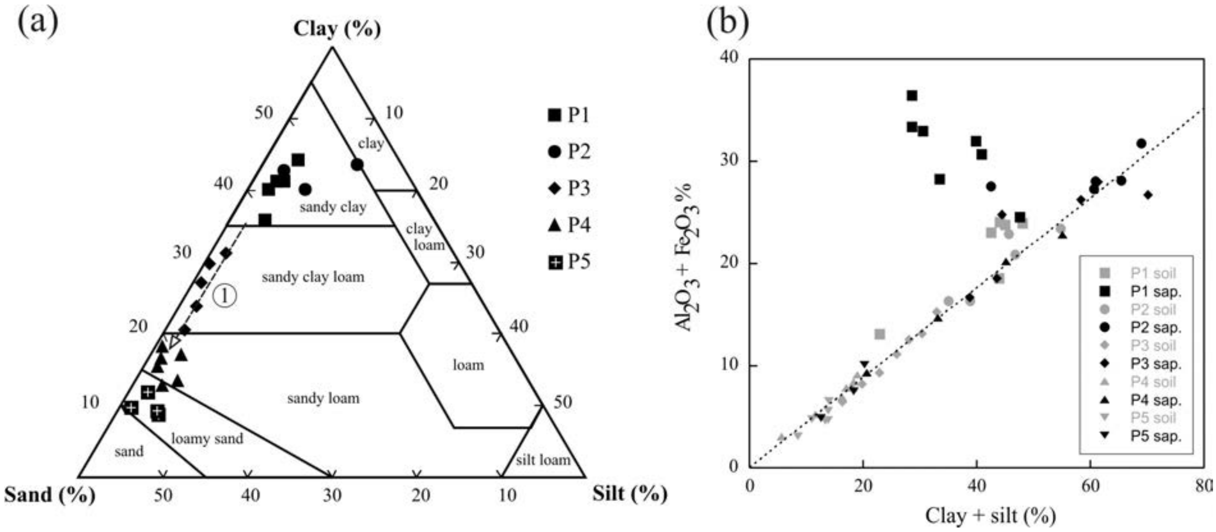


Figure 4*. (a) Ternary representation of the percentage of clay, silt and sand in soil samples of the B-horizons from the five profiles (P1 to P5) with corresponding soil texture classification, showing the gradual loss of fine clay minerals towards the depression (arrow 1), (b) positive correlation between the amount of clay + silt (< 50µm) weight % determined from particle-size extractions and the amount of clay minerals assessed from the Al_2O_3 + Fe_2O_3 % in bulk samples (negative correlation for P1).*

Losses of fine particles is also linked laterally in the soil cover to soil structure breakdown and to changes in mineral assemblage on thin sections between coarse primary minerals (mostly quartz) and finer secondary clay minerals (mainly kaolinite and goethite), as already discussed in Fritsch et al. (1989) for a soil catena of western Africa at the transition between forest and savannah. Indeed, soil structure tends to exhibit a greater range of aggregate size in P3 and P4 than in P1 and P2 and to become massive in P5. Concomitantly on thin sections (not shown), the assemblage between primary and secondary minerals (Brewer, 1964) is (i) dense with numerous, well-defined, thin cracks (porphyrosquelic) in P1 and P2 (Clay% > 35), (ii) less dense with larger and ramified macro-voids delineating soil matrix aggregates of various sizes (agglomerplasmic) in P3 and P4 (15 < Clay% < 35), and (iii) more open and porous with almost adjacent quartz grains and clay bridges between some of them (intertextic) in P5 (5 < Clay% < 15). The more macro-porous and compact assemblage of quartz sands (granular), linked to an almost total loss of clay particles (Clay% < 5), was not reached as it mostly characterizes the eluviated E horizons of podzols (out of the selected zone for this study). Accordingly, the selective but continuous loss of matter leads in a first stage to soil structure breakdown that most likely should reduce soil permeability and in a second step to a gradual increase in macro-voids between quartz grains, that become closer and closer, thus increasing in return water fluxes in soils (Fritsch et al., 1989; Bruand et al., 1990).

In the underlying clay loam to sandy clay loam saprolite, lateral changes of colour and texture are more abrupt and neatly dissociated along the transect. Redder colours as compared to the overlying soils are at first noted in the freely drained saprolite of the plateau edge, as illustrated on figure 3a by higher wavelengths (L_d), with an average value of 593nm in both P1 and P2. However, the saprolites also exhibit fainter reddish colours in P2 than in P1 (decrease of the excitation purity P_e, arrow 2 in Fig. 3a). They also display bleached mottles or layers at different depths that become more and more abundant from P2 to P4 (see also arrow 3 in Fig. 3a). Veins of kaolin were also found at depth in bleached saprolites of P4. In P5 and close to the downslope podzolic area of the depression, the saprolite is completely bleached and its upper part is also strongly depleted in fine particles. The groundwater table reached the clay-depleted area of the saprolite during the dry season (e.g. at 2.4m the 15th of November 2006).

3.4.2. Geochemistry of major and trace elements

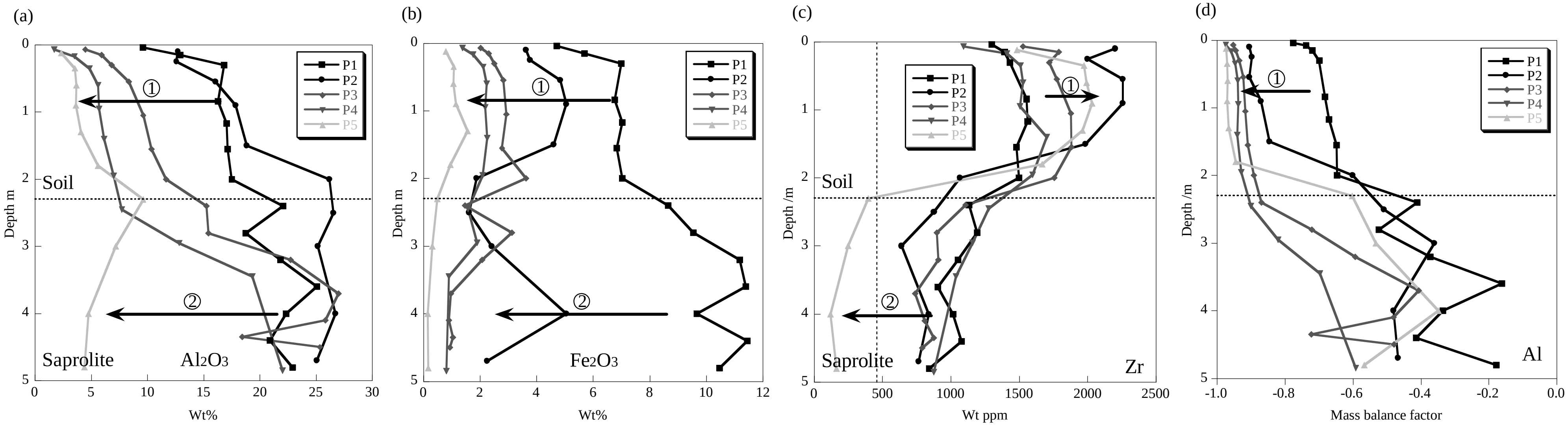
Major elements (Si, Al, Fe, Na, K, Ca and Mg) and Zr

All five profiles are strongly depleted in base cations (Na, Ca, K and Mg) as the mass balance factor ($_{j,w}$) calculated in the whole regolith, using Zr as an invariant, is almost nil for each of these highly mobile chemical element (not shown), with the exception of the bottom part of the saprolite only reached in P1. This suggests the almost total weathering of the feldspars (albite, anorthite and microcline) and ferromagnesiens (biotite and amphibole) inherited from the bedrock (see also the average chemical composition of these primary minerals and that of the granite in Tab. 1). Petrographic observations confirm the disappearance of these primary minerals in the regolith. Moreover, the extremely low CEC (< 10 cmolc/dm^3) and base cation saturation of the exchangeable sites (<4%), predominantly occupied by Al^{3+} and H^+, thus pertains to low activity clay soils specific to laterites and confirm the strong leaching conditions, which have prevailed in both soils and saprolites.

The amounts of total Al and Fe also vary vertically and laterally according to major morphological patterns. Firstly, the total amounts of clay plus silt in both soils and saprolites is positively correlated to the Al_2O_3 + Fe_2O_3 content (Fig. 4b) and negatively correlated to the SiO_2 content, excepted in P1 due to the occurrence in the sand fractions of small nodules of gibbsite. This indicates that most of the clay minerals (i.e. kaolinite and Fe-oxides) is in particle-size fractions smaller than 50µm. As we previously reported greater amounts of silt in

saprolites than in soils, we then conclude to the occurrence kaolinite populations of larger particle size at depth than close to the surface. At the margin of the plateau in P1, the total amounts of Al_2O_3 (Fig. 5a) but also of Fe_2O_3 (Fig. 5b) tend to decrease vertically upwards from saprolites to soils. The reverse trend is reported for Zr (Fig. 5c), the less mobile chemical element of these regoliths. Accordingly decreasing size of clay minerals from saprolites to soils seems also to be link to loss of these secondary minerals, and consequently to a residual accumulation of the more resistant primary minerals to chemical weathering, i.e. predominantly quartz but also accessory minerals, such as zircon.

From the plateau edge to the margin of the depression, the amounts of clay minerals assessed predominantly by the Al_2O_3 content remain almost unchanged in the soils from P1 to P2, and then decrease gradually from P2 to P5 (arrow 1 in Fig. 5a). These amounts are much higher in saprolites than in soils from P1 to P4 and then decrease abruptly in P5 (arrow 2 in Fig. 5a). As already reported from textural data, two clay-depleted zones are reported downslope close to the podzolic area (arrows 1 and 2 for P5 in Fig. 5a). In the deeper clay depleted one of P5 (arrow 2 in Fig. 5a), loss of clay minerals is also linked to an important loss of Zr (arrow 2 in Fig. 5c, note that the Zr values are there lower than that in the bedrock, materialized by a vertical dashed line on the figure). This likely indicates physical transfer and loss of zircon, of mostly silt particle size, due to the development of macro-voids in clay-depleted saprolite and abundant lateral fluxes in groundwater. As a matter of fact, Zr can no longer be used as a chemical invariant in such a place. The amounts of Fe-oxides, assessed by the Fe_2O_3 content, decrease laterally in soils, from P1 to P5 (arrow 1 in Fig. 5b). In the underlying saprolite, it decreases significantly from P1 to P2 that exhibits faint reddish yellow colours and reaches smallest values further downslope in bleached saprolites (from P3 to P5) (arrow 2 in Fig. 5b). Mass balance factor calculation ($_{j,w}$) confirms the vertical losses of Al and Fe from saprolites to soils on the plateau edge (Fig. 5d and e). Losses increase laterally towards the depression (from P1 to P5). Mass balance factors also show that 60% of the initial stock of Si from the bedrock is lost in saprolites following the dissolution of primary minerals (mostly feldspars and ferromagnesians) and the neoformation of clay minerals (Fig. 5f). In the overlying soils, Si losses slightly increase (arrow in Fig. 5f), likely due to greater dissolution rates of secondary minerals.



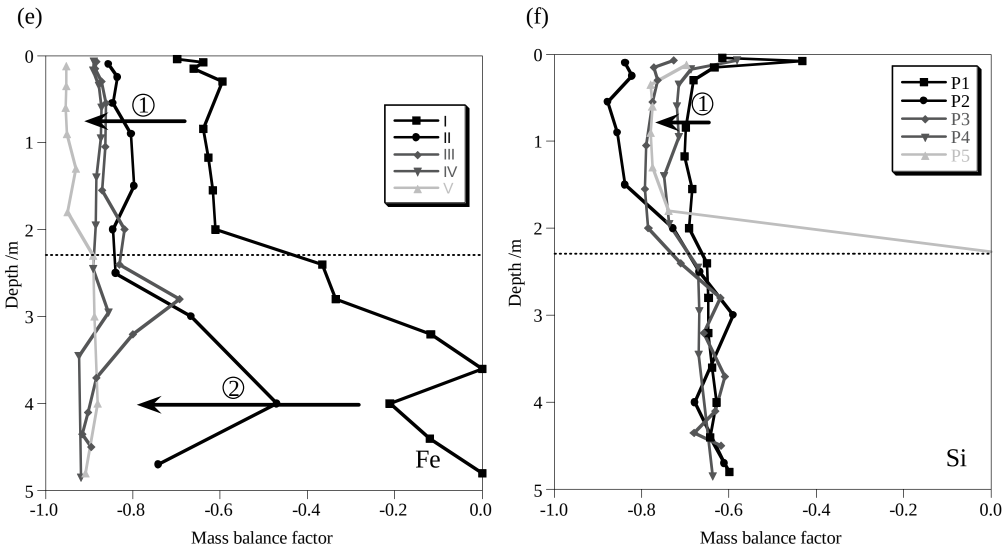


***Figure 5**. Oxides % for (a) Al_2O_3, (b) Fe_2O_3 and Zr contents (ppm) versus depth in bulk samples of the five profiles (P1 to P5), and mass balance factor with Zr as an chemical invariant for (d) Al, (e) Fe) and (f) Si in the same profiles (arrows 1 and 2 display the major lateral trends between profiles).*

The relative loss of Fe as compared to Al appears quite different in soils and saprolites, as illustrated by the Al_2O_3/Fe_2O_3 ratio as a function of the Zr content for all samples (Fig. 6). On the plateau edge in P1, the Al_2O_3/Fe_2O_3 ratio is equivalent in both saprolites and soils, indicating therefore an upward residual accumulation of both Al and Fe. Towards the depression from P2 to P5, this ratio also remains almost unchanged in soils. Al and Fe are thus exported simultaneously either by chemical erosion or physical transport. However the ratio increases slightly from the bottom to the top of each profile suggesting a greater dissolution of Fe-oxides than kaolinites. This trend is strongly amplified in bleached areas of the underlying saprolites thus indicating a massive dissolution of Fe-oxides.

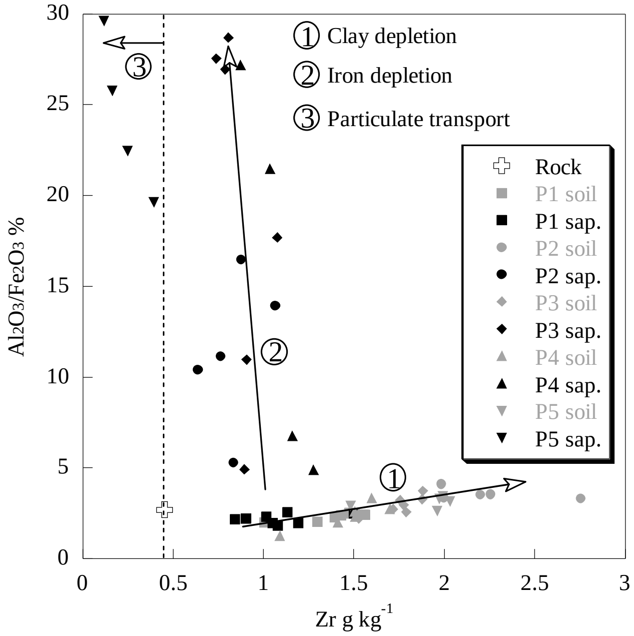


Figure 6*. Al_2O_3/Fe_2O_3 ratios of bulk samples in the five profiles (P1 to P5), showing the pathways for clay depletion, selective iron depletion and particle transport (1, 2 and 3 respectively in the figure) in soils (grey symbols) and saprolites (black symbols).*

Accessory elements (Ti, P, La, Ce, Yb, Th, U and Pb)

Accessory elements enable to distinguished saprolites from soils, as well as freely drained environment (P1 and P2), from more hydrated or waterlogged ones (from P3 to P5). The more abundant accessory element, Ti (up to 2.5% of TiO_2), is about half lost in saprolite according to mass-balance calculations (Fig. 7a). Petrographic observations (not shown) and electron punctual microprobe analyses (EPMA) (Tab. 1) relate Ti losses to the weathering of titanite crystals that surround opaque minerals (mostly poorly weathered magnetite) from rich-mafic

clots in the mafic-bearing granites. Such losses increase upwards and become stabilized in soils following the complete weathering of titanite. The remaining Ti in soils belongs to primary rutile and secondary anatase from XRD (not shown), and represents about 40% of the initial stock of Ti in P1 and 20% in the other profiles (Fig. 7a).

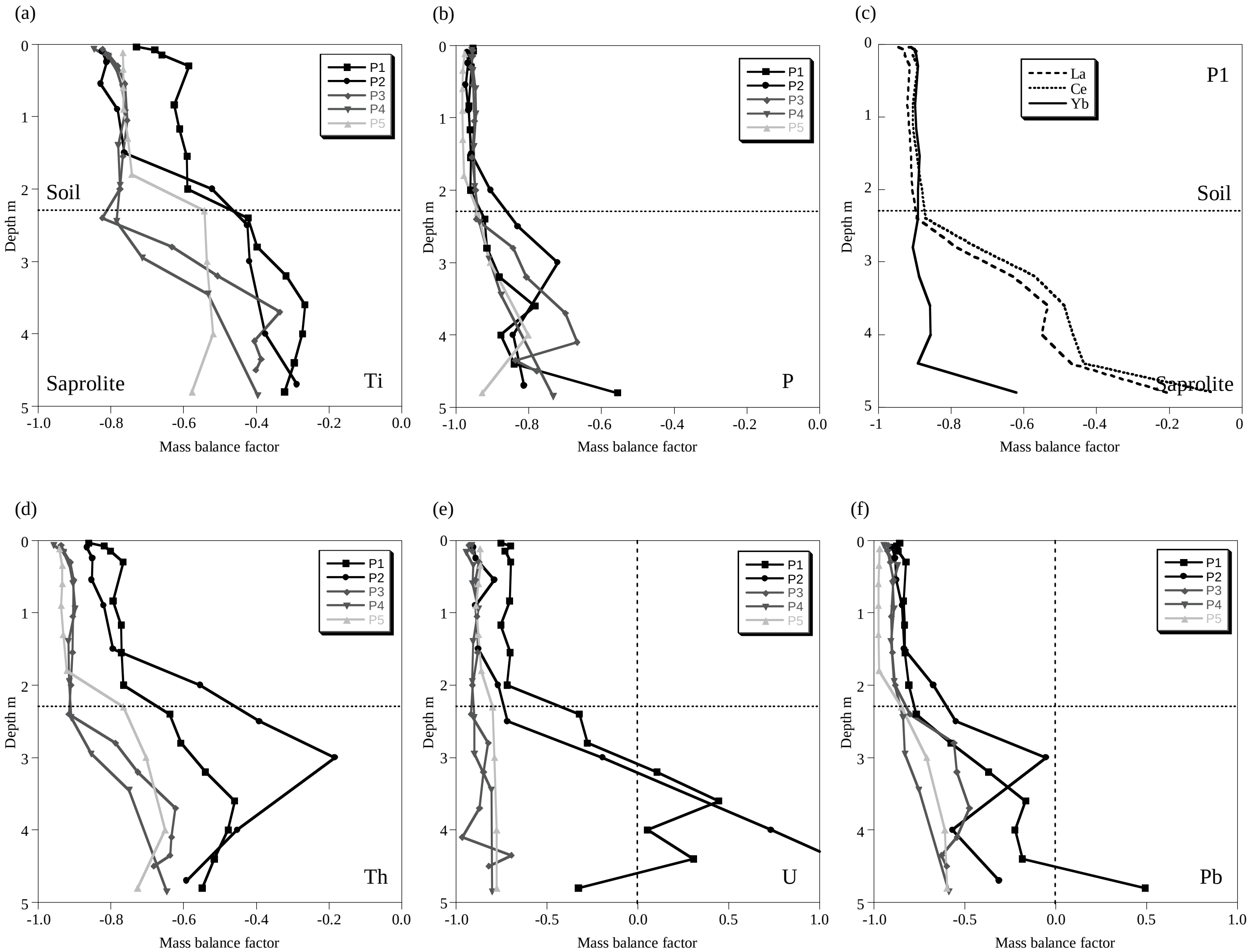


***Figure 7**. Mass balance factors versus depth for (a) Ti, (b) P in the five profiles (P1 to P5), for LEE (La and Ce) and HEE (Yb) in P1, and for (d) Th, (e) U, and (f) Pb in the five profiles (horizontal dashed line demarcates the saprolite from the overlying soil and the vertical dashed line relates to no loss or gain of chemical elements).*

Although present in much less quantities in the bedrock (Tab. 1), the phosphorous (P) and light earth elements (LEE) exhibit similar trends upward in saprolites and soils. Losses of P (Fig. 7b) and LEE (see La and Ce in Fig. 7c) are mainly attributed to the weathering of apatite and allanite crystals, respectively according to EPMA (Tab. 1). Phosphorous is almost completely lost in soils following the complete disappearance of apatite crystals. By contrast,

about 10% of the initial stock of LEE in preserved in soils. Heavy earth elements (HEE) behave differently than LEE in saprolites. They are more rapidly lost likely due to their incorporation in more easily weatherable minerals (see Yb in Fig. 7c).

Three other trace elements (Th, U and Pb) also display similar trends that however differ significantly from the plateau edge to the margin of the depression (i.e. from P1 to P5). Actinides in these lateritic regoliths are most likely incorporated in zircon (Balan et al., 2005) but also in apatite and allanite (occurrence of fission tracks in the surrounding primary minerals of the granite). The upward losses of Th (Fig. 7d), U (Fig. 7e) but also of Pb (Fig. 7f) is likely due to the opening of the decay chains of Th and U during the weathering of apatite and allanite. However, U and Pb behave differently between freely drained (P1 and P2) and poorly drained environments (P3 to P5). In P1 and P2, losses of both elements in soils are linked to gains of the same elements at depth (positive values are locally obtained for mass balance factors in saprolites). By contrast, this kind of vertical transfer does not occur from P3 to P5. Indeed, greater losses of both elements are reported in bleached saprolites and consequently smaller losses upward in soils. This confirms the downward accumulation of actinides in freely drained, red lateritic profiles and the contribution of Fe-oxides in the storage of these elements at depth (P1 and P2). The quite specific chemical behavior assigned to these accessory chemical elements during the vertical development of the lateritic regoliths must be linked to the occurrence of mafic bodies in the granitic rock basement of the transect.

3.4.3. Mineralogy of clay minerals

DRX (not shown) and spectroscopic data in the infra red (FTIR) and visible (DRS) ranges reveal a quite monotonous mineral composition for clay minerals (mostly kaolinite, gibbsite, hematite and goethite as secondary minerals and residual magnetite as primary mineral) but a high variability in the proportions of these minerals from bottom to top of the regolith and from the plateau edge to the margin of the depression in bulk samples of both soils and saprolites (Figs. 8 and 9). The changes in the proportion of the Al-bearing minerals (kaolinite and gibbsite) are assessed from FTIR (Fig. 8), whereas those of the Fe-oxides (hematite, goethite and magnetite) are deduced from second-derivative spectra - SDS (Fig. 9).

Al-bearing minerals (kaolinite and gibbsite)

The redder lateritic profile from the edge of the dissected plateau (P1) is easily differentiated from the other profiles (P2 to P5) by the much larger quantities of gibbsite in the pool of Al-bearing minerals. In this profile (Fig. 8a), the largest contents of gibbsite are reported in the saprolite, more specifically in the lower section of this layer and at different depths. In particular, Al hydroxides are almost exclusive at 3.6 and 4.8m deep. In the overlying soils, the relative proportion of kaolinite increases significantly and becomes nearly as abundant as gibbsite.

The reverse trend is observed towards the depression with dominant kaolinite in more yellowish soils and in the underlying faint red to bleached saprolites (i.e. from P2 to P5). Gibbsite is mainly observed in the soils, more specifically in their lower sections and is barely detectable in the underlying bleached and waterlogged saprolites (depths > 2.5m in Figs. 8b, c and d). According to such trends, the longer periods of episodic (soils) or more permanent (saprolites) water saturation in regoliths seem to restrict the formation of gibbsite. The vertical trends in profiles also suggest the downward accumulated of gibbsite following the dissolution of kaolinite in overlying regolith compartments. This vertical transfer of Al and precipitation of Al hydroxides is likely limited (hardly detected by mass balance factors) but slightly enhanced by textural discontinuities, in particular just above the rock/saprolite transition in freely drained environments (P1), and closer from the soil surface at the soil/saprolite transition in poorly drained environments (from P2 to P5). The upward depletion of clay minerals in soils and towards the depression is linked to simultaneous collapse of the OH vibration bands for both kaolinite and gibbsite (Figs. 8b, c and d).

In the dominant kaolinitic and poorly drained area of the transect (e.g. from P3 to P5 in Figs 8b, c and d), the high resolution of the two internal bands (3668 and 3652 cm^{-1}) for the out-of-phase motion modes of inner-surface OH groups reveal low defect kaolinites (Balan et al., 2001). Defect in kaolinites are better observed in normalised spectra, as larger crystallographic disorder are mainly linked to significant changes in the two internal bands, with a decrease of the magnitude of the band at 3668 cm^{-1} and a broader and intense band centred at 3650 cm-1 (Balan et al., 2005). Normalised spectra (not shown) reveal weak crystallographic changes both vertically and laterally along the transect. The well-ordered kaolinites always occur in saprolites, more specifically at different depths in P3 and P4 (kaolins, see for instance 3.9m deep for P4 in Fig. 8c). Disorder in kaolinites can increase slightly in the overlying soils (for example in P3 and P4), but always remains limited. This

strongly differs from other lateritic profiles of the Manaus region, where lateritic soils mostly consist of high defect kaolinites (Balan et al., 2005).

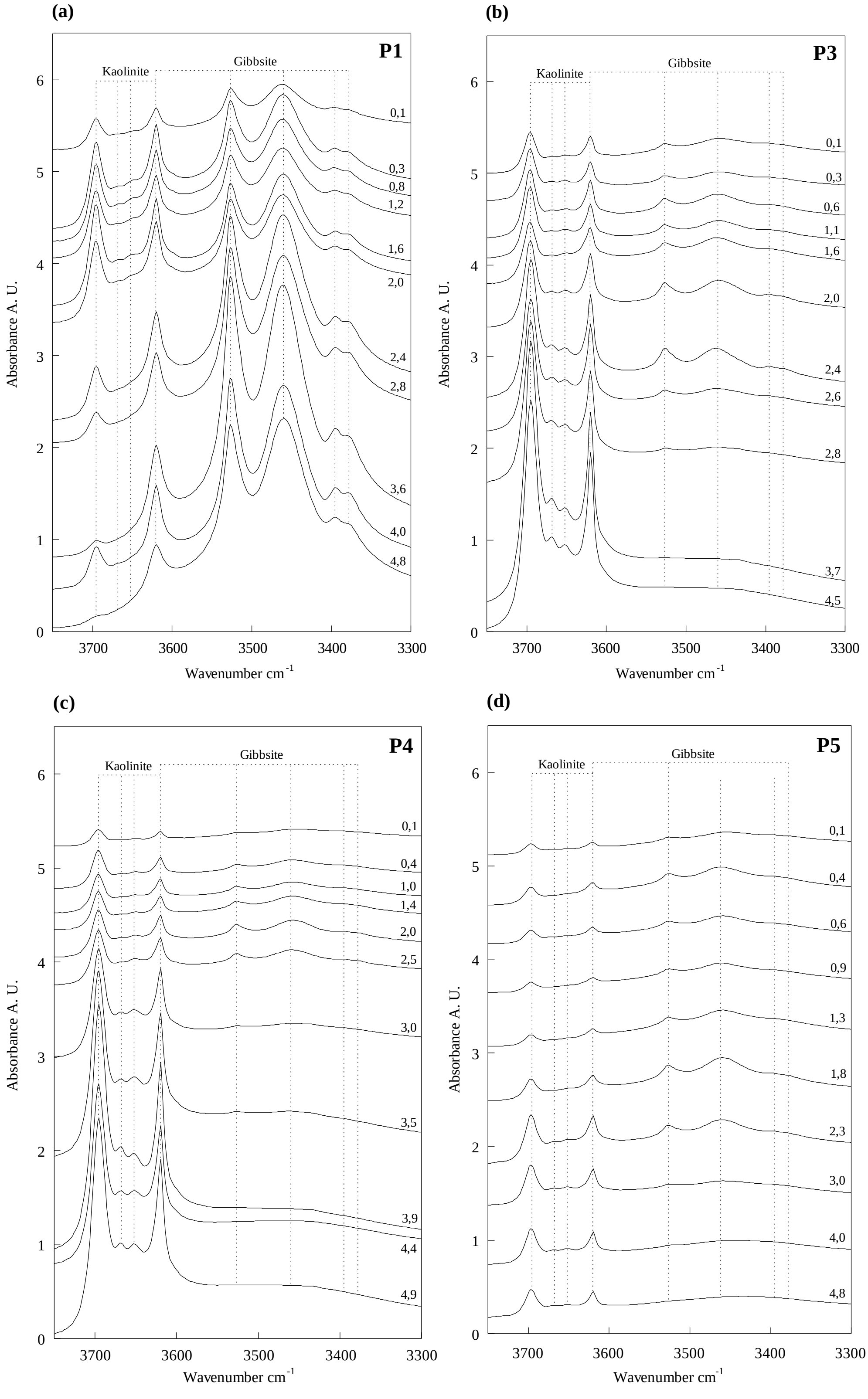


Figure 8. *FTIR spectra in the OH stretching region showing the four characteristic bands of kaolinite (3695, 3668, 3652 and 3620 cm^{-1}) and the five bands for gibbsite at lower*

wavenumbers (3620, 3527, 3460, 3395 and 3378 cm^{-1}), as well as changes in the intensity of the bands (or proportion of these Al-bearing minerals) in bulk samples of profiles (a) P1, (b) P3, (c) P4, and (d) P5 (P2 is not presented as it displays similar FTIR spectra than P3).

Fe-oxides (hematite, goethite and residual magnetite)

Major colorimeric changes observed both vertically and laterally at the border of the dissected plateau (from P1 to P2), are related to contrasted changes in the contents of hematite (Hm) and goethite (Gt) (Fig. 9). The proportion of hematite is much larger in saprolites than in the overlying soils, but also decreases significantly in saprolites from P1 to P2 (Figs. 9a and b). On this regards, the assignment of the three major bands for Hm and Gt are related to minima on the second derivative of the remission functions. In the saprolites, the low contents of Hm and Gt assessed by DRS, as compared to the amount of total Fe determined by chemical analyses, indicate large proportions of magnetite, which are easily recognized on thin sections. Upward in profiles P1 and P2, the amount of hematite decreases slightly and that of goethite increase strongly (Figs. 9d and e). Simultaneously the content of magnetite decreases drastically, more specifically in P1 (Fig. 9d). Accordingly, the intense weathering of magnetite in soils contributes largely to the formation of goethite. However, hematite to some extend seems also to contribute to the formation of goethite through dissolution/cristallisation cycles, as already proposed by Fritsch et al. (2005) in other lateritic profiles.

From the margin to the center of the plateau, yellowing in soils is at frist related to significant losses of Hm (from P1 to P2, Figs. 9a and b) and fading to losses of the remaining Gt (from P2 to P5, Figs. 9b and c, see also Figs 9e, f, g and h). Bleaching in saprolites is mostly assigned to the disappearance of both hematite and goethite (Fig. 9c, see also Figs 9f, g and h).

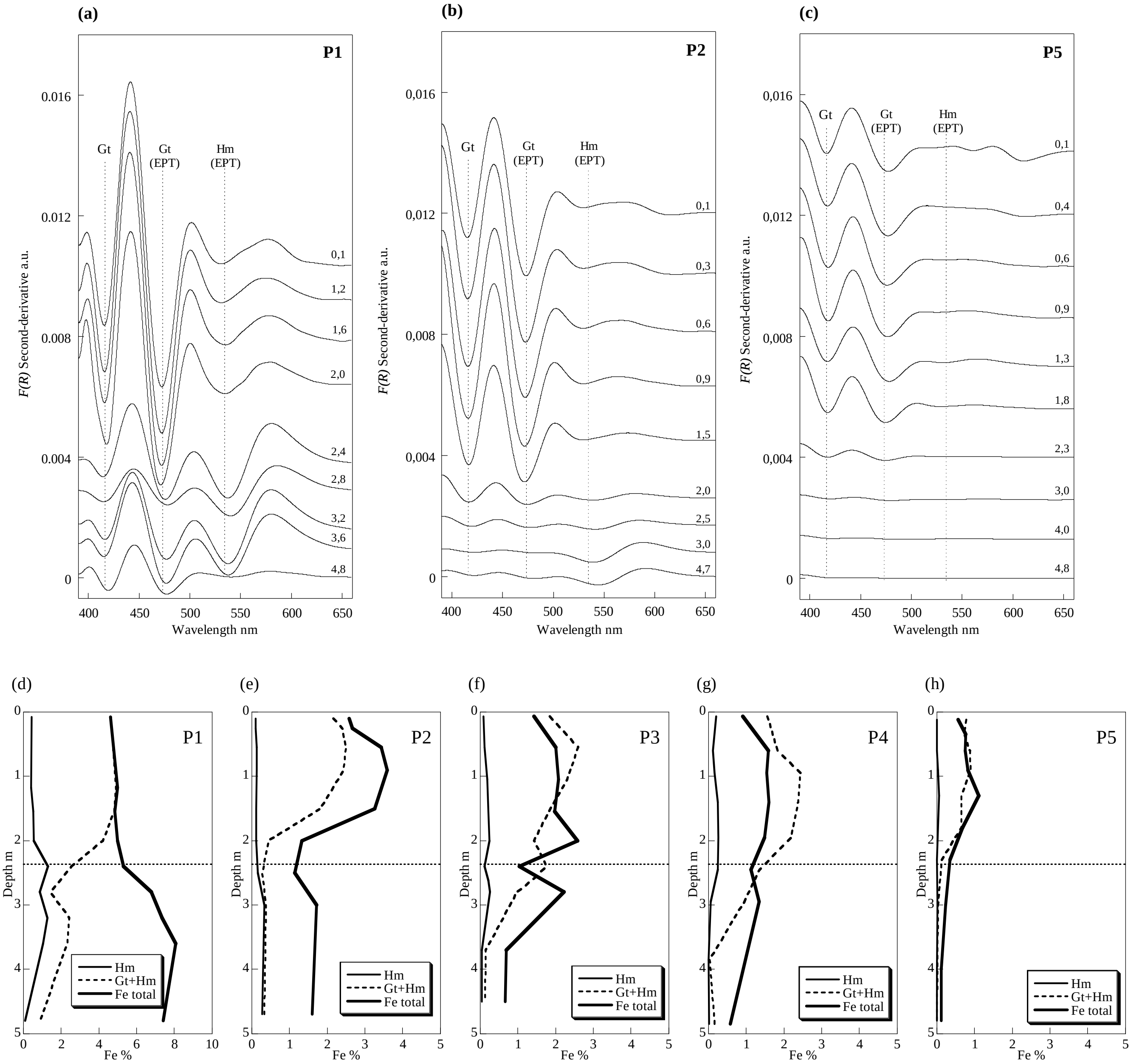


Figure 9*. Second-derivative spectra of the remission function f(R) (DRS) showing the absorption bands (minima) for goethite (Gt) and hematite (Hm) in selected bulk samples from (a) P1, (b) P2 and (c) P5 and assessment of the relative proportion of hematite (Hm,), goethite and magnetite (determined indirectly) from DRS and total chemical analyses in (d) P1, (e) P2, (f) P3, (g) P4, and (h) P5 (horizontal dashed line demarcates the saprolite from the overlying soil).*

3.5. Discussion and conclusions

The study enables to establish major geochemical and mineralogical changes in the vertical differentiation of lateritic profiles from (titanite)-(amphibole)-biotite granites of the margin of the Guyana Shield. It also enables to establish selective geochemical and physical erosion trends in their lateral transformation following the incision of *Ucayali* peneplain surface by the modern Amazon drainage system. River incision formed the low elevation plateaus of the upper Amazon Basin. In this kind of humid tropical landscape, the freely drained conditions favourable to the vertical development of red clayey laterites are preserved on the edges of the plateaus. They mainly result from the incision of the plateau edges by numerous tributaries of river systems. By contrast, poorly drained conditions have settled in the central parts of the plateaus and have likely increased in space and time. They have enhanced the lateral and internal erosion of laterites, generated depressions and prepared their ultimate transformation into highly degraded and waterlogged podzols. In the study site, the lack of sedimentary structures in regoliths from the edge to the centre of the plateaus then assigns the geochemical and physical erosion of laterites to yellowing in soils, bleaching in saprolites, as well as to an ultimate depletion of clay minerals in both kinds of compartments.

On the edges of the plateaus, lateritisation has led to complete depletion of base cations and partial loss of silica at the bottom of deeply weathered profiles and therefore to residual accumulation of Al and Fe in secondary minerals (kaolinite, gibbsite, goethite and hematite) following the complete dissolution of major primary minerals of the granites of the Uaupés Suite (mostly feldspars, biotites and amphiboles). The occurrence in these granites of pegmatites and mineralised zones have also generated differential chemical weathering processes and led to specific geochemical signatures in regoliths. Accessory minerals of the mafic-bearing granites, more resistant to chemical weathering, are indeed partly preserved in the overlying regoliths. They mostly consist of titanite, apatite, allanite, and magnetite, which are particularly rich in Fe, Ti, Ca, P, LEE and actinides.

As commonly reported in the tropics, lateritisation is a two-step process that first leads to the vertical development of thick saprolites and ultimately to the accumulation of more intensively weathered, bioturbated and aggregated products in soils (Gombeer and D’Hoore, 1971; Nahon, 1991; Tardy, 1993; Fritsch et al., 2002; Balan et al. 2005). The second weathering step frequently marks greater losses of chemical elements as well as relevant changes in the proportion and nature of primary and secondary minerals. In other deeply weathered lateritic profiles of the Amazon basin, these changes were mostly assigned to

decreasing size and increasing crystal disorder in populations of kaolinites, suggesting alternate dissolution - recrystallisation steps leading to residual accumulation of small and poorly ordered soil kaolinites (Balan et al., 2005). Changes in the nature and Al substitution rates of Fe-oxides were also reported upwards in these soils (Fritsch et al., 2005). In our study site, the upward transition between saprolites and soils also marks a decrease in the particle size of kaolinites, but is not linked to relevant changes in the crystal order of kaolinites. Indeed, low defect kaolinites in saprolites remains weakly altered upward in soils. By contrast, the transition also results in an intense weathering of the accessory mineral remnants inherited from the mafic bodies. In particular, it marks the complete disappearance of titanite, apatite and allanite, as well as the ultimate dissolution of magnetite that feeds the pool of secondary Fe-oxides (i.e. hematite and goethite) in soils.

The freely drained conditions prevailing at the margin of the plateaus also favour the crystallisation of hematite over goethite, as well as that of gibbsite over kaolinite, more specifically at depth in the highly porous saprolite. The larger amount of gibbsite at depth could also result from the downward accumulation of Al following the dissolution of kaolinite in the overlying soil compartment with however a global loss of this element to the rivers as pointed by mass balance factor calculations. This downward transfer of matter in oxic environments also affects actinides, which accumulate significantly at depth in iron-rich saprolites. The larger amounts of kaolinite and goethite in the overlying soil likely result from denser and less permeable materials, which are finely divided and more frequently and durably hydrated by rainfalls. This trend is enhanced laterally, illustrating therefore longer periods of hydration in soils or waterlogging in saprolites from the margin to the centre of plateaus. However, small quantities of gibbsite may still be produced and accumulated downward at the transition between soils and saprolite.

We also recognised two distinct compartments (soils and saprolites) subject to significant losses of matter from the plateau edge to the margin of depression. The first one corresponds to unsaturated soils that average 2.3m of thickness in our investigated site. In this upper compartment, losses of matter are progressive in space and probably slow in time. They are most likely linked to selective dissolution of clay minerals and soil leaching, which could result from increasing periods of soil wetting towards the depression of the plateau, particularly during the rainy season. In this soil compartment, losses of matter are at first limited. They are mostly assigned to selective dissolution of Fe-oxides, particularly hematite, and therefore related in the field to soil yellowing (e.g. Peterschmitt et al., 1996). This

chemical erosion is closely followed by the weathering of the remaining clay minerals (i.e. goethite and kaolinite) and thus to clay depletion and soil fading (Fritsch et al., 1989; Chauvel et al., 1977, Chauvel & Pedro, 1978). By contrast, losses of matter are more abrupt at two distinct places in the underlying saprolitic compartment. They are first related to the complete removal of secondary Fe-oxides (i.e. hematite and goethite) and therefore to bleaching under the action of the groundwater. They enable to differentiate in saprolites the saturated zone from the unsaturated one at higher elevations. Further downslope and at the margin of the depression, groundwater dynamics may also lead to depletion of fine clay particles in the upper part of the bleached saprolite, likely due to greater lateral water fluxes.

Losses of matter change the type of assemblage (from compact to granular) between coarse primary minerals (mostly quartz) and finer secondary clay minerals. These textural changes induce the development of macro-voids between quartz grains (Fritsch et al., 1989), which favour the transfer of fine particles (mostly clay but also silt) during gravity flows (Bruand et al., 1990). This leads us to suggest that chemical erosion (lixiviation) with preferential dissolution of F-oxides could at first prevailed in sandy clay to sandy clay loam soil horizons and favour particle dispersion and soil structure breakdown. Later on, the development of interconnected macro-voids in sandy loam to loamy sand horizons would also favours the transfer of suspended fine particles (first clay then silt) during lateral water flows and the formation of eluviated compartments and close to major groundwater reservoirs (Bocquier, 1971; Boulet, 1974; Fritsch et al.,1990a, 1990b; Bravard and Righi, 1990; Lucas et al., 1996).

Losses of matter in the unsaturated topsoils and at greater depth in the waterlogged saprolites lead to the formation of a highly porous eluvial compartment that clearly displays a double tongue-like shape transition towards upslope positions. The abundant and interconnected macro-voids produced in this compartment enable the downward migration of humic substances in soils, their accumulation at depth and at the margin of the depression in clay-depleted laterites. This accumulation of organic matter in less permeable materials tends to waterproof the periphery of the eluvial compartment thus favouring the implementation of a perched groundwater in newly formed podzols, which are widely spread in the region. The study thus reveals that yellowing, bleaching and losses of clay minerals in soils and saprolites are preliminary steps to podzolisation. It also points out that the characteristic and spectacular double tongue-like shape transition, which demarcates the upslope clay-depleted laterites from the downslope podzols, has been acquired before the transfer of organic substances, by chemical and physical erosion and according to major hydraulic fluxes in regoliths.

Acknowledgements

The research was funded by CAPES-COFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l'Univers du CNRS), through the "Ecosphère continentale" programme: "Podzolisation des latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)".

CAPITULO 4. PODZOLIZAÇÃO DOS SOLOS LATERÍTICOS E INCISÃO DOS PODZÓIS HIDROMÓRFICOS NO ALTO RIO NEGRO

Résumé

Le chapitre présente les résultats d'une étude minéralogique et structurale d'une séquence de sols développés sur les granites de la formation Uaupés de la région de São Gabriel da Cachoeira, à la bordure des aires fortement podzolisées du bassin versant du Curicuriari (site 4). Ce bassin versant, podzolisé sur prêt de 95% de sa superficie, présente des eaux noires et des sables blancs dans les lits de ses principaux tributaires, attribués à l'érosion physique des podzols. Appartenant aux vastes pénéplaines podzolisées et inondées d'une surface d'érosion, la séquence débute sur une colline résiduelle à latérite et se termine dans un bas de versant convexe résultant d'une incision d'un tributaire du Curicuriari. Le long de cette séquence de 80m de long, six tranchées de sols et d'altérites ont été ouvertes, décrites et échantillonnées. L'étude intègre des caractérisations pétrographiques, minéralogiques (DRX, IRTF et DRS), géochimiques et des calculs des fonctions de transfert (éléments majeurs et en trace). Dans un premier temps, l'étude vise à établir les analogies minéralogiques et structurales par rapport à ce qui a déjà été révélé dans les environnements podzoliques peu incisés de la région du Jaú (site 3). Les principales différences entre sites (3) et (4) sont abordées dans un second temps. Elles nous conduisent à traiter des effets des incisions du réseau hydrographique sur la morphologie et géochimie des podzols et donc des interactions entre podzolisation et incisions en relation avec la dynamique des nappes dans les paysages.

De grandes analogies sont révélées entre les deux sites d'étude ce qui laisse présager d'une grande similitude de processus et de fonctionnement dans la mise en place de ces podzols. La plus importante est la reconnaissance des mêmes ensembles structuraux, avec les sols jaunes appauvris surmontant les ensembles hydromorphes, essentiellement saprolitiques, des laterites de l'amont et les aires podzoliques de l'aval. L'autre analogie de grande importance, qui a toujours été reconnue lors d'étude de séquence de sols en Amazonie, est la transition latérale en forme de "double langue" entre laterites et podzols. La langue supérieure témoigne d'un développement de podzols faiblement différenciés sur les latérites (horizons éluviés surmontant un horizon spodique Bhs). Plus à l'aval, la base de podzols mieux différenciés repose en profondeur sur les saprolites hydromorphes des latérites. Elle se prolonge à l'amont dans la partie supérieure hydromorphe des latérites formant ainsi la seconde langue inférieure de la transition (cette dernière peut correspondre en 3D à des chenaux remontant le versant sur plus de 15m). Cette connexion témoigne de ce fait d'interactions entre deux systèmes de nappe : (i) une nappe phréatique à eaux claires pour les latérites amonts et (ii) une nappe perchée à eaux noires dans les horizons sableux des podzols. Ces distributions relatives montrent également le contrôle des discontinuités structurales (dans le cas de l'étude entre sol et saprolite) dans le développement vertical des podzols et sa contribution dans la différentiation des horizons spodiques. En effet, la discontinuité sol-saprolite limite le développement vertical des podzols et favorise à l'inverse son expansion latérale dans les paysages. Par ailleurs, l'horizon Bh s'individualise à la base ou périphérie des réservoirs sableux des podzols et l'horizon BCs dans la partie supérieure des saprolites hydromorphes sous jacentes. Les accumulations absolues de matières organiques dans les horizons spodiques des podzols réduisent la porosité de ces matériaux et assurent de ce fait la mise en charge de la nappe perchée. Des reliques de matériaux latéritiques imprégnées par la matière organique dans les aires podzoliques aval montrent également que le précèdent équilibre entre structures et fonctionnement de nappe est précaire et que ces systèmes podzoliques peuvent se développer assez brutalement vers l'amont.

De grandes analogies minérales et géochimiques sont également établies entre les deux sites. Les latérites jaunes appauvries de l'amont sont dominées par le quartz mais aussi par des phases minérales résiduelles, essentiellement de la kaolinite mais aussi de la gibbsite et goethite. L'étude montre aussi, et d'une façon plus claire que dans celle du Jaú, que l'enrichissement en gibbsite dans le niveau saprolitique sous-jacent (essentiellement dans sa partie supérieure) est relié à une baisse des teneurs en kaolinite et que cette gibbsitisation bien

marquée à l'amont de la séquence tend à s'estomper vers l'aval. Ces évolutions minéralogiques ne vont pas sans rappeler notre précédente étude sur la pré-podzolisation et confirment de ce fait qu'elles soient bien antérieures à la podzolisation. Le calcul des fonctions de transfert révèle pour les éléments majeurs et en trace une altération latéritique dominante couplée à une perte considérable de matières (essentiellement en Al, Si et Fe) qui est attribuée en grande majorité à un appauvrissement de ces sols en minéraux argileux. Ces calculs montrent également que cet appauvrissement a affecté la partie supérieure et la plus altérée du niveau saprolitique. Ce dernier a de ce fait été scindé en une saprolite fine très altérée et appauvrie, surmontant une saprolite plus grossière, moins altérée (grains de microcline, anorthite, amphibolite) et non appauvrie. Si les pertes attribuées à la podzolisation restent minimes (moins de 12% de l'Al total et 5% du Fe total de la roche), elles n'en demeurent pas moins significatives. L'étude montre aussi l'importance non négligeable du transport particulaire dans ces pertes de matières en environnement podzolique ou pré-podzolique. Dans les horizons sableux blanchis, les plus poreux des podzols, nous révélons ainsi une perte significative en éléments traces (surtout Ti et Th, mais aussi Zr à l'aval de la séquence), présents dans des phases minérales réputés stables et difficilement altérables (rutile, anatase, thorianite, zircon…). Ces éléments se retrouvent accumulés dans les horizons spodiques sous-jacents (Ti plutôt dans Bh et Th plus en profondeur dans BCs). Ces accumulations absolues pourraient résulter de la formation et du transfert vertical de complexes organo-métalliques (comme pour Al et Fe). Toutefois, elles ont pu être reliées pour l'un d'entre eux (Ti) à un accroissement très important des phases minérales porteuses de l'élément considéré (anatase), confirmant de ce faite le transfert de particules de la taille des argiles (<2 µm) dans les podzols. Ce transfert d'éléments fins est confirmé plus à l'amont par la présence de revêtements argileux (cutanes) dans les horizons blanchis et appauvris (Bg) du sommet du réservoir de la nappe phréatique des latérites. Enfin et comme dans la séquence du Jaú, l'accumulation de substances organiques dans les horizons spodiques des podzols peu différenciés (Bhs), ou plus en profondeur de ceux de podzols mieux différenciés (Bh et BCs), est couplée à une accumulation de métaux, qui s'observe aussi à plus grande profondeur pour Al (dans Bhs et BCs) que pour Fe (essentiellement dans Bh).

Les podzols incisés de cette site (4) présentent des différences notoires par rapport à ceux étudiés antérieurement au Jaú (Site 3) dans des dépressions. Ces différences s'observent à deux niveaux : (i) à l'amont au niveau des fronts latéraux de podzolisation, soulignés en surface par un léger affaissement topographique, et (ii) à l'aval des versants qui acquiert alors

une forme convexe du faite d'une érosion régressive par les rivières. A l'amont, les accumulations de matières organiques sont nettement moins abondantes dans les fronts de podzolisation, plus particulièrement dans les horizons spodiques des podzols peu différenciés (moindre épaisseur des horizons Bhs), mais aussi dans les horizons Bh (fins et discontinus) de la bordure des réservoirs sableux. D'autre part, la plus grande abondance de ségrégations ferrugineuses dans les saprolites hydromorphes jouxtant les aires podzoliques de l'amont témoigne de périodes d'oxydation plus prolongées. A l'aval, l'érosion du bas de versant semble propice à une nette réactivation du processus de podzolisation. Cette réactivation se traduit par la descente du front de podzolisation dans les saprolites fines puis grossières des latérites et la formation d'une seconde génération d'horizons spodiques très fortement imprégnés par les substances organiques. De l'amont vers l'aval des aires podzolisées, l'accroissement en profondeur des imprégnations organiques dans les horizons illuviés ou spodiques est étroitement couplé à un épaississement des horizons éluviés de surface où prédominent les résidus organiques. Ce gradient latéral affectant à la fois les horizons éluviés et illuviés des podzols peut dans un premier temps être attribué à une augmentation des apports organiques, avec le développement d'une forêt plus ouverte à l'amont en milieu mieux drainé et d'une forêt dense ripariènne dans la zone d'affleurement de la nappe à l'aval. Il est aussi le reflet de conditions de drainage contrastées. Le rabattement des nappes à l'amont des aires podzoliques améliore les conditions de drainage, réactivant de ce fait la minéralisation des substances organiques des horizons spodiques des podzols et libérant de ce fait les métaux préalablement associés à ces composés organiques. A l'inverse, le maintien de conditions anoxiques en bas de versant favorise l'accumulation de substances organiques sans doute plus récentes. La faible acidification de ces nouveaux environnements podzoliques riches en minéraux altérables favorise la production de grandes quantités de complexes organo-métalliques (principalement Al).

4.1. Introduction

We present in this study results of geochemical, mineralogical and structural investigations performed along a 80m long soil catena, which illustrated the lateral transition between clay-depleted laterites and podzols, and the consequences of the downslope incisions of waterlogged podzols by river incisions. Soils of the catena are formed on granites of the Uaupés Suite and are localised 30km West of the town of de São Gabriel da Cachoeira, at the

border of the widely podzoliszed region of the Curicuriari subcatchment (Radam Brasil, 1974). This subcatchment is located in the high rainfall region of the upper Negro River watershed and covered by waterlogged podzols on 95% of its surfaces. It is then dominantly drained by black waters and presents in major riverbeds white sands from the physical erosion of podzols. Belonging the huge podzolised and waterlogged peneplains of the *Ucayali* surface (Campbell et al., 2006), the soil catena extends from yellowish clay-depleted laterites on a residual hill-top of the peneplain to waterlogged podzols eroded by a tributary of the Curicuriari river. Results of this study are compared to those obtained previously on less podzolized landscapes and drier climates of the Jaú region, 600km South East of São Gabriel da Cachoeira in the middle Negro River Watershed (Nascimento et al., 2004). In the Jaú region, small areas of poorly drained waterlogged podzols are found in the central parts of low elevation plateaus. The main objectives of this study is to establish the structural and mineralogical analogies between both types of soil catena and to reveal the major differences, which mostly result from the incision and drainage of waterlogged podzols of the upper Amazon Basin.

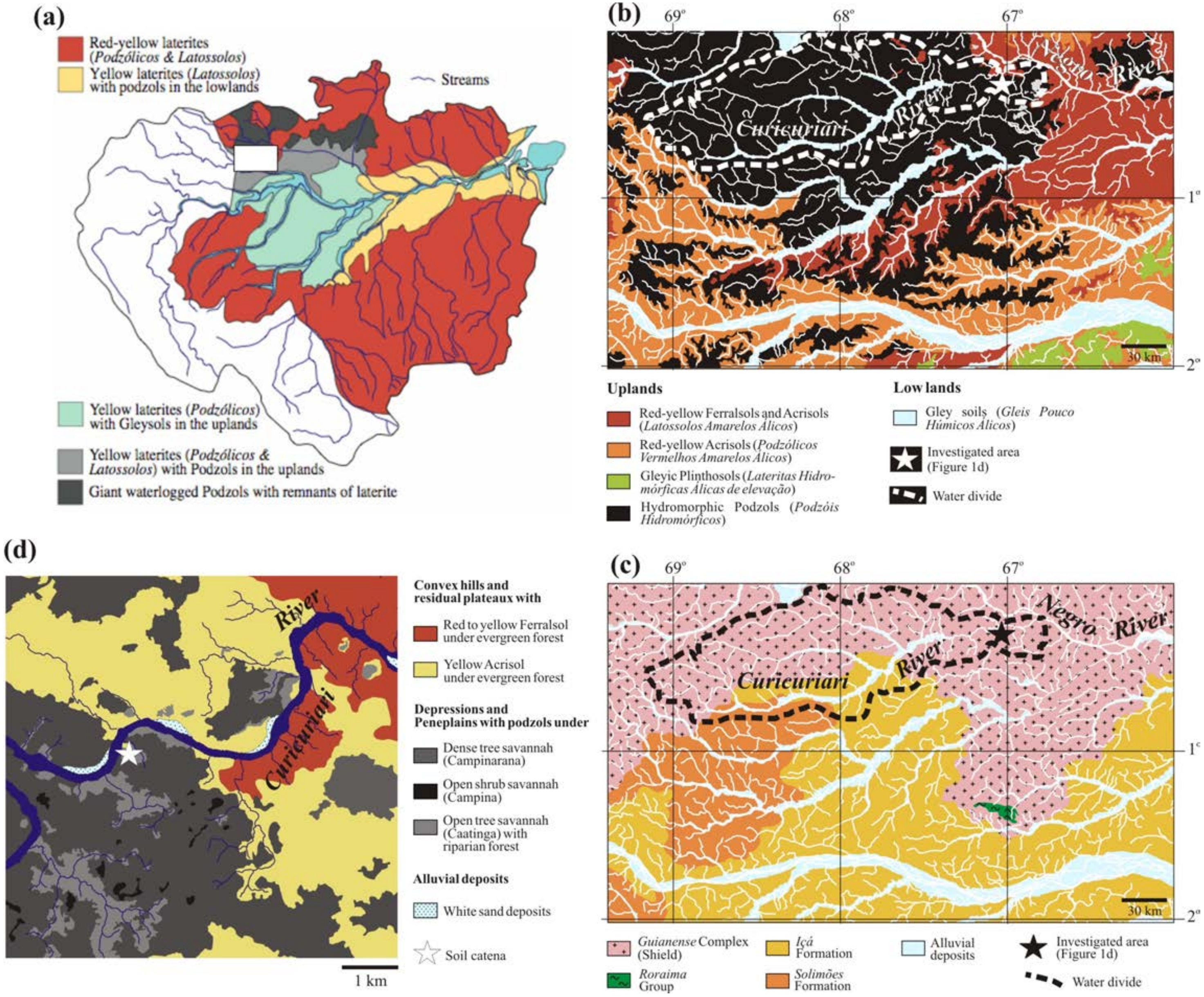


***Figure 1**. (a) Broad scale soil map of the Brazilian Amazon Basin (reduced and simplified from Radam Brasil maps at 1:2 500 000) showing the extent of podzols in the upper Basin (white rectangle insert refers to Figure 1b,c). (b) Regional soil and (c) geological maps (extracts from the Radam Brasil maps at 1 :1 000 000) showing the distribution of Gleyic Plinthosols and Hydromorphic Podzols in relation to better drained lateritic soils (Ferralsols and Acrisols) of the low elevation peneplain formed on both rock and sedimentary formations (stars insert refers to Figure 1d). Note that the Curicuriari watershed (water divide in dashed line) is almost completely podzolised. (d) Local geomorphological and vegetation map at the lateral weathering front between laterites and podzols (white star insert refers to the soil catena).*

4.2. Materials and methods

Soil description and sampling

Soil profiles were photographed on clean cuts trenches and pits and described according to the ISRIC-FAO (1994) vocabulary along a 80m long soil catena. Photographs (Figure 2a) and soil description allowed the construction of a bi-dimensional representation of the soil organization along the catena using graphic softwares (Figure 2b) (Rinder et al., 1994). The soil catena illustrates the transition between well-drained Acrisols and waterlogged Podzols of the low elevation peneplain of the upper Rio Negro watershed (Figure 1d). A small brook of the Curicuriari River incises the downslope podzols of the catena. This brook is 5m below the hill-top level with Acrisols. The soil catena presents a convex sloping side and extends from a forest on the hill-top to a *Caatinga* in the midslope position and an inundated riparian forest near the brook.

Soil profiles were described in detail and sampled at 8 key sites along the catena (I to VIII in Figure 2b). A total of 89 bulk samples were collected vertically in soil and saprolite of the investigated profiles for chemical, physical and mineralogical investigation. We also sample in cardboard boxes 32 undisturbed fragments of soil horizons, saprolites and rocks from pits or nearby riverbed outcrops. Air-dried undisturbed samples were oven dried at 35^{o}C during 1 week, impregnated with resin, cut and ground for thin section elaboration according to Fitzpatrick (1970). Thin sections were observed with a Zeiss Axioskop 40-Hall 100 microscope, under plain-polarized light (PPL) and cross-polarized light (CPL).

Chemical and physical analyses

Air-dried soil samples were sieved through a 2-mm screen prior to chemical and physical analyses. Particle-size distribution was determined by sieving (sand fractions) and pipetting (clay and silt fractions), after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. pH was measured both in water and M KCL (soil:solution; 1:2.5). Organic C and N were determined on air-dried samples using a Carmograph LECO CHN analyser. Total chemical analyses were performed at Actlabs Ltd (Canada) on crushed and pulverised samples passing a 150-mesh (106 µm) sieve. Chemical composition of the samples was determined by inductively coupled plasma atomic emission spectrometry for major elements and inductively coupled plasma atomic mass spectrometry for trace elements. Mass balance factors (j,w) were calculated vertically at the 8 sampling sites (Figure 2b) according

to the iso-element approach of Brimhall et al. (1991) to assess the relative losses or gains of major and trace elements. Calculations were done as follow (Chadwick et al., 1990):

$$_{j,w} = \frac{C_{j,w} / C_{i,w}}{C_{j,p} / C_{i,p}} - 1$$

where Cj,w and Ci,w is the concentrations of the element (j) and the invariant (i) in the weathered material (w), respectively; and Cj,p and Ci,p is the concentrations of the same elements (j and i) in the protore or parent rock (p) .

X-Ray diffraction and spectroscopic analyses

Mineralogical composition of the samples was assessed on fine earths (<2mm) and clay size fractions (<2µm) by powder X Ray Diffraction (XRD) with a PHILLIPS PW 1730 using Cu K radiation and operating at 40 kV and 30 mA. XRD patterns were collected for 2 angles ranging from 3 to 90° with a 0.03° steps and a counting time of 15s per. Fine earth samples were manually ground to powders (± 30 m) in an agate mortar and prepared according to the technique of the "back pack-mounted slide" (Bish and Reynolds, 1989). Identification of the mineral phases was carried out by comparing the experimental XRD patterns with those from the mineral references of the ICDD data set.

Fourier-transform Infra-Red spectroscopy (FTIR) was performed in the transmission mode using a Nicolet Magna 560 IR Spectrometer. One mg of oven-dried and dispersed clay was mixed with 300 mg KBr and pressed twice at 10 ts.cm^{-2} to form a KBr disc. The KBr discs were heated at 105°C overnight to remove absorbed water. The spectra were run in the 400 to 4000 cm^{-1} range with a 2cm^{-1} resolution.

Diffuse reflectance spectra were obtained from gently ground bulk samples, oven dried at 60°C overnight. Samples were put into a 27 mm diameter hole in an Al disk (3 mm thick) then gently pressed against a quartz glass. Spectra were taken from 200 to 2500 nm at 0.1 nm increments using a Cary 5G US/VIS/NIR spectrophotometer with a 150 nm integrating sphere (Labsphere, Inc., USA). Reflectance measurements were made relative to a teflon standard covered with a quartz glass. The wavelength-dependent reflectance functions were transformed into remission functions, which were smoothed using a cubic spline fitting procedure then the second derivatives were calculated (Malengreau et al., 1996). The same smoothing and derivative parameters were applied for all the spectra.

Colours were determined from the reflectance curves in the visible range (from 360 to 830nm) as follows: the CIE tristimulus values (X, Y, Z) were computed from the spectral reflectance and energy of the light source for each wavelength using the colour matching functions of the CIE standard illuminant C (Wyszecki & Stiles, 1982). Tristimulus values were converted into colour units (x, y and Y%) of the CIE System (1931) and in those of the Helmholtz coordinates (L_d and P_e). They were ultimately plotted in the colour diagram of the visible range. In this diagram, the dominant wavelength (L_d) is the slope between the white light source and a given dot, and is related to the tint of the sample. The excitation purity (P_e) is equivalent to the chroma of the Munsell colour chart. It is scaled between 0 % for a colourless sample and 100 % for a pure colour monitored at the output of a monochromator (Bedidi et al., 1992).

4.3. Results and discussion

Vertical and lateral soil differentiation along the catena

According to structure and consistency, two superimposed and unconsolidated sets of horizons can be distinguished over the fresh granitic basement (R) of the catena (Figure 2): (1) a dense and compact saprolitic layer (C, CB and BC horizons), and (2) a loose soil mantle (A, AE, B and E horizons) less than 2.5m thick. The saprolite lacks soil structure, and presents a continuous groundmass. At the base of the saprolite, the porphyric texture and heterogeneous colours of the granite are preserved (C and CB horizons). Coarse sands (200 – 2000µm) are abundant (Figure 3a) and primary minerals are partly weathered (Figure 3b). More strongly weathered materials with finer sands are observed in the upper section of the saprolite, mostly in midslope positions (BC horizons), but also in the overlying soil mantle (A, AE, B and E horizons) (Figure 3a,b). However in the downslope position, the lower part of the soil mantle (E/C horizon) exhibits coarse sands and partly weathered primary minerals, as in the underlying coarse saprolite (C and CB horizons) (Figure 3a,b).

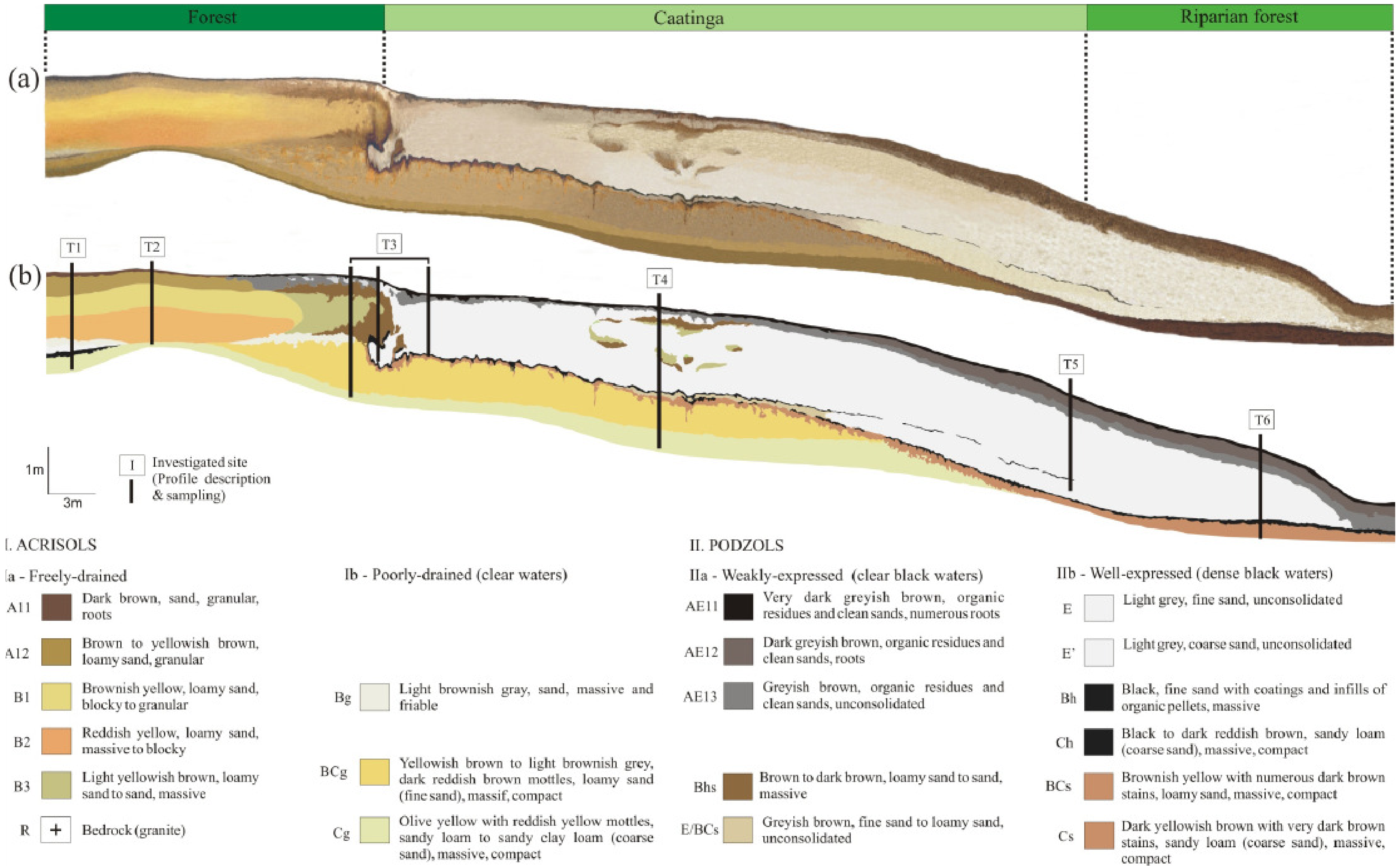


Figure 2*. Soil catena and type of vegetation from a hill-top to a major incision of a tributary of the Curicuriari River: (a) photo composition of pits and trenches used with detailed field descriptions to delineate (b) the major horizons at the weathering front between Acrisols and Podzols. Horizons are grouped in three major compartments of contrasted hydro-geochemical properties (I, II and III).*

The saprolite and soil mantle can further be dissociated in three main compartments according to texture and colour (I, II and III in Figure 2). The three compartments correspond to: (1) the freely drained topsoil A and B horizons of Acrisols on the hill-top, (2) the hydromorphic subsoil Bg, BCg and Cg horizons of Acrisols in upslope and midslope positions and (3) the eluviated topsoil (AE & E) and illuviated subsoil (Bhs, Bh, BCh & BCs) horizons of podzols in midslope and downslope positions. Similar types of compartments were already recognised in the podzolised soil landscapes of the upper Amazon Basin (Dubroeucq et al., 1999; Nascimento et al., 2004). They were assigned to contrasted hydrological regimes and geochemical environments, with clear waters in permanent deep groundwater for the upslope and hydromorphic subsoil, and black waters in perched groundwater for the downslope podzolic area (Nascimento et al., 2008). Moreover, the drastic hydro-geochemical change reported in the topsoil between the upslope Acrisols (freely drained) and the downslope podzols (acidic and periodically waterlogged) has significant impacts on the vegetation. It explains that the structure of the vegetation match those of the soils (Figure 1d, 2a).

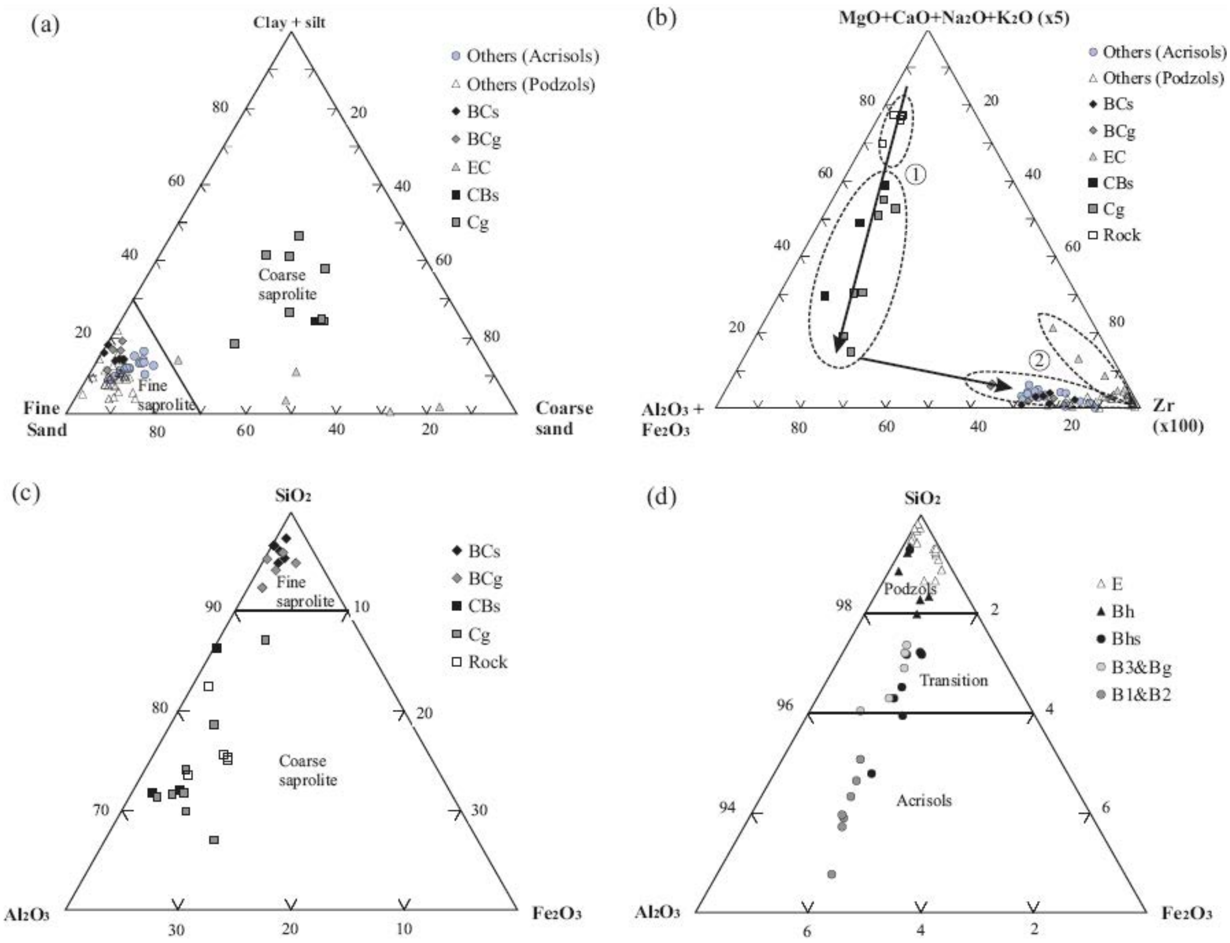


Figure 3*. (a) Textural and (b) chemical plots of major horizons in ternary diagrams showing (a) large proportion of coarse sands and (b) less weathered materials at the base and downslope part of the soil catena (C, BC and E/C). Proportion of SiO_2, Al_2O_3 and Fe_2O_3 in*

ternary diagrams of (c) saprolite and (d) soil horizons of the soil catena, illustrating (c) the drastic loss of Al- and Fe-bearing minerals from the coarse to the fine saprolite and (d) the minor but ultimate loss of such minerals from the upslope Acrisols to the downslope podzols.

The 1st compartment on the hill-top of the catena is covered by forest. The relative homogeneity of its A and B horizons, and their light textures and blocky to granular structures are indicators of a freely drained environment with dominant vertical water flows. The mineral B-horizons are loamy-sand and present the largest clay contents of the soil mantle (8 - 12%). They grade progressively upwards from reddish yellow (7.5YR6/8) in B2 to brownish yellow (10YR6/6) in B1. Under microscope, the iron coloured clay domains are scattered, around or between close packed quartz sands (Figure 4d). Towards the surface, the slight decrease in clay contents and net increase in organic matter leads to the differentiation of the yellowish brown to dark brown (10YR4/3 - 5/6) A12 and A11 horizons. Laterally, the mineral B1 and B2 horizons give progressively place to a light yellowish brown (2.Y6/4) B3 horizon, which marks the transition with the downslope podzols. This last horizon reveals a slight decrease of the clay content and a complete soil structure breakdown.

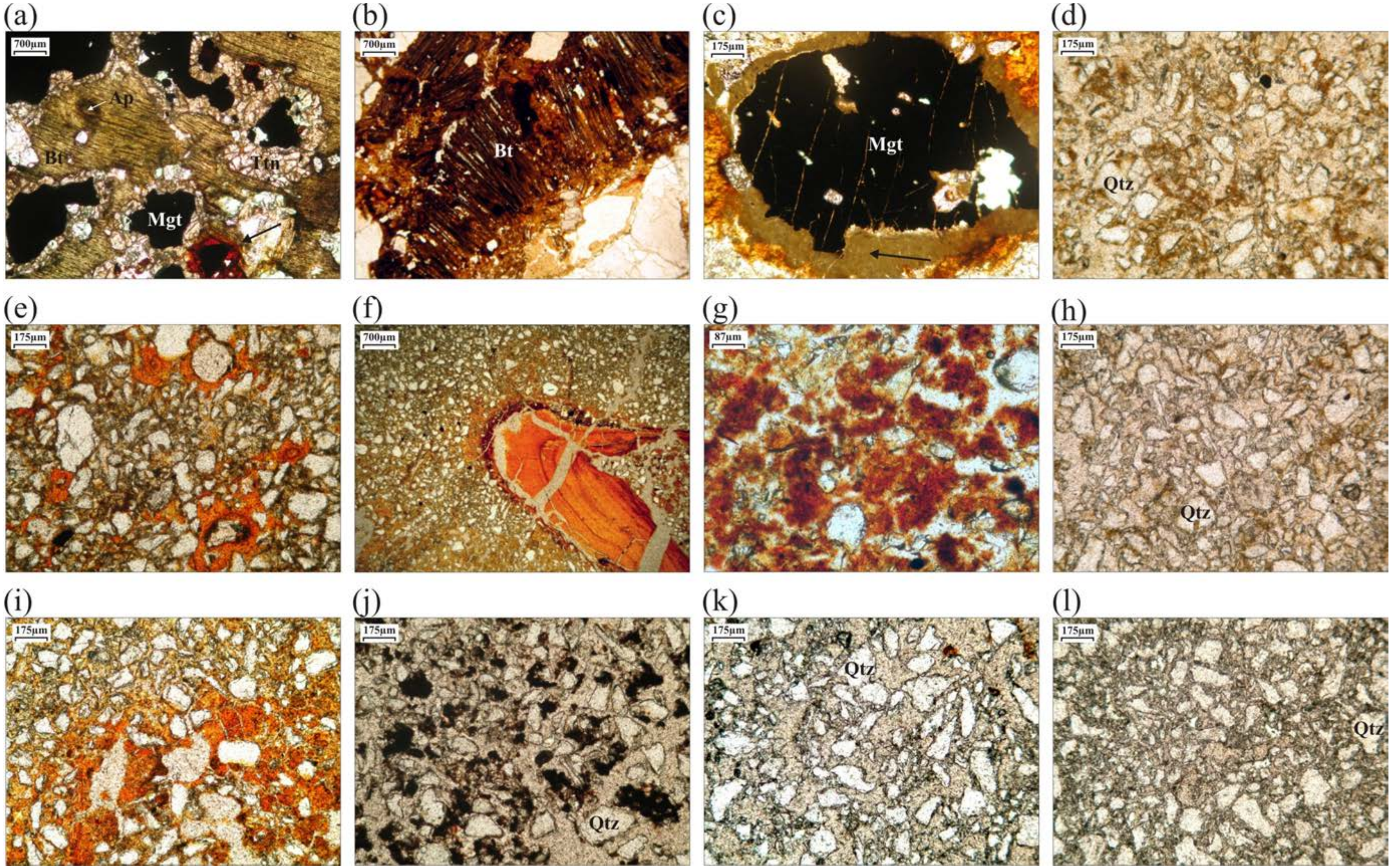


***Figure 4**. Petrographic fabrics of rocks and soil horizons under unpolarized light: (a) detailed view of a mafic body in the granite showing large crystals of biotite (Bt) with smaller inclusions of magnetite (Mgt) surrounded by grains of titanite (Ttn), note red weathered products at the*

margin of a magnetite (black arrow) and an apatite crystal (Ap) with surrounding fission tracks in biotite, (b) weathered biotite (Bt) residues strongly impregnated by Fe-oxides in coarse saprolite (BC2g), (c) yellowish brown weathered products (arrow) of titanite at the margin of a magnetite grain in coarse saprolite (BC2g), (d) dispersed iron coloured clays around or between close packed quartz sands (Qtz) in B-horizon of Acrisols, (e) reddish iron stains around quartz grains or on pore walls in fine saprolite (BC1g), (f) dark reddish iron stains on the wall of a macrovoid and cracked clay cutan infill variously coloured by Fe-oxides in fine saprolite (BC1g), (g) Dark brown organic compounds coating clay minerals in Bhs horizons of podzols, (h) low proportion of clay minerals between close packed assemblage of quartz (Qtz) in Bg horizon, (i) Dark brown, fine-grained and cracked organic coatings on clay minerals in the upper part of the fine saprolite, (j) Black organic decays aggregated in pellets that infill incompletely the interstices between quartz grains in Bh horizon, (k) sandy and porous AE horizons of podzols with dispersed fresh organic residues and black organic pellets, (i) close packed assemblage of quartz (Qtz) in E horizons of Podzols.

The 2nd compartment of the catena is observed at greater depth in upslope and midslope positions and related to Bg, BCg and Cg horizons (Figure 2), which clearly exhibit redoximorphic features. It thus corresponds to the aquifer of the deep groundwater. At the base of this compartment, the coarse saprolite (Cg) is sandy loam to sandy clay loam and is highly heterogeneous, with a dominant olive yellow colour (2.5Y6/6). The coarse saprolite may contain up to 35 wt% of clay, which are mostly inherited from the weathering of the predominant feldspars of the granite (albite, anorthite and microcline). The reddish yellow (5YR5/5) mottles of this saprolite are, on the opposite, mostly assigned to the weathering of mafic minerals (biotite, amphibolite and magnetite), which are grouped in scattered millimetric to centimetric bodies in the granite (Figure 4a). Biotites and amphibolites are strongly weathered in the coarse saprolite. Iron segregations are either observed as coatings on primary mineral remnants (Figure 4b) or as stains on secondary clay minerals. By contrast, the more resistant magnetite to chemical weathering are locally preserved as small grains in the saprolite and overlying soil mantle (Figure 4c,d). Small crystals of titanite are commonly surrounding the gains of magnetite in granite (Figure 4a). They are rapidly dissolved and replaced by yellowish brown weathering rings in the coarse saprolite (Figure 4c). The overlying fine saprolite (BCg) is laterally discontinuous along the catena and particularly thick in midslope positions (Figure 2b). It is clay depleted and deeply weathered (Figure 3a,b). Mafic minerals and feldspars are much less abundant than in Cg, and the quartz grains have predominantly a fine sand particle size. This saprolite is loamy sand and presents similar clay contents than the above Acrisol B-horizons (8 - 12%). It exhibits a yellowish brown (10YR5/4) to light brownish grey (2.5Y6/2) groundmass with dark reddish brown (2.5YR3/4) iron segregations. The latter surround remnants of mafic minerals (mostly magnetite) or more commonly impregnate clay minerals as diffuse stains on pore walls or within the groundmass (Figure 4e). Crescent clay cutans, variously impregnated by Fe-oxides, are also observed in macrovoids of the saprolite (Figure 4f). Both iron stains and clay cutans are more abundant in the upper part of the fine saprolite than in its lower part, particularly close to the podzolic area. At this location, a thin and discontinuous Bg horizon can dissociate the fine saprolite from the overlying B-horizons of Acrisols (Figure 2b). This horizon is light brownish grey (2.5Y6/2), almost devoid of iron stains, and is lacking soil structure and consistency. It has less clay contents (4 - 8%) and also displays under the microscope less clay minerals (Figure 4h) than its overlying B (Figure 4d) or underlying BC (Figure 4e) horizons.

The 3rd compartment of the catena corresponds to the podzolic area that expands from midslope to downslope positions on a convex sloping side (Figure 2). It comprises eluviated horizons over illuviated ones (also named spodic horizons) and corresponds to the aquifer of a perched groundwater drained by the river network. An open forest (*Caatinga*), with smaller trees than those growing on the upslope Acrisols, covers the podzols in midslope positions. It gradually gives place to a riparian forest close to major river incisions, and thus reveals wetter lands in downslope positions. Podzol development differs on both types of topographic location and vegetation cover. In midslope positions, the vertical development of podzols is impeded, at about 1.5m deep, by the fine saprolite. Podzols thus mostly expand laterally at the expense of the upslope A, B and Bg horizons of Acrisols. Both types of soils display laterally a characteristic double tongue-like shape transition (Figure 2), which has been systematically observed at the margin of the podzolised areas of the upper Amazon Basin (Dubroeucq & Volkof, 1998; Dubroeucq et al., 1999; Nascimento et al., 2004). This kind of transition has recently been assigned to the dynamics of the groundwater (Nascimento et al., 2008).

At high water levels, the perched groundwater seeps at the surface at the margin of the podzolic area. Weakly developed podzols can then form at the expense of the A and B3 horizons of the upslope Acrisols and gives place to the AE and Bhs horizons, respectively, with the local individualisation in between of bleached E materials (upper section of pits III and IV). In the AE horizons, the clay content is less than 4%. The mineral phases consist of clean sands and the organic ones of fresh plant remains (leaves and roots) as well as coarse dark brown to black organic decays. These organic substances and the fine roots of the open forest decrease downwards from the very dark greyish brown (10YR3/2) AE11 horizon at the surface to the greyish brown (10YR6/2) AE13 horizon in the subsurface. They nearly disappear in the underlying and downslope light grey (10YR7/1) E horizon. The latter is bleached and unconsolidated. It is almost free of clay minerals and consists of close packed quartz grains of a dominant fine sand particle size in midslope positions (Figure 4i). Fine grained organic matter accumulates at the margin of podzolic area into the B3 and forms the brown (10YR5/3) to dark brown (10YR3/3) Bhs horizon. It impregnates the clay minerals between the quartz grains and demarcate at micro-scale diffuse, dark brown organic stains on pore walls and within the groundmass (Figure 4g).

At low water levels, the deep groundwater of the upslope Acrisols can seeps into the lower part of the podzolic area and thus feeds the perched groundwater. Greater trough flow and loss of matter in perched groundwater explain the lateral expansion of the E horizon into the

hydromorphic subsoil horizons of the upslope Acrisols (Nascimento et al., 2008). The lower tongue then forms at the base and margin of the podzolic area (lower section of pit IV). Moreover, podzolic horizons can expand upslope on longer distances (up to 15m) at the favour of twisting channels, more specifically within the clay-depleted and light brownish grey Bg horizon of Acrisols (one of these channels is cut perpendicularly in the lower section of pit II). This reveals that eluviation and illuviation of clay in the upper part of the groundwater aquifer might be pre-existing mechanisms to podzolisation. Due to larger losses of clay particles, a small topographic slope break marks the connection of the upper and lower tongues (between pits IV and V). Downslope, remnants of B3 and Bhs within the bleached E horizon of well-expressed podzols (upper section of Pit VI) suggest that the upslope expansion of the latter is not a continuous process. This lateral expansion has likely acted abruptly in successive steps, most likely during periods of exceptional high rainfalls. At least, spodic Bh and BCs horizons are also formed at the base and margin of the podzolic area. They result from the vertical transfer of organic substances in the perched groundwater of podzols and their physical fractionation and accumulation in texture contrasted subsoil horizons during the recede of that groundwater (Duchaufour, 1972; Fritsch et al., 2009). Organic colloids or particles, accumulated at the margin and base of the eluviated E horizon, form the black (10YR2/1) Bh horizon. The latter is thin and discontinuous at the margin of the podzolic area. Under the microscope, it exhibits black organic pellets that fill incompletely the interstices managed by the quartz grains (Figure 4j). Finest organic substances accumulate at greater depths, mainly in the upper part of the saprolite. They form dark brown and cracked organic stains or coatings (Figure 4i) in brownish yellow (10YR6/6) to dark brown (7.5YR3.5/3) BCs horizon, as in Bhs (Figure 4g).

Towards downslope positions, the convexity of the slope increase, the podzols deepen and the granite outcrop in the brook. Physical denudation of the downslope podzols, which has fed in white sand deposits the Curicuriari river, has thus also favoured its downward expansion into the saprolites (Figure 2). This soil dynamics starts at the nicking point of the convex sloping side and is initiated by the formation, under the thin Bh horizon, of a greyish brown (10YR5/2) sandy E/BC horizon (lower section of pit VI). This horizon gradually turns light grey downslope (E horizon) and a second generation of spodic horizons are formed at greater depths. In low-lying positions and under the riparian forest, podzols expand ultimately into the coarse saprolite forming the light grey (10YR7/1) E/C horizon above the black (5YR3/1) and dark yellowish brown (10YR4/4) spodic horizons (CBh and CBs, respectively).

Observation of the whole catena (Figure 2) also shows that organic compounds weakly accumulate at the margin of the podzolic area and, on the opposite, deeply impregnate the eroded soil landforms in lowlying positions. In particular, the thicknesses of the eluviated organic topsoil (AE) and spodic subsoil horizons (Bh and BCs, and ultimately CBh and CBs) of podzols increase gradually towards the brook likely due to longer periods of waterlogging and change of vegetation (from *Caatinga* to riparian forest).

Geochemistry of trace elements (Zr, Ti and Th)

Deep weathering of rocks in tropical regions commonly leads to complete removal of alkali and alkali hearth elements (Na, K, Mg and Ca), partial depletion of Si and therefore to residual accumulation in soils of less mobile elements such as major metal cations (mostly Al and Fe) and trace elements. Trace elements such as Zr, Ti and Th generally accumulate from bottom to top of autochtonous tropical soils (e.g. Ferrasols) and the positive correlations established between each other testimonies of their weak mobility during weathering processes (Fritsch et al., 2002). This is commonly attributed to their incorporation in accessory minerals, which are very resistant to chemical weathering (e.g. zircon for Zr). They are thus commonly used as invariants for mass balance modelling and assessment of losses and gains of more soluble elements in weathered profiles (e.g. Braun et al., 1993). However, chemical analyses of water systems have established that organic acids could initiate the chemical weathering of these accessory minerals in waterlogged environments and contribute to the transfer of trace elements to river systems (Viers et al., 1997). Chemical investigations along soil catena has also emphasised that losses and gains of such elements could also be related to biological uptakes, runoff and selective translocation of their parent minerals according to particle size (Fritsch et al., 2007).

Zirconium behaves differently than Ti and Th in the study site. As expected for most tropical soils, the Zr content increases from rock to saprolite and ultimately to the overlying soil horizons (Figure 3b). The reverse trend is reported for both Ti and Th (Figure 5a). This is consistent with the incorporation of Zr in zircon, an accessory mineral highly resistant to chemical weathering (Balan et al., 2001; Taboada et al., 2006). Zircon in granites and regoliths of the study site has also an average particle size of about 150µm that prevents its translocation in most soil horizons. It was then used as a chemical invariant to calculate mass balance factors and assess relative losses or gains of other chemical elements. Results obtained for trace elements indicate that 80% of the initial stock of Ti and 90% of the Th are

lost in the fine saprolite and overlying soil horizons of the upslope Acrisols (Figure 5b). This is attributed for Ti to the weathering of titanite crystals in coarse saprolite (Figure 4c) and the formation in soils of small grains (< 2µm) of anatase, according to petrographic and XRD investigations. Similar mechanisms have likely happened for thorium with the dissolution at depth of Th-bearing minerals (e.g. apatite and allanite) and the formation in soils of thorianite crystals. However, the tiny size and the small concentration of the latter have prevented its identification.

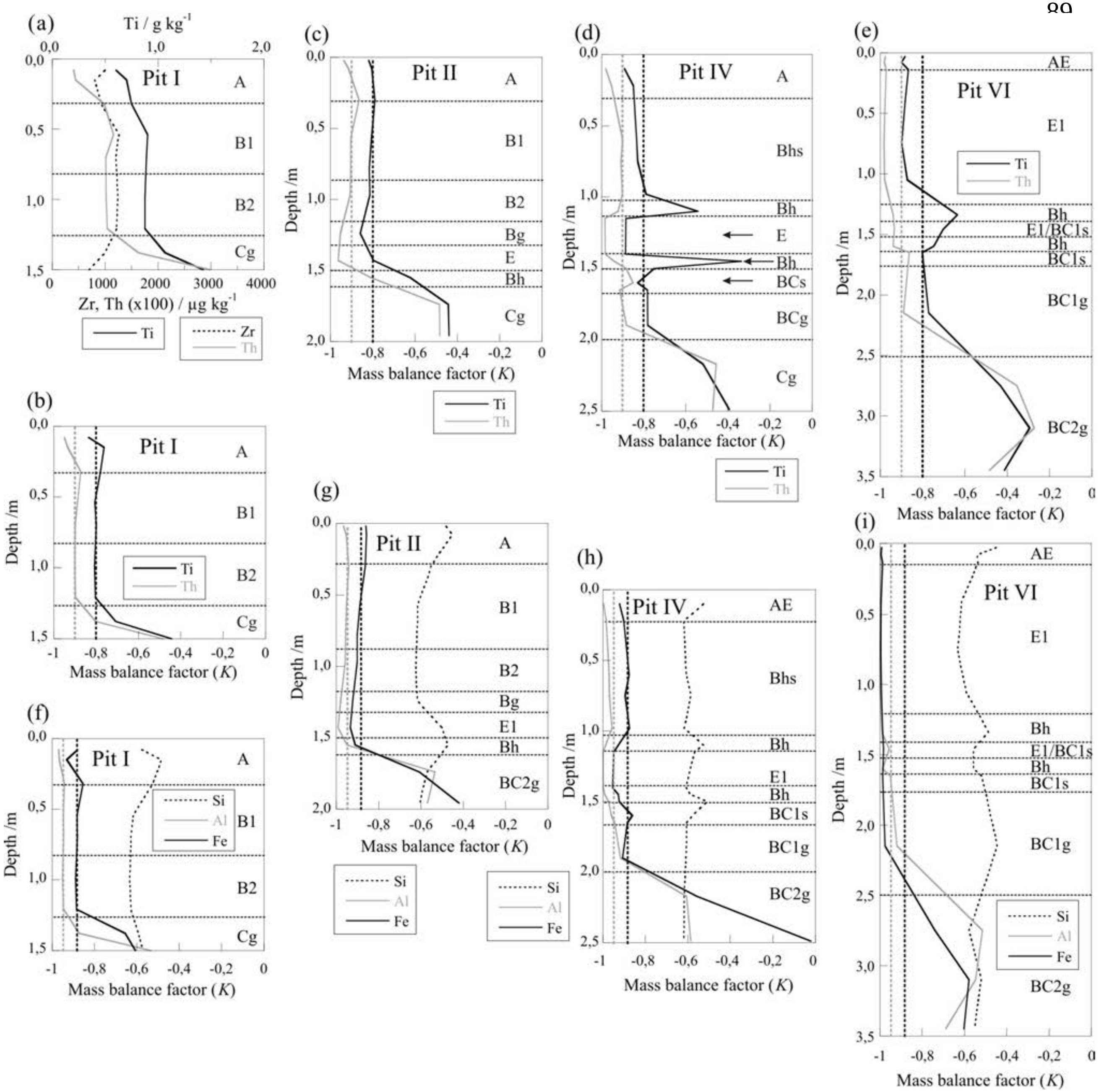


Figure 5*. (a) Vertical distribution of Zr, Ti and Th in the upslope Acrisol (Pit I) and mass balance factors calculated vertically for (b, c, d and e) Ti and Th, and (f, g, h and i) Si, Al and Fe in four profiles of the soil catena (I, II, IV and VI, respectively).*

As the eluviated and illuviated horizons of podzols mainly form laterally at the expense of the upslope Acrisol soil horizons, the remaining fractions of Ti (20%) and Th (10%) stored in the latter will be used as new threshold values for assessing losses and gains of both elements in the downslope podzols (see vertical dashed lines in Figure 5). Figure 5c,d,e shows that the development of podzols into Acrisols leads to drastic losses of Ti and Th in their eluviated horizons and, on the opposite, gains of the same elements in their illuviated or spodic B-horizons. Losses of Ti and Th are initiated at depth in the Bg and E horizons of the twisted channels that enter into the upslope Acrisol, on top of the saprolite (bottom section of pit II in Figure 5c). In the transition zone (pit IV in Figure 5d), losses of both elements are also initiated near the surface in the AE and Bhs horizons of weakly expressed podzols (upper tongue). These losses become more relevant at the same topographic location, but at greater depth, in the bleached E horizon of better differentiated podzols (lower tongue). They are optimal and remains almost unchanged in the eluviated AE and E horizons of the well-developed podzols in midslope and downslope positions (pit VI, in Figure 5e). Thorium has almost been completely removed from these horizons whereas half of the initial stock of Ti stored in Acrisols has been lost. Both elements are on the opposite accumulated in the illuviated or spodic horizons of well-expressed podzols (Figure 5d,e). These gains are more important for Ti than Th and the former accumulate at shallower depth in Bh horizons than the latter in the underlying BCs horizons. This dissociation with depth of both types of trace elements in two superimposed spodic horizons suggests that they could be bound to distinct organic carriers, and translocated vertically according to their particle size. Dissolved organic carbon and their chelated Th would then accumulate at greater depth in BCs than higher molecular weight organic fractions and associated Ti. However, Ti and Th could also be incorporated in crystals of anatase and thorianite, whose particle sizes (< 2µm) allow their vertical transfer in the macro-voids of AE and E horizons of podzols. As thorianite crystals are much smaller than that of anatase, they can accumulate at greater depth in less porous horizons. XRD investigations on clay size fractions (< 2µm) confirm the physical translocation of anatase, as the main diffraction peak for the latter appear much more important in Bh horizons than in their overlying E or underlying BCs horizons (not shown). Physical transfer of organic and mineral phases is thus an important mechanism in podzol development and consistent with the concept of eluviation and illuviation commonly attributed to the formation of these soils. Obviously, this does not exclude the contribution organic acids in the weathering of clay and accessory minerals and the formation and transfer of organo-metallic complexes. The greater loss of Th than Ti in eluviated horizons of Podzols

and their smaller accumulation in their underlying spodic horizons also indicate that this element is massively exported in the black waters and rivers of podzolic environments.

Geochemistry of major elements (Na, K, Ca, Mg, Si, Al and Fe)

The contents of alkali and alkali earth elements (Na, K, Mg and Ca) stored in the bedrock decreases rapidly upwards in the weathered mantle, first in the coarse saprolite and ultimately in both the fine saprolite and overlying soil horizons (Figure 3b). The extremely low contents measured in the latter attest of the strong weathering conditions, which led to the almost complete weathering of feldspars, biotites and amphiboles from granites and the formation of Al- and Fe-bearing secondary minerals (predominantly kaolinite and gibbsite, and at lesser extent Fe-oxides). The contents of Al_2O_3 and Fe_2O_3 do not change significantly between granites and coarse saprolites but drop abruptly between latter and both fine saprolites and soil horizons (Figure 5c,d). These geochemical trends reveal that fine saprolites are clay-depleted whereas the underlying coarser ones are not. As already discussed, a third category of materials can be distinguished. They correspond to the base of the eluviated horizons of the downslope Podzols (E/C in Figures 2b and 3b), which is clay depleted but still contains alkali and alkali earth elements. This last trend confirms that podzols have ultimately expanded downwards in less weathered materials close to major river incisions.

According to mass balance factor calculations, about 60% of the Si, 90% of the Fe and 95% of the Al stored in granites have been lost by chemical weathering in the A and B horizons of the upslope Acrisols (Figure 5g). Losses seem to be less in A horizons than in B-horizons (particularly for Si), which is likely not the case as clay depleted topsoils appear also depleted in Zr (Figure 5a). As for trace elements, the remaining fractions of Al (5%) and Fe (10%) stored in the upslope B-horizons of Acrisols (see the vertical dashed lines in Figure 5) were used as new threshold values for assessing losses and gains of both metal cations in podzols (Figure 5h,i). Only losses are reported for Al and Fe, and both elements seem to be exported simultaneously (Figure 3d). Such losses, initiated in B3 and Bg horizons of Acrisols, become almost total in eluviated horizons of podzols (AE and E). For spodic horizons of podzols, their chemical compositions approach those of the surrounding horizons in which they have formed: BCg and Cg for BCs and Cs (Figure 3c), B3 and Bg for Bhs and E for Bh (Figure 3c,d).

Al-bearing secondary minerals (kaolinite and gibbsite)

DRX (not shown) and spectroscopic data in the infra red (FTIR) range reveal a monotonous mineral composition for secondary Al-bearing minerals (kaolinite and gibbsite) but a high variability in their relative proportions and total contents in bulk samples from bottom to top and upslope to downslope positions of the catena (Fig. 6). In the A and B-horizons of the upslope yellowish clay-depleted laterites (Acrisols), the contents of gibbsite are larger than that of kaolinite (Figure 6a). It slightly increases downwards in these horizons, and more abruptly in the upper part of the underlying coarse and clayey saprolite (Cg). This vertical trend in laterites likely results from the weathering of the Al-bearing minerals in the upper section of the soil profiles and the downward accumulation of Al, which precipitate as gibbsite and in larger proportion at the textural transition. It then indicates that both clay depletion and soil gibbsitisation are prior to soil podzolisation.

At the margin of the podzolic area, similar variations are observed (Figure 6b), with however lower amounts of gibbsite and kaolinite in the upper A and B horizons (AE, Bhs, B3 and Bg), but also in the underlying fine saprolite (BCg). Strong textural contrasts then exist between the fine (BCg) and coarse (Cg) saprolites, the latter still exhibiting larger amounts of Al-bearing secondary minerals and greater proportions of gibbsite in its upper section. Towards the downslope podzols, this trend is maintained. The textural contrast between the clay-depleted and upper section of the soil and the lower clay-rich saprolite in enhanced, mainly due to greater losses of Al-bearing minerals in the former (Figure 6c,d). In the midslope position (Figure 6c), the spodic horizons (Bh and BCs) do not form at this textural transition but just above at the structural transition between soil horizon and saprolite. It then confirms that clay depletion is prior to soil podzolisation but also reveals the structural control of the upper saprolitic limit in the downward expansion of podzols at the margin of the podzolic area. It also explains that podzolisation can locally pass through this transition, more specifically towards low-lying positions following deep river incisions in the landscapes. At least, gibbsite seems to be inexistent in the eluviated compartment of the downslope podzols whereas traces of kaolinite are still observed (Figure 6c,d). This new trend suggests greater dissolution rates for gibbsite than kaolinite in podzolic environments (Nascimento et al., 2004). However in the remnants of the Bhs horizons, which are preserved in the midslope position and contains greater amount of clay minerals, gibbsite is also weakly present (Figure 6c). We thus rather suggest that podzols have expanded in poorly drained laterites, restricting therefore the formation of gibbsite in their upper section.

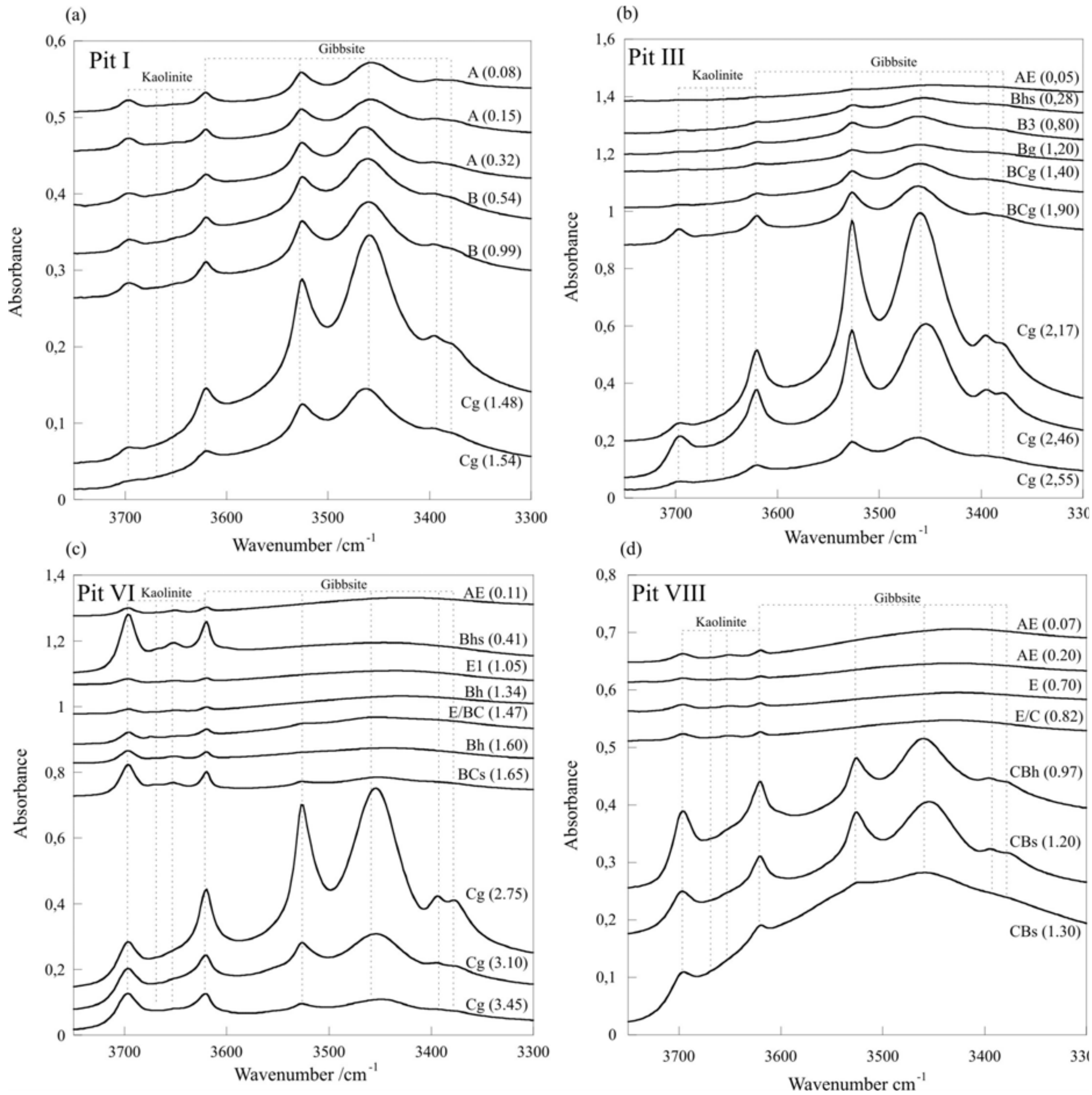


***Figure 6**. Infra Red spectra in the OH stretching band region of kaolinite and gibbsite of bulk samples from (a) the upslope Acrisol (Pit I), (b) the transition zone (Pit III) and (c,d) the downslope podzols (Pits VI and VIII, respectively) (sampling depth in meter of each sample is given in brackets).*

Fe-oxides and organically bound Fe

Diffuse reflectance spectroscopy reveals the nature and proportion of secondary Fe-oxides as well as the relative abundance of organically bound Fe (Figure 7). Soil profiles of the catena mainly contain goethite as Fe-oxides, whose proportion decreases significantly from the iron coloured topsoil A and B horizons of the upslope Acrisols to their underlying hydromorphic and downslope podzolic areas. Such global trend is illustrated with samples exhibiting on a

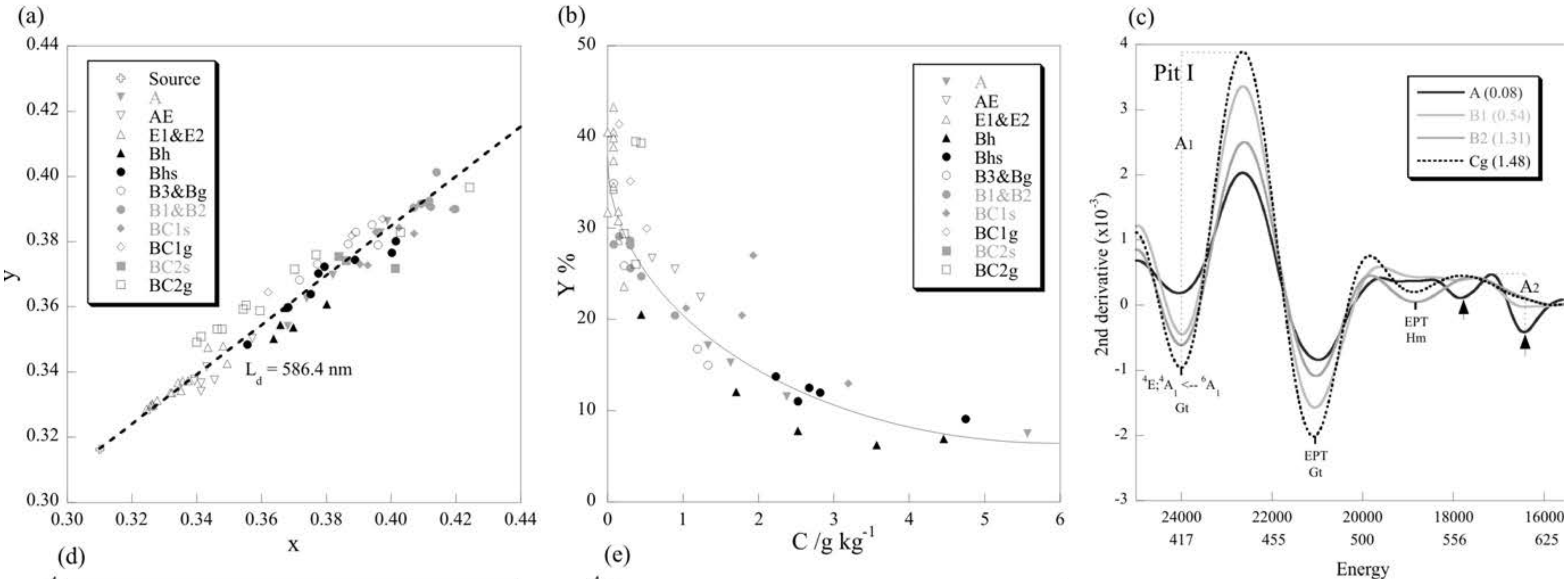
colorimeric diagram similar L_d (dominant wavelength) but contrasting P_e (excitation purity) (Figure 7a). The average L_d of 586nm is characteristic of goethite. The iron-rich samples (largest P_e values) correspond to the topsoil A and B horizons of Acrisols and the iron depleted ones (lowest P_e values) to the greyish samples of their underlying hydromorphic area (Bg, BC1g, BC2g) and all the topsoil bleached horizons of the downslope podzols (AE, E, E/C). Spodic horizons of podzols (Bhs, Bh, BC1s, BC2s) present intermediate values.

Second derivative of the remission function from reflectance curve in the visible range also exhibits two major bands (minima) for goethite (Gt) but also a minor band for hematite (Hm) at lower wavenumbers for the topsoil A and B horizons of the upslope Acrisols (Figure 7c). The relative proportion of hematite in the pool of Fe-oxides (i.e. both hematite and goethite) is optimal at the base of the B horizon and almost nil in its upper part, which is consistent with a gradual change of colour from reddish yellow (7.5YR6/8) in B2 to brownish yellow (10YR6/6) in the overlying B1. A significant decrease of the two minima for goethite (Gt) in the topsoil A horizon of Acrisols can also be linked to the appearance of two additional bands, at 16350 cm^{-1} (610 nm) and 17500 cm^{-1} (565 nm) (arrows in Figure 7c), which were assigned to organically bound Fe^{III} (Nascimento et al., 2004, Fritsch et al., 2009). At the transition between clay-depleted laterites and podzols, loss of goethite increases and the organically bound Fe is also reported in weakly expressed podzols, in topsoil AE horizons but also and mainly in their underlying Bhs horizons, as shown by the amplitudes of the two additional bands at 16350 and 17500 cm^{-1} (Figure 7d). This is further enhanced laterally in better-expressed podzols, where the organically bound Fe is also abundantly found in Bh horizons. By contrast, it is less abundant or absent in the underlying spodic BCs horizon. This is consistent with the formation of organically bound Fe following the dissolution of goethite in topsoil horizons of the margin of the podzolic area and the downward and downslope accumulation of organic colloids and Fe in Bh horizons of better-expressed Podzols (Fritsch et al., 2009).

Organic matter, organically bound Al and soil acidity

Carbon contents decrease regularly with increasing depth in the upslope clay-depleted laterites from up to 24 g kg^{-1} in A horizons to less than 3 g kg^{-1} in B horizons and the C:N ratio ranges from 10 to 27. In the podzolic area the carbon content increases (Figure 8a), more specifically in spodic horizons (up to 48 g kg^{-1}). The C:N ratio increase slightly near the surface in Bhs horizons of weakly expressed podzols, and more significantly at greater depths in Bh and BCs horizons (up to 67). The contents of Al extracted by the pyrophosphate

treatment (Al_p), which permit to assess the amounts of organically bound Al (Figure 8b), gave similar values than that obtained by Nascimento et al. (2004) on another catena associating on short distances clay-depleted laterites and waterlogged podzols. The Al_p contents in bulk samples of B-horizons average 1 g kg^{-1} in the upslope clay-depleted Acrisols. It remains almost unchanged or decreases significantly in organic-rich AE and Bh horizons of podzols and, on the opposite, increases in spodic Bhs and BCs horizons of podzols. This general trend is thus consistent with previous results of Bardy et al. (2007).



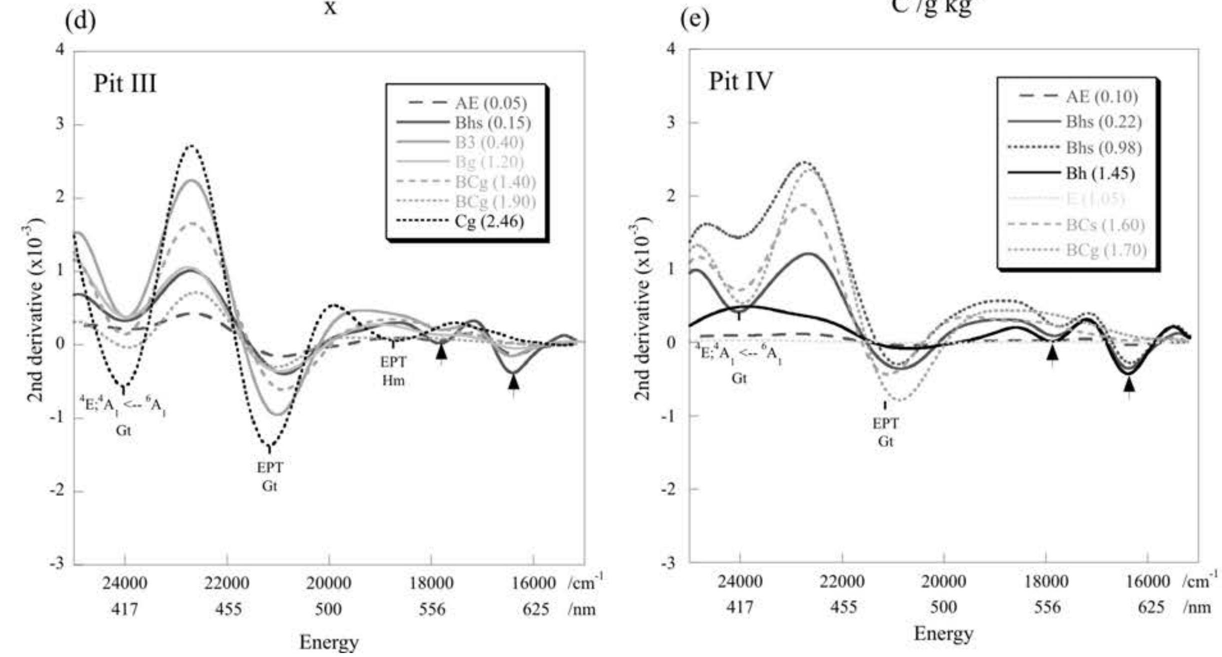


***Figure 7**. (a) x and y values of tristimulus coordinates (CIE system, 1931) in a colorimeric diagram showing similar dominant wavelength (L_d) for all samples but distinct excitation purity (P_e) (tristimulus values were converted in Helmholtz coordinates: L_d and P_e), (b) Y% coordinate (CIE system, 1931) versus carbon content (C), Second-derivative spectra of the remission function f(R) in the visible range of Fe-oxides (Gt: Goethite, Hm: Hematite) in bulk samples of (c) the upslope Acrisol (Pit I) and (d,e) the midslope podzols (Pits III and IV, respectively) (sampling depth in meter of each sample is given in brackets).*

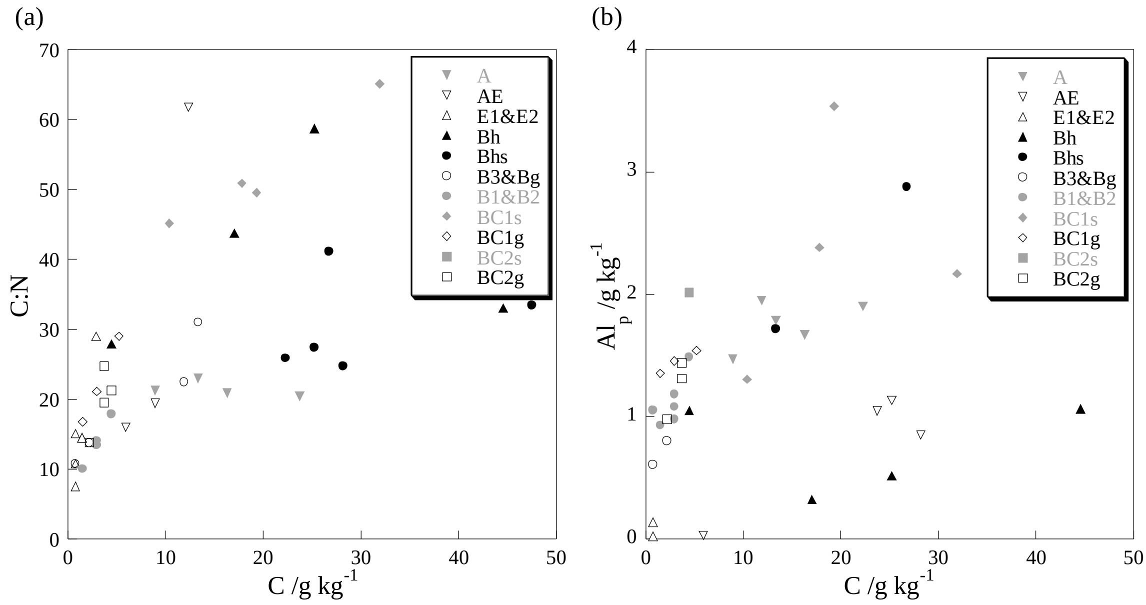


***Figure 8**. (a) carbon content (C) versus C/N ratio, (b) carbon content (C) versus amount of extractable Al by the pyrophosphate treatment (Al_d).*

The pH of soils and saprolites ranges between 5.5 and 4.0 along the catena (Figure 9). Highest pH values are reported in the topsoil A and B horizons of the upslope Acrisols. pH decreases slightly in the underlying hydromorphic horizons of these soils. It also decreases laterally in podzols. It reaches the lowest values (pH = 4) at the base of the bleached E horizons at the margin of the podzolic area in midslope positions. By contrast, pH increases downslope in eroded and less weathered waterlogged podzols.

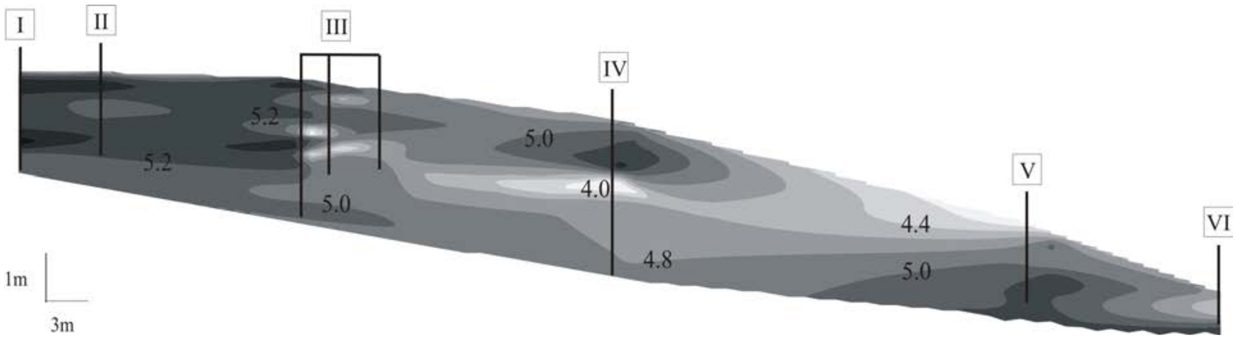


***Figure 9**. Range of pH along the soil catena.*

4.4. Discussion and conclusions

The soil catena investigated in this paper presents major structural and mineralogical analogies with that studied by Nascimento et al. (2004) in less podzolised soil landscapes of the Negro River watershed. The main analogy is the identification of the same type of structures along the catena with (i) the clay-depleted and freely drained upper part of laterites (Acrisols), (ii) their hydromorphic lower part, predominantly formed in saprolites, with their corresponding deep groundwater and (iii) the upper and downslope podzolic area, which sustains a perched groundwater. The second major analogy, which has systematically been observed along soil catena of the Amazon Basin, is the "double tongue-like" transition between the upslope laterites and the downslope podzols (Turenne, 1975; Bravard & Righi, 1989, 1990; Dubroeucq & Volkof, 1998; Lucas et al., 1987, 1996; Nascimento et al., 2004). The upper tongue results from the upslope and downward development of weakly expressed podzols on the clay-depleted laterites, thus forming thin eluviated AE and E horizons over weakly differentiated Bhs horizons. Further downslope and at greater depths, the bottom part of better-differentiated podzols is lying on the hydromorphic saprolite of laterites. It expands laterally into the upslope bleached and clay-depleted Bg horizons of the upper part of the groundwater aquifer, forming the second tongue or, in 3 dimensions, twisted channels on more than 15m long. These structures result from the interactions and dynamics of two groundwaters: (i) a permanent deep groundwater with clear waters fluctuating in the hydromorphic part of the laterites, and (ii) a more seasonal perched groundwater with black waters fluctuating in the eluviated horizons of podzols (Nascimento et al., 2008).

Soil organisations and groundwater dynamics also reveal the contribution of major structural discontinuities (in both study sites: the transition between soil and saprolite) in the vertical development of podzols and their consequences in the individualisation of well-differentiated spodic Bh and Bs (or BCs) horizons. The vertical development of podzols is impeded as soon as they reach this discontinuity, initiating therefore the lateral expansion of podzols in the landscape. In both study sites, the downward accumulation at the base of the eluviated E horizon of black organic colloids during the recede of the perched groundwater built up the Bh horizon in podzols. The accumulation just below of dissolved organic carbon in the less permeable hydromorphic saprolite of the laterites forms the BCs horizon. These accumulations of organic matter, at depth but also at the margin of the podzolic areas, reduce the porosity of their spodic horizons and favour the implementation of a perched groundwater in their overlying eluviated and bleached horizons. Remnants of lateritic horizons

impregnated by organic compounds are observed in the latter. They indicate that podzols may expend abruptly upslope at the expense of freely drained and clay-depleted laterites in response to major rainfall events and subsequent expansion of perched groundwater aquifers.

Soils and saprolites in both study sites also exhibit strong geochemical and mineralogical analogies. Better than that of the Jaú site, this study reveals that massive gibbsitisation of the upper clayey saprolite is likely linked do the downward accumulation of Al following the dissolution of Al-bearing minerals (mainly kaolinite and gibbsite) in the upper clay depleted horizons of laterites. This hypothesis suggests that gibbsitisation has occurred before the podzolisation of laterites. The greater proportion of kaolinite in the pool of the remaining Al-bearing minerals within the overlying soil horizons and towards the podzolic area also suggests higher dissolution rates for gibbsite than kaolinite in more acidic environments (Nascimento et al., 2004). However, such a trend could also result from the development of poorly drained conditions in laterites, before their ultimate podzolisation, which should restrict the formation of gibbsite.

In both study site, podzols are formed laterally at the expense of yellowish clay depleted laterites with mainly contains quartz grains but also residual clay minerals (kaolinite, gibbsite and goethite). Massive iron and clay depletion, confirmed by mass balance calculations, are preliminary weathering steps to soil podzolisation. Such preliminary weathering steps may even affect the upper part of the saprolite in hydromorphic environments. Losses of clay minerals develop interconnected macrovoids between quartz grains that promote the migration of fine particles. Chemical erosion of laterites then generates particulate transfer in clay-depleted horizons. Clay transfer mostly occurs in the deep groundwater of the upslope laterite and is consistent with the individualisation in their upper bleached and clay depleted Bg horizon or BCg saprolite of clay cutans in macrovoids. Transfer of clay and silt particles is strongly enhanced in the sandy and bleached horizons of podzols and is also associated with the downward accumulation of Th-, Ti-bearing minerals in spodic horizons. Simultaneously, the accumulation of organic substances in spodic horizons of weakly expressed Podzols (Bhs horizons of the margin of the podzolic areas), or at a greater depth in those of better differentiated podzols (Bh and BCs horizons) is associated with the accumulation of metals bound to organic ligands, which occur at greater depth for Al (Bhs and BCs) than for Fe (Bhs and Bh).

Podzols in the incised inundated peneplain of the study site also display relevant differences with the waterloged podzols studied elsewhere by Nascimento et al. (2004) in poorly drained

plateau depressions. Major morphological differences in podzols result from the incision of the podzolic areas by river systems. They are observed at two distinct places within the soil catena: (i) at the lateral weathering front between the upslope clay-depleted laterites and the midslope podzols, and (ii) in the downslope eroded podzols developing convex sloping sides with the river network. The accumulation of organic matter at the lateral weathering front is less abundant, in particular in the thinner spodic Bhs of weakly expressed podzols but also at greater depth in the thin and discontinuous Bh horizon of better differentiated podzols. Besides, the hydromorphic saprolite, directly in contact with the upslope podzolic area, locally displays numerous iron segregations. These major morphological changes likely result from shorter periods of anoxia due to river incisions and the recede of the perched groundwater from the upslope podzolic area. Indeed, shorter periods of anoxia at the lateral weathering front speed up the mineralization of organic mater, release the organically bound metals, and favour the precipitation of Fe-oxides. Downslope on the convex sloping side, the podzolic weathering front has expanded downwards into the fine and clay-depleted saprolite and ultimately in low-lying positions into the coarse saprolite. Consequently, this weathering front has initiated the formation of a second generation of eluviated and illuviated or spodic horizons in strongly and ultimately in less weathered saprolitic materials. The deeper impregnation of organic matter in spodic horizons from the upslope to the downslope position of the podzolic area is closely linked to a simultaneous increase of the thickness of the organic-rich and eluviated topsoil horizons of podzols. This lateral trend results from drastic structural changes in the vegetation cover and therefore in the organic inputs to soils, with a more open forest (*Caatinga*) in the upslope podzols and a dense riparian forest in the downslope podzols. It also assigned to contrasted hydrological regime, with higher turnovers of organic matter in better-drained podzols of the *Caatinga* and slower ones in the waterlogged podzols of the riparian forest. Moreover, the weak acidification of the downslope podzols mainly formed on weakly weathered saprolites prevents the release of metals bound to organic ligands.

Acknowledgments

The research was funded by CAPES-COFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l'Univers du CNRS), through the "Ecosphère continentale" programme: "Podzolisation des

latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)”.

CAPITULO 5. ALTERAÇÃO E EROSÃO DAS SUPERFÍCIES CENOZÓICAS E GÊNESE DOS PODZÓIS HIDROMÓRFICOS NA BACIA DO RIO NEGRO

Résumé

Ce chapitre est un essai de reconstitution de la dynamique d'expansion des podzols à nappes dans le bassin du Rio Negro à partir d'études ponctuelles réalisées sur des séquences de sols, de documents cartographiques obtenus à des échelles régionales et des connaissances actuelles sur l'histoire géodynamique et géologique du bassin amazonien. Les études minéralogiques et structurales réalisées le long de séquences de sols situées dans des points clés des paysages faiblement ou fortement podzolisés du bassin versant du Rio Negro (sites (3) et (4)) ont permis d'élaborer un modèle d'évolution de ces paysages qui intègre : (i) processus majeurs associés aux re-mobilisations et exportations de matières, et (ii) fonctionnements hydriques associés. La reconnaissance des principales surfaces géomorphologiques (surfaces d'aplanissement, dépôts sédimentaires, chenaux fluvio-lacustres…) de ce bassin nous a amené à extrapoler ce modèle à plus petites échelles, révélant alors les principaux facteurs associés à l'expansion des podzols à nappe dans les paysages latéritiques d'Amazonie.

Le modèle proposé oppose des processus d'altération propices à une fonte géochimique des formations continentales à des processus érosifs associés à l'incision de ces formations par le réseau hydrographique et à l'accumulation des produits de cette érosion dans les lits des rivières. Dans le bassin du Rio Negro, les surfaces continentales appartiennent essentiellement aux vastes pénéplaines du Tertiaire, qui ont été incisées au Quaternaire par les tributaires du

Rio Negro et ont de ce fait formé les plateaux surbaissés de ce bassin. Dans les parties hautes et bien drainées de ces plateaux, l'érosion chimique des formations continentales a conduit à la formation de latérites plus ou moins épaisses par accumulation résiduelle d'Al et Fe dans les minéraux argileux du sol. Dans les parties centrales et moins bien drainées de ces plateaux, l'érosion chimique accrue de ces latérites est associée à une plus grande mobilité d'Al et Fe. Les pertes de ces éléments sont reliées à un appauvrissement des latérites en milieu faiblement (au voisinage de la surface) ou fortement (en profondeur) anoxique puis, lorsque le milieu devient suffisamment perméable, à une podzolisation de ces latérites. Cette étape ultime dans l'érosion des latérites est liée à la dissolution des quelques minéraux argileux qui subsistent dans ces sols par des substances organiques qui migrent et s'accumulent dans les fronts latéraux de podzolisation sous forme de complexes organo-métalliques. Ce processus marque de ce fait un changement de spéciation majeur pour les métaux (du minéral vers l'organique). Il est étroitement lié à l'individualisation et fluctuation d'une nappe perchée dans le réservoir sableux des podzols et au développement de conditions réductrices et acides au sein de cette nappe. Les deux grands processus (appauvrissement puis podzolisation) transformant les latérites en un résidu sableux progressent de façon centrifuge, depuis le centre vers le rebord des plateaux. A cette fonte chimique des latérites s'oppose une érosion physique progressant dans une direction complètement opposée. Cette érosion régressive des bords des plateaux par les incisions des ruisseaux alimentent en sédiments les lits des rivières. Dans les plateaux faiblement podzolisés du bassin moyen du Rio Negro (site (3)), les dépressions à podzols sont faiblement incisées par les ruisseaux et l'érosion régressive des rebords des plateaux latéritiques fourni d'abondants sédiments argileux aux eaux brunes des rivières. Dans les vastes pénéplaines à podzols du haut bassin du Rio Negro (site (4)), les incisions du réseau hydrographique drainent les nappes de ces podzols et fournissent d'abondants sables blancs aux eaux noires des rivières.

Dans le bassin du Rio Negro, les surfaces continentales appartiennent (i) à la surface d'aplanissement pan-américaine *Ucayali* du Miocène Moyen, (ii) au dernier épisode sédimentaire du Tertiaire attribué à la Formation Içá, épisode qui s'est achevé fin Pliocène lors de la naissance du réseau hydrographique actuel du fleuve Amazone, et (iii) aux surfaces d'érosion et de sédimentation du Quaternaire. Les sédiments Quaternaires se sont essentiellement accumulés à deux endroits dans le lit majeur du Rio Negro formant les archipels de: (i) Mariuá (bassin moyen) et (ii) Anavilhanas (bas bassin). L'épaisseur des formations latéritiques du bassin du Rio Negro dépend étroitement de l'age de ces surfaces.

Ces formations sont généralement épaisses, parfois faillées, sur la surface d'aplanissement pan-américaine *Ucayali* et, à l'inverse beaucoup moins développées sur la Formation Içá (<1m). Cette dernière présente de nombreux chenaux et dépressions qui pourraient correspondre à d'anciens chenaux fluvio-lacustres.

La répartition des podzols dans le bassin du Rio Negro montre un contrôle lithologique et pluviométrique majeur dans l'expansion de ces formations dans les principales surfaces géomorphologiques du bassin. L'expansion des podzols est réduite dans les couvertures latéritiques peu épaisses de la Formation Içá. Elle est limitée aux chenaux ou dépressions de cette formation, ce qui laisse présager d'un contrôle de structures fluvio-lacustres dans la mise en place de ces podzols. L'expansion des podzols dans les paysages devient beaucoup plus importante au Nord et au Nord Ouest, dans les régions les plus pluvieuses du bassin. Dans ces régions, les vastes étendues à podzols se sont également développées sur des couvertures latéritiques plus anciennes et plus épaisses de la surface d'aplanissement *Ucayali*. Les plus grandes étendues de podzols au Nord Ouest sont drainées et incisées par les principaux tributaires du haut Rio Negro. Ils ont alimenté en sables blancs les lits des rivières et construit l'archipel de Mariuá dans le bassin moyen du Rio Negro, le plus grand piège à sédiments de podzols du bassin amazonien.

L'étude montre ainsi que les podzols à nappes du bassin versant du Rio Negro se sont essentiellement développés sur les surfaces d'aplanissement et sédimentaires les plus anciennes du Tertiaire ce qui laisse présager d'un grand âge pour ces sols. Leur plus grande expansion dans les paysages est contrôlée à la fois par les apports pluviométriques (propices aux engorgements par leur abondance) et la nature du support sur laquelle elles se forment (accrue sur latérites très altérées et anciennes de la surface d'aplanissement *Ucayali*). L'incision linéaire des surfaces Tertiaires, il y a environ 2.5 Ma lors de la mise en place du réseau hydrographique moderne du fleuve Amazone, a permis de drainer les aires les plus podzolisées à l'amont et au Nord du bassin du Rio Negro. Ce drainage associé à une érosion des bords de berges a permis de restreindre l'expansion de ces vastes étendues à podzols dans les paysages et d'alimenter en sables blancs les bords de berges et le principal piège à sédiments situé juste à l'aval de ces grandes étendues à podzols (archipels de Mariuá). Une seconde génération de podzols s'est ultérieurement développée sur les surfaces incisées des rebords de plateaux et les dépôts Quaternaires soulignant ainsi la grande continuité dans le temps du processus de podzolisation. En effet, ce processus continue de nos jours à alimenter en substances organiques et métaux les eaux noires des rivières du bassin versant du Rio

Negro, contribuant ainsi à entretenir un environnement extrême peu propice au développement de la vie.

5.1. Introduction

The Negro River catchment belongs to the northern part of the Amazon flat surface, bordered by residual hills, inselbergs and *Mesas* of the Guyana shield in the Northeast (Fig. 1). The dissection of this vast surface has generated a plateau-like relief (*Amazonian planalto)*, some tens meters above average river levels (90 to 60m a.s.l.), and the formation of narrow alluvial terraces in major river corridors (Franco et al., 1977; Costa et al., 1978). These low elevation plateaux (*terra firma*) commonly present dissected edges, with flat-top to convex hills, as well as dispersed and ramified depressions in their centre (Franco et al., 1977; Costa et al., 1978; Bezerra, 2003). While the most elevated relieves present some uniformity on their bauxite, iron pans, or reddish and clayey Ferralsols, the widespread low elevation plateaux with their incised edges and ramified depression network show high diversity of soils (Costa et al., 1978; Yamazaki et al., 1978; Dubroeucq et al., 1999). Such soil diversity is also manifest on the vegetation physiognomy that grade from an evergreen forest to a shrub savannah (SILVA et al., 1977; Magnago et al., 1978). Maps of the RadamBrasil Project (1972-78) reveal that diversity. Freely drained soils (Ferralsols and Acrisols) under forest are commonly present on plateau edges whereas waterlogged soils with various types of vegetations occupy the alluvial terraces and the depressions of the plateaux. Waterlogged soils on the plateaux are either clayey or sandy and correspond respectively to Gleyic Plinthosols and Hydromorphic Podzols. In waterlogged Podzols, the development of reducing and acidic conditions enhanced the production of organic acids, the weathering of clay minerals, the formation and downward accumulation organo-metallic complexes and their exportation to the river network (Lundström et al. 2000; Do Nascimento et al, 2004, 2008, Bardy et al., 2007, 2008, Fritsch et al., in review). The abundance of Podzols in the Negro River catchment explains the small quantity of suspended load, the extent of organic colloids and associated metals in most surface waters, and their dominant black colour (Allard at al. 2002, 2004; Benedetti et al. 2003).

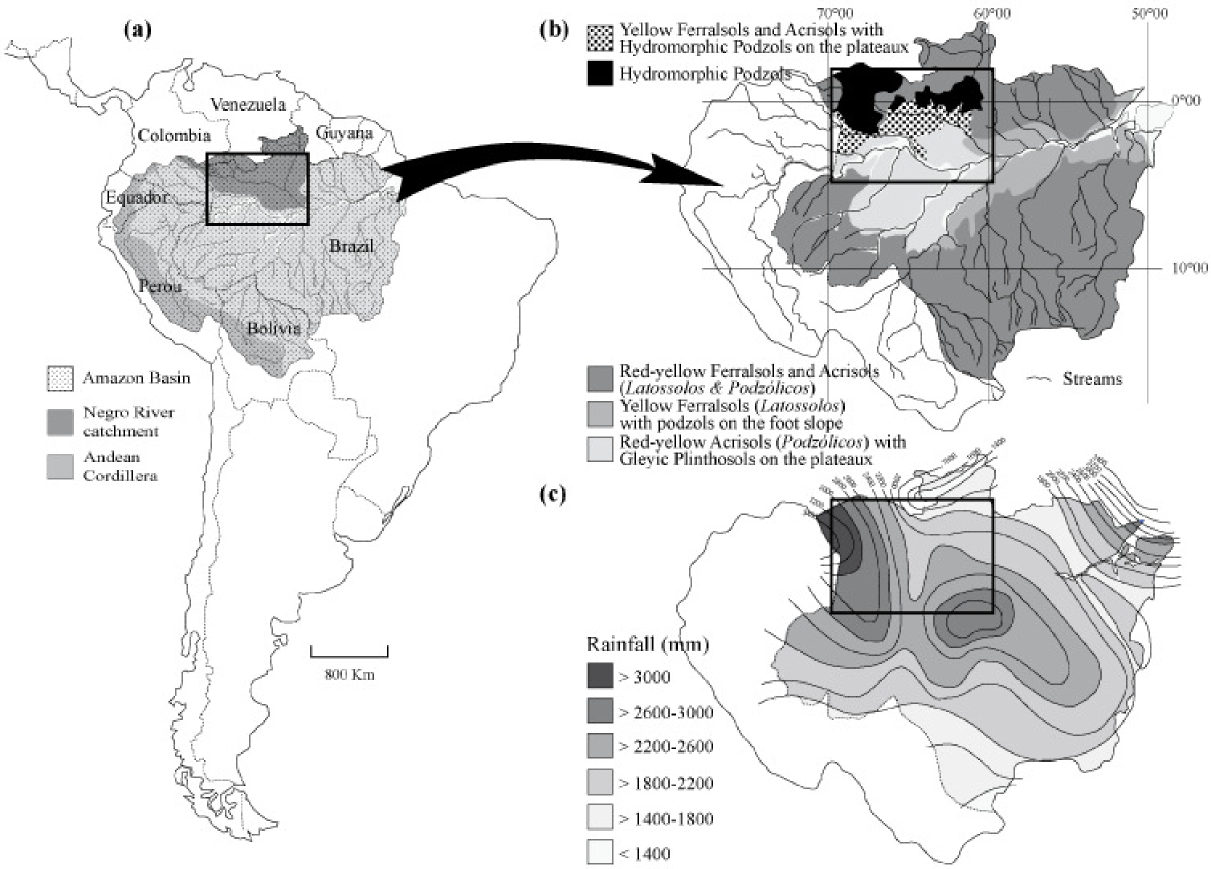


Figure 1*. (a) The Negro River catchment within the Amazon Basin in South America, (b) broad scale soil map (reduced and simplified from Radam Brazil maps at 1:1000.000) and (c) average annual rainfalls (from ANA) of the Brazilian Amazon Basin (black rectangle insert refers to site location in Fig. 2).*

The low elevation plateaux of the upper Amazon Basin is usually explained based on the principle of planation by erosion cycles, deriving from King's proposition (King, 1953). According to this author, the flat surfaces are elaborated by erosion and lateral slope retreat, mainly under dry climates, generating residual relieves, pediplains and ultimately sandy deposits (*playa* and *bajada*) at low elevations. Base-level lowering due to positive epeirogenesis or marine regression (King, 1953), or climatic oscillations towards the humid (Bigarella & Andrade, 1965; Franco et al., 1977; Costa et al., 1978) would be responsible for river incision phases which, alternating with planation phases, generated polycyclic landscapes. According to this model, the *Mesas,* inselbergs and major hills of the Negro River catchment would correspond to the residual relieves, the widespread flat surface to an active phase of soil denudation and the sandy deposits in depressions (*playa* and *bajada*) to sedimentation (Franco et al., 1977; Costa et al., 1978), generated during the late pediplanation

and sedimentation in the upper Amazon Basin. Deep river incisions and development of a ramified network of brooks (*igarapes*) in the lands would have eroded the edges of the low elevation plateaux and built up the alluvial terraces.

An alternative genetic explanation for the development of low elevation lands follows the principle of soil collapse governed by hypodermic chemical erosion. This approach proposes that geochemical processes, which act into the soil and saprolite mantles, drive landscape evolution towards planation (Bocquier, 1971; Boulet R., 1974; Millot, 1983, Dubroeucq et al., 1991). Indeed, soil change processes that transform laterally one soil type into another (Fanning and Fanning, 1989) are commonly related to losses of matter. Such losses generate soil collapse and therefore surface lowering. They first produce depressions and ultimately vast plains following the upslope expansion of weathering fronts. The importance of this kind of internal erosion depends on the type of weathering process involved in this soil dynamics, which is frequently linked to altered water regimes (e.g. changes from freely drained to waterlogged environments). On this regards, mobilization and export of iron in reducing environments is commonly related to dramatic colour changes in soils (Fritsch et al., 1986; Fritsch et al., 2004) but to limited losses of matter. This process would therefore have weak repercussion on landscape evolution. By contrast, the breakdown of Fe-clay and plasma-skeleton bonds, followed by the mobilization or destruction of clay minerals (Bocquier, 1971; Boulet, 1974; Chauvel et al., 1977) would lead to significant losses of matter, residual accumulation of sands, as thus to relevant change in the physiography of the landscape (Lucas et al., 1987; 1988, Dubroeucq et al.; 1991). Moreover, by producing slope gradients in closed or open depressions, this soil landscape dynamics and associated chemical erosion may generate at or near the surface various types of physical erosion (e.g. sheet, rill, gully and piping) (Planchon et al. 1987, Fritsch et al, 1994). According to this second approach, intense geochemical erosion of weakly or strongly weathered laterites that form clay-depleted soils (Acrisols) and ultimately sandy Podzols would correspond to the major driving process for the development of depressions and vast inundated plains within the low elevation plateaux of the Negro River catchment (Dubroeucq et al., 1991; 1999).

Two opposite interpretations are thus given in the literature to explain the formation of waterlogged Podzols in the Northern part of the upper Amazon basin. The first approach closely links the formation of Podzols to sandy deposits (e.g. Klinge 1965; Bezerra, 2003), suggesting therefore a major sedimentary control in the development of weathering processes. The second approach reveals that waterlogged Podzols may form in poorly drained

environment (between major tributaries of the Negro River) from *in situ* weathering of laterites leading the residual accumulation of quartz sands and major exportations of organo-metallic complexes to the river network (e.g. Lucas et al., 1987; 1988). Both sedimentary and weathering processes could also have acted simultaneously in the Negro River catchment. This highlights that the large development of degraded soil landforms in this catchment, with the ultimate formation of waterlogged and acidic Podzols, must be replaced in the frame of the late Tertiary sedimentation in the upper Amazon Basin and the birth of the Amazon River system during the Quaternary.

We have undergone pedo-geomorphic investigations at three different scales in the Negro River catchment (from global to very detailed field surveys and related laboratory investigations) to reveal major landforms and associated chemical and physical erosion processes that have contributed to the formation of highly degraded lands. In the discussion of this paper, a schematic model of soil landscape evolution is proposed to explain the formation of these lands in the frame on the sedimentary, tectonic and climatic history of that part of the Amazon Basin.

5.2. Environmental Setting

We present in this section the most recent interpretations on the Tertiary history of the Amazon lowlands and the ultimate birth of the Amazon River system. Tectonic events (Quechua I and II), related to the collision between the South American and Nazca tectonic plates and the birth of the Andean cordillera, have strongly altered the physiography of the upper Amazon basin during the Tertiary. From the early to the mid-Miocene Quechua I orogenic phase of Andean tectonism, the drainage system of the Amazon basin discharged sediments into a Pacific embayment. It formed the largest continental deposits of the world, known in Brazil as the Solimões formation (Sampaio and Northfleet, 1973). This sedimentary event was followed by intense phase of erosion associated with the formation of the Andean cordillera during major orogenic events of the Quechua II. This orogenic event cut the western drainage system and forced the rivers to turn east. A very extensive marsh and lake-region was born in the middle of the upper Amazon Basin (Campell et al. 2006). In the late Pliocene, base-level lowering has initiated the development of the modern Amazon River system, the incision of the lowlands and thus formed the low elevation plateaux of the upper Amazon Basin.

A more accurate chronology of the Tertiary events has been recently proposed by Campbell et al. (2006) and generalized to the whole upper Amazon Basin using stratigraphic unconformities and subsequent depositional features at widely separated areas within the Andes of Bolivia, Peru and Ecuador. A Pan-Amazonian surface has been identified and related to major erosion events leading to the formation of the Ucayali Peneplain. Peneplanation within the upper Amazon Basin likely started at the mid-Miocene, i.e. 15 Ma ago at the end of Quechua I, and terminated abruptly near the beginning of the late Miocene Quechua II orogenic event at ~ 9.5 Ma. This was followed by the late Tertiary sedimentation, which starts blanketing the lowlands and forms ultimately deltaic and lacustrine deposits of moderate to low energy within a giant lake (*Lago Amazonas*) following the closure of the gates to the Pacific ocean, in both the South and North directions. These deposits previously assimilated to the Solimões Formation in Brazil are now differentiated from the latter and assigned to the Içá formation (DNPM, 1981). This last continental sedimentation ends up in the late Pleistocene at ~ 2.5 Ma with the birth of the modern Amazon River system.

Detailed and regional surveys on soils derived from the Içá formation in the North region of PortoVelho (Fritsch et al., 2007) reveal less weathered materials and thinner soils (≤ 1 m) than those exposed on the Ucayali Peneplain of the Manaus (Fritsch et al., 2004) or São Gabriel da Cachoeira (Montes et al., 2007) regions (2 - 15 m), suggesting therefore younger soils. On this regards, datation of kaolinite, a ubiquitous clay mineral of tropical soils, using radiation-induced defects, could not be done for the youngest soils due to the presence of residual primary minerals (mostly mica) but gave an age ranging from 25 to 65 Ma for saprolitic materials of deeply weathered soils (Ferralsols) of the Manaus region (Balan et al., 2005). This apparent age is much older than that attributed to the late Tertiary sedimentation (2.5 Ma) and thus ignition of soil weathering on the Içá formation. It is also older than that related to the late orogenic events of the Quechua I (15 Ma) and indicates the formation of deeply weathered lateritic materials prior to the implementation of the Ucayali Peneplain.

The buried Peneplain, described by Campbell et al. (2006) on river cut-banks, separates eroded, often folded, faulted, and weathered, moderately to well consolidated materials from the unconsolidated, near horizontal, upper Tertiary deposits (Içá formation in Brazil). Spectacular faulting through deeply weathered lateritic profiles developed on the Alter do Chão, with hectometric uplifted and sunken blocks are observed on all road cuts of the Manaus region (Fritsch et al., 2004). It thus indicates that the Ucayali Peneplain is exposed at the surface in this region. It also suggests that faulting in old lateritic materials is likely

contemporary to Quechua II orogenic events and attributed to reactivation of the deepest faults of the Amazon graben (Hasui et al., 1984; Bezerra, 2003).

The end of Quecha II, with the ultimate formation of the Andes, is closely followed by the birth of the modern Amazon River System. This is nearly coincident with the onset of the Plio-Pleistocene glacial climatic regime and the lowest sea level stands since the latest middle Miocene (Campbell et al., 2006). This climatic event is likely at the origin of the deepest cuts in the riverbeds and incisions of the edges of the newly formed plateaux. River cuts show strong tectonic controls in the investigated catchment, more specifically at the extremity of the Amazon trough with dominant N45°W and N70°E lineaments in the lower Negro River catchment and N70°W and N-S lineaments in the middle one (Fig. 2). In the main drainage system of the Negro River, major sunken blocks linked to reactivation of deep faults of the Amazon graben has led to the formation of two archipelagos, separated by narrow river corridors with rock outcrops (Latrubesse and Franzinelli, 2005).

The formation of the Andes has also led to the establishment of a climatic gradient, oscillating from humid to dry during the Quaternary. The present climate is hot and humid. Mean annual temperature is elevated and almost constant throughout the Negro River catchment, decreasing slightly from the East (27 ^{o}C) to the West (25 ^{o}C) (Costa et al., 1977; Yamazaki et al., 1978). Mean annual precipitations present significant seasonal and regional changes. They increase westwards, from 1750 mm to more than 3500 mm. At Manaus (lower catchment) the average month precipitations are uni-modal, with a maximum on April (319 mm) and a minimum on August (43 mm) (Yamazaki et al., 1978). At São Gabriel da Cachoeira (upper catchment) precipitations are bi-modal, with maximum on January (289 mm) and April (339 mm) and minima on February (282 mm) and August (124 mm) (Costa et al., 1977).

5.3. Materials and methods

Pedo-geomorphologic investigations were carried at three major scales: (i) at global scale in the Northwestern part of the upper Amazon Basin in order to display the relative distribution of Podzols in the landscapes of the Negro River catchment, (2) at regional scale in two selected sites of the catchment to display contrasted abundance of Podzols in these landscapes and (3) at local scales in both selected sites to show gradual changes of colour and texture in well-drained upland soils observed along selected transects as well as abrupt ones along soil catena (lateral appearance of waterlogged Podzols).

Global scale

For the Negro River catchment, the data sources were the soil, geological, vegetation and geomorphological maps at 1:1.000.000 scale of the RADAM Project, and the Landsat TM satellite images. The three maps generated from these data using GIS softwares display soil types in relation with major geological and geomorphological units (Fig. 2). They revealed the distribution and relative abundance of waterlogged soils (Gleyic Plinthosols and Hydromorphic Podzols) in relation to better-drained ones (Ferralsols and Acrisols) of the uplands as well as the extent of Quaternary and modern deposits in terraces and riverbeds (Gleysols). The tendency of an orderly distribution of Podzols in the landscape and spatial expansion in an ESE-WNW direction, more specifically between two major rivers of the upper Amazon Basin, i.e. the Solimões and Negro Rivers, oriented the selection of two sites for detailed pedo-geomorphological investigations. The two sites belong to the low elevation plateaux of the basin. The first one (Jaú site), located in the lower Rio Negro catchment, marks the appearance of waterlogged Podzols in the uplands. The second one (Curicuriari site), 650 km upstream, belongs to the upper Rio Negro catchment. It is an almost completely podzolized soil landscape. The Jaú site is located within a National Park and the Curicuriari site inside an Indigenous Reserve. Accordingly, the impact of human activities on soil landscapes is negligible.

Regional scale

For each site, the relative distribution and the abundance of well-drained and waterlogged soils of the uplands (low elevation plateaux) and lowlands (terraces) in relation with major geological formations were estimated from digitized soil and geological maps at 1:100.000 of the RADAM Project (Fig. 2a,b and Fig 3a,b). More detailed maps (Fig. 2c and 3c) and block diagrams (Fig. 2d and 3d) of soil and vegetation in relation to major landforms were elaborated from aerial photographs (1980) for the Jaú site and from Ikonos satellite images (2005) for the Curicuriari site. The mapping was based on the photograph/image texture and tonality and on the degree of relief dissection that are function of vegetation type, soil drainage conditions and intensity of river incision, respectively. Field surveys were carried out in these selected areas to check map unit demarcations and to obtain precise altimetric data using topographic GPSs Topcon Hiper and a pair of Paulin Altimeters under vegetation cover. Aerial photographs or satellite images coupled with topographic GPS and altimeter data allowed the elaboration of the block-diagrams for each site using 3D design softwares.

Local scale

Detailed topographic and soil surveys in pits or drilling cores were conducted in the two sites. They were particularly abundant along two transects, extending from the margin of the river Jaú or Curicuriatri to the central part of the plateaux (Fig. 2e and Fig. 3e). The transects illustrate gradual changes of colour and texture in the soils and underlying deeply weathered rock formations (saprolites). They are 4.3 km long at the Jaú site and 1.6 km long at the Curicuriari site. In the latter, five profiles (P1, P2, P3, P4 and P5 in Fig. 3e), developed on a granitic rock basement, were selected to better illustrate and interpret the vertical and lateral changes of colour and texture in soils and saprolites. Soil colour was determined in the laboratory on dry fine earth samples (< 2 mm) by spectroscopy measurements in the visible range. The samples were gently grounded, oven-dried at 60^{o}C overnight during 24 h, put into a 27 mm diameter hole in an Al disk 3 mm thick and then gently pressed against a quartz glass. Diffuse reflectance spectra were taken from from 360 to 830 nm at 1 nm steps using a Varian Cary 5G UV/Vis/NIR spectrophotometer. The CIE tristimulus values were calculated using the colour matching functions of the CIE standart illuminant C (Wyszecki & Stiles, 1982) and a software was used to convert these values into Munsell notations (H for Hue, C for Chroma and V for Value). Particle-size distribution was determined by sieving of sand fractions and of clay-silt by pipetting after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. The particle size classes are: clay (< 0.2 µm), silt (20 – 50 µm), fine sand (50-200 µm) and coarse sand (200 – 2000 µm).

Soil and mineralogical investigations were also performed along two soil catena. The soil catena is 120 m long at the Jaú site and 80 m long at the Curicuriari site. They both exhibit the spectacular lateral transition between freely-drained, clay depleted soils (Acrisols) in upslope positions and waterlogged Podzols in downslope or low-lying positions (Fig. 4). Soil were described in pits or trenches (in particular at the transition) and photographed. Soil horizon or feature demarcations were then extended on the whole soil catena using graphic softwares (Rinder et al. 1994). Detailed geochemical, mineralogical and petrographic investigations were performed on each soil catena (e.g. see Methods in Do Nascimento et al. 2004). In the Curicuriari site, a detailed soil and topographic survey was also conduced in highly incised podzolised area (50 m spaced grid on 32.5 ha) and a ground penetrating radar (GPR) survey was carried out during the early rainy season (Novembre 2006).

5.4. Results

5.4.1 Soil landform distributions at global scale: the Negro River catchment

Figure 2 displays the major geological formations (Fig. 2a), geomorphic landforms (Fig. 2b) and soil units (Fig. 2c) of the Rio Negro catchment. Archean gneisses, granites and migmatites of the Guyana Shield are exposed in the Northern part of the catchment (Fig. 2a). They are covered in the South by the sediment pile of the upper Amazon Basin. The oldest sediments of the catchment outcrop in the East. They belong to Paleozoic (Properança, Trombetas) and Cretaceous (Alter do Chão) deposits, which have filled up the Amazon graben and are now exposed at the margin and central part of the Amazon trough (only the extremity of this Amazon trough is seen in Fig 2a). The Southern part of the catchment is predominantly covered by the Içá formation, the youngest Tertiary deposits overlying the weathered materials of the Guyana Shield in the North and those of the Solimões formation in the South and the West. Four types of erosion and sedimentation surfaces may be identified in the catchment (Fig. 2b): (1) the Ucayali Peneplain, i.e. the widest surface of erosion, (2) the Içá formation, which marks the late Tertiary sedimentation in the Amazon lowlands, (3) the depressions, drains or plains assigned to chemical erosion or physical erosion in former drainage networks of the Içá formation or both and, (4) the incisions and deposits (alluvial terraces) of the modern Amazon River system.

Hydromorphic podzols of the upper Amazon basin are mainly concentrated in the Negro River catchment (Fig. 2c), where they cover 200.000 km^2 of the lands, i.e. 33% of the surface of the catchment. They are formed on different geological formations (Fig. 2a), which are assigned to two major geomorphic surfaces: (i) the depositional surface of the Içá formation, mainly in the lower and middle Negro River catchment and (ii) the Ucayali Peneplain in the upper Negro River catchment (Fig. 2b). Hydromorphic Podzols display similar distribution pattern than Gleyic Plinthosols in the lower and middle Negro River catchment (I and II, respectively in Fig. 2c). Indeed, both kinds of waterlogged soils are lying in ramified networks of drains and depressions, and are both surrounded by slightly higher elevated and better-drained lateritic soils (Ferralsols and Acrisols). As suggested elsewhere by Fritsch et al. (2007), they most likely mark the emplacement of former drainage systems of the Içá formation. Widely extended in the southern part of our investigated region (between the Negro and Madeira rivers), this ancient drainage system is locally cross cut by the modern one, more specifically by the Quaternary alluvial deposits of major Andean rivers (see for example those of the River Solimoes in Fig.2b). This suggests that the development of both

kinds of soils and associated weathering processes (i.e. hydromorphy and podzolisation) in this major sedimentary structure could be prior to the birth of the Amazon River system (i.e. 2.5 Ma).

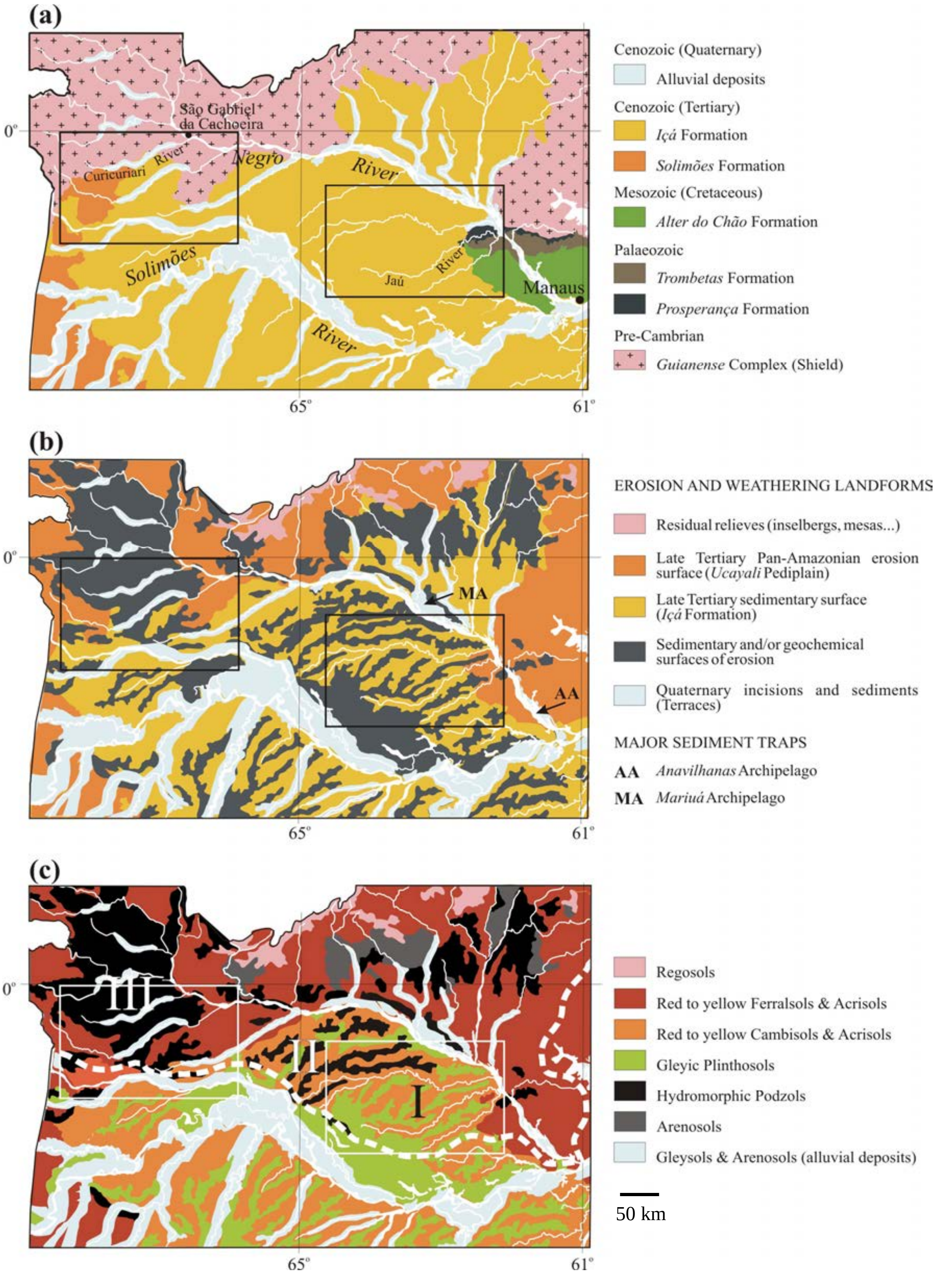


Figure 2*. Broad scale maps of the Northwestern part of the Brazilian upper Amazon Basin showing the major: (a) geological formations (reduced and simplified from DNPM geological*

map at 1:2.500.000), (b) geomorphic landforms (adapted from (a)) and (c) soil units (reduced and simplified from IBGE soil map at 1:5.000.000) of the Negro River catchment. Thick dashed white line refers to the water divide of the Negro River catchment, black or white rectangle inserts refers to regional maps of the Jaú and Curicuriari sites (Figure 3 and 4, respectively).

Figure 2c shows that the superficies covered by Hydromorphic Podzols increase in a Northwestern direction. Such a trend can be related to the establishment of a major climatic gradient after the definitive implementation of the Andean cordillera, with a total annual rainfall that reaches nowadays 1750 mm downstream of the Negro river (Manaus) and becomes greater than 3500 mm upstream. In the lower Negro River catchment (I in Fig. 2c), Hydromorphic Podzols are scarce and scattered whereas Gleyic Plinthosols are widely present in the ramified depressions of the plateaux. The reverse trend is observed in the middle Negro River catchment (II in Fig. 2c), the Gleyic Plinthosols giving rapidly place to hydromorphic Podzols. In the upper Negro River catchment (III in Fig. 2c), the Hydromorphic Podzols, formed on different geological formations of the Ucayali Peneplain, are widely developed on right side of the Negro River and drained by its major tributaries.

In the investigated region, the implementation of the modern river system (Fig. 2) is tectonics controlled and inherited from reactivation of deep structures of the Amazon graben during: (i) the separation of the Gondwanaland and (ii) the early to late Miocene Quechua I and II orogenic events (formation of the Andes). Headwater incisions of the lands by rivers has formed low elevations plateaux but produced weak quantity of sediments in the riverbanks, as the Negro River catchment mostly drained low elevated lands and strongly weathered soils. This is quite different from the major Andean rivers in the South (e.g. the Solimões River in Fig. 2c), which exhibited large alluvial terraces mostly related to active headwater erosion of weakly weathered soils in upstream high elevated Andean lands. However, two major sediment traps have been recognized in the main corridor of the Negro River: (i) the Mariuá Archipelago in the middle catchment (MA in Fig 2c) with white sandy deposits and (ii) the Anavilhanas Archipelago in the lower catchment (AA in Fig. 2c) with dominant clayey or muddy deposits (Latrubesse and Franzinelli, 2005).

5.4.2 Soil landform distribution at regional scale

Jaú River subcatchment (lower Negro River catchment)

Figure 3a better displays at regional scale, the ramified network of waterlogged soils (Gleyic Plinthosols and Hydromorphic Podzols) in the depressions of the plateaux as well as the alluvial deposits in major corridors of the Negro River tributaries. Both kinds of hydromorphic formations are dissociated and separated by better-drained lateritic soils (Ferralsols and Acrisols) on the plateau edges. Soils on the plateaux have formed on different geological formations of the Ucayali Peneplain in the East (Guianense complex, Prosperança and Trombetas formations of the Paleozoic, Alter do Chão Formation of the Cenozoic) and on deposits of the Içá formation elsewhere (Fig. 3b). Headwater incisions have intensely reworked the edges of the plateaux in numerous hills via a dense network of brooks (*igarapés)* and locally built up alluvial terraces (*Igapó*) in narrow river corridors (Fig. 3c,d,e). The brook incisions are less abundant towards the centre of the plateaux. They locally drain the waterlogged Podzols of the depressions (Fig. 3c,d).

This high diversity of soils and associated landforms is also manifest in surface water quality and colour (Do Nascimento et al. 2008, Fritsch et al. in review). Clear waters in brooks are dominant in the region and draining waterlogged areas of lateritic soils (Ferralsols and Acrisols) as well as, near the surface, those of Gleyic Plinthosols. Black waters are restricted to the brooks that drained the waterlogged Podzols in depressions of the plateaux. Both kinds of waters are almost free of suspended clay minerals. By contrast, surface waters of the Jaú River are brown and richer in suspended clay minerals. In the lower course of the Negro River and its major tributaries, suspended particulate phases in surface waters were mostly related by spectroscopic methods to poorly ordered kaolinite and tiny Fe-oxide mineral phases (Allard at al. 2002, 2004), i.e. the ubiquitous minerals systematical identified in the topsoil of deep lateritic profiles from the same region (Balan et al. 2005; Fritsch et al. 2005). This clearly reveals the origin of the deposits in the alluvial terraces of major tributaries of the Negro River. However, plateau edges are colonized by evergreen forest nowadays and do not exhibit wide, fresh eroded lands. Therefore, remobilisation of clay minerals in major river systems of the medium and low Negro River catchment seems to result from the more recent erosion of the alluvial terraces, which have likely contribute to the formation of the Anavilhanas Archipelago, one of the major sediment trap recognized in the lower course of the Negro River (AA on Fig. 2c).

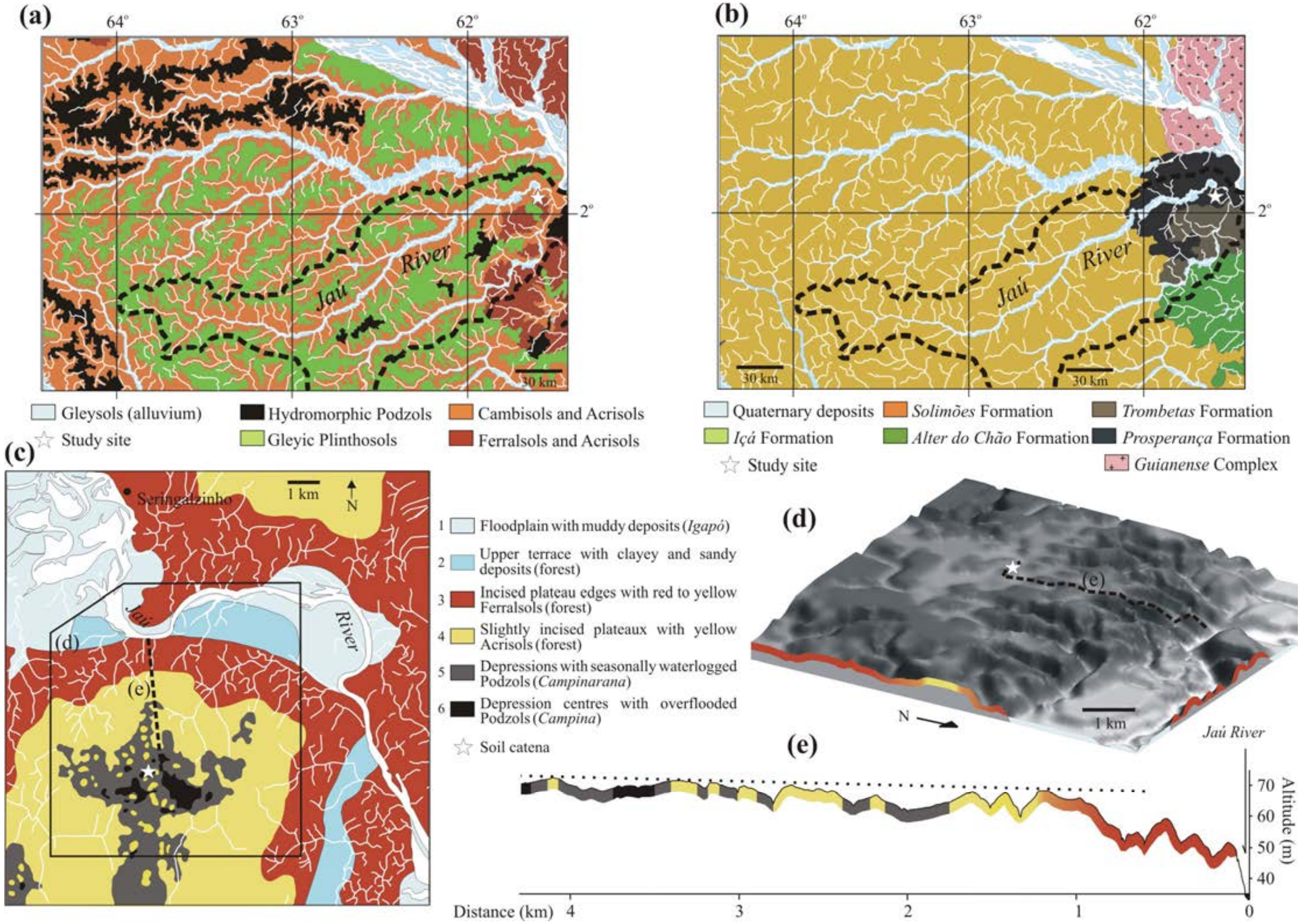


***Figure 3**. (a) Regional soil map and (b) geological map of the Jaú site (extracts from the Radam Brazil maps at 1:1000.000 and modified from the DNPM geological map at 1:2.500.000) plus documents elaborated from aerial photographs and detailed field surveys: (c) map showing major soil landform units and corresponding vegetation covers (see star in (a) and (b) for site location), (d) 3D representation of the same area (see black rectangle insert in (c) for location of the selected zone), (e) soil transect (see dashed line in (c) and (d) for transect location).*

Within the Jaú catchment, waterlogged Podzols in ramified depressions of the plateaux only represent 5% of the lands. One of them has been investigated in detail downstream and on the right bank of the Jaú River (star in Fig. 3a,b, Fig. 3c,d,e). In the study site, soils (Fig. 3a) have formed on sandstones of the Prosperança formation (Fig. 3b). The plateau surface is almost at 40 m above the average water levels of the Jaú River (Fig. 3e). The deeply incised edges of the plateau are bearing reddish-yellow, clayey, low activity clay soils (Ferralsols), covered by evergreen forests (unit 3 in Figure 3c). These clayey soils have built up the Ancient and Recent alluvial terraces in the twisted corridor of the Jaú River (units 1 and 2 in Fig. 3c, respectively). Towards the centre of the plateau, the low activity clay soils turn yellow in their upper part and become progressively depleted in fine particles (Acrisols). They are still covered by the evergreen forest and are weakly incised by a diffuse network of brooks (unit 4 in Fig. 3c). An elongated and ramified depression, locally drained by the brooks, marks the extent of the podzolic area in the centre of the plateau. It is 5 m lower than the plateau surface. The margin of the podzolic area (unit 5 in Fig. 3c) is periodically waterlogged, slightly incised by numerous rills of less than 0.2 m depth and covered by a high density population of smaller trees (*Campinaranas*). The centre of the podzolic area (unit 6 in Fig. 3c) is permanently inundated during the rainy season and covered by a shrub savannah (*Campinas*). Small hill-like landforms bearing Acrisols with evergreen forest and altitudes equivalent to that measured on the plateau are abundant in the depression (Fig. 3c). They have to be considered as lateritic remnants in strongly podzolised lands and thus highlights the contribution of specific processes in the chemical erosion of the lands.

Curicuriari River subcatchment (upper Negro River catchment)

Figure 4a reveals the large extent of Hydromorphic Podzols in the upper Negro River catchment. Podzols occupy huge inundated plains and are thus directly connected to major tributaries of the Negro River. All these tributaries belong to black water systems and are then almost devoid of suspended clay particles (Allard at al. 2002, 2004). As for the Jaú region but at a much larger scale, remnants of freely drained lateritic soils (Ferralsols and Acrisols) are restricted to some dissected plateau edges, near major river corridors, and residual hills or “islands” in huge and weakly elevated inundation plains (Fig. 4a). Podzols in the region are supposed to have formed on weathering products of the *Guianense* shield in the North and the Solimões formation in the West that are both related to the Ucayali Peneplain but also on the Içá formation in the South (Fig. 4b). However, the accumulation of unconsolidated sands in

these huge inundated plains makes difficult the recognition of their parent materials. This is in particular highlighted by the soil map patterns (Fig. 4a), which display certain inconsistencies with that allowed to geological formations (Fig. 4b). Indeed, this study tends to assign the “dendritic” pattern of waterlogged soils developed on the low elevation plateaux (Gleyic Plinthosols and Hydromorphic Podzols) to domains covered by the Içá formation, and therefore to admit the lack of such a pattern for waterlogged soils developed on eroded lands of the Ucayali Peneplain.

As for the other parts of the Negro River catchment, the production of deposits in river beds is limited. However, headwater erosion by the brook and major tributaries of the Negro River now act in unconsolidated sandy materials of Podzols, highly prone to physical denudation. Accordingly, bright white sands are carried in the black waters of the region during periods of high water falls. They have formed waving sandy benches on each side of the rivers. They have also built up the major sandy deposits of the Mariuá Archipelago (MA in Fig. 2b), the other major sediment trap of the Negro River. These bright sandy deposits are certainly one of the most striking features of these highly degraded lands.

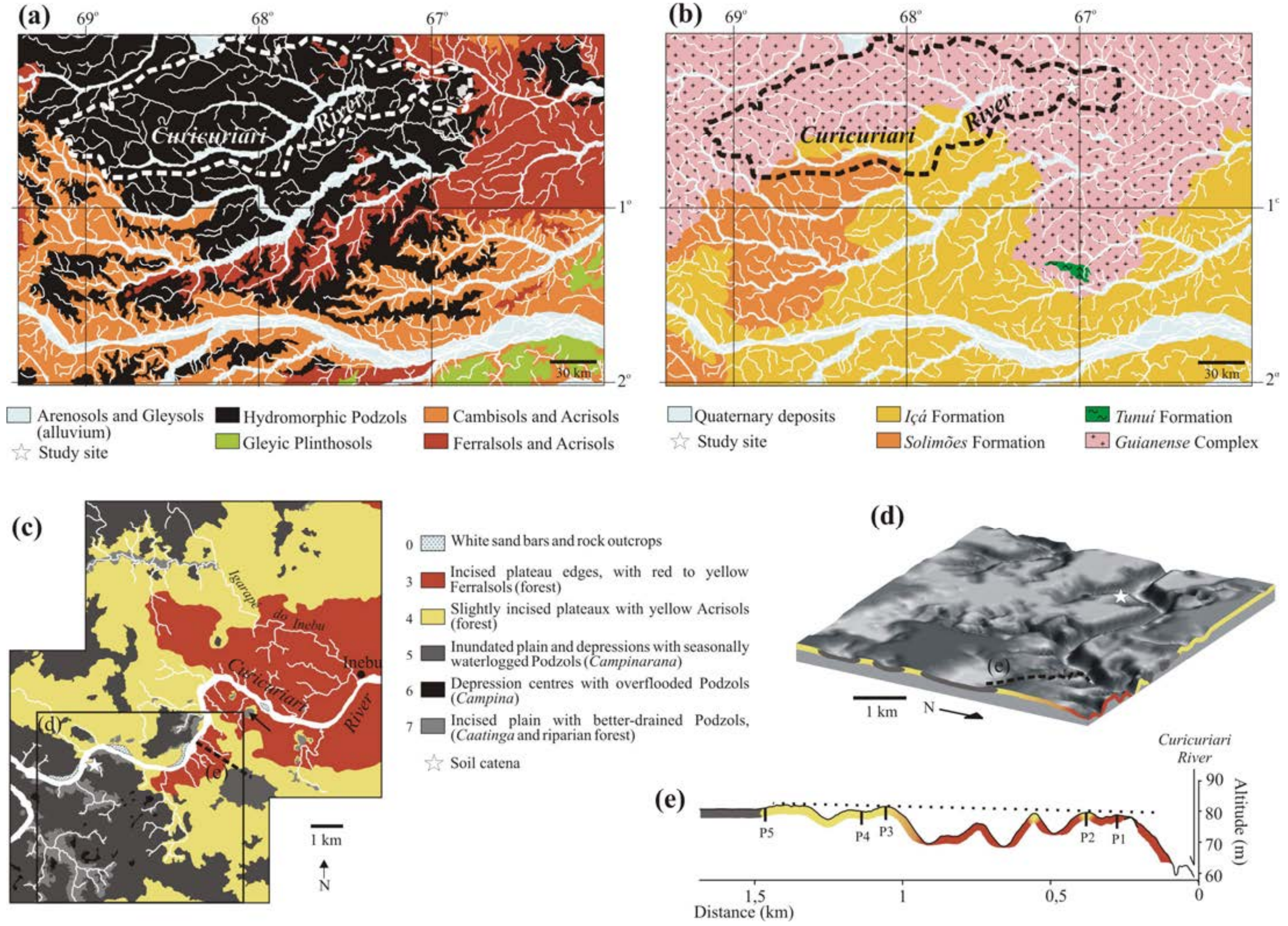


__Figure 4__. (a) Regional soil map and (b) geological map of the Curicuriari site (extracts from the Radam Brazil maps at 1:1000.000 and modified from the DNPM geological map at 1:2.500.000) plus documents elaborated from satellite images and detailed field surveys: (c) map showing major soil landform units and corresponding vegetation covers (see star in (a) and (b) for site location), (d) 3D representation of the same area (see black rectangle insert in (c) for location of the selected zone), (e) soil transect (see dashed line in (c) and (d) for transect location) with selected profiles (from P1 to P5) for colorimeric and particle size distribution of soil and saprolite samples (see Fig. 5).

Waterlogged podzols cover 95% of the surfaces of the Curicuriari River subcatchment. Detailed field surveys were conducted downstream of the Curicuriari River at the transition between the huge inundated plain with Podzols in the West and the better drained, low activity clay laterites (Ferralsols and Acrisols) in the East (Fig. 4c,d,e). Both types of soils are developed on granitic rocks. Their transition is strongly indented and also characterized by the occurrence of spots of waterlogged Podzols in the freely drained and clay-depleted low activity clay soils (Acrisols). As for the Jaú site, these Podzols are lying in depressions of different sizes and shapes and are thus precursors of the huge podzolised plain (Figure 4c,d). They are 3 to 7 m lower than the low elevation plateau and the latter is about at 20 m above the average water level of the Curicuriari River (Fig. 4e), which is about half of that measured in the lower Negro River catchment (Jaú site). Landform units similar to that recognized in the Jaú site were also identified from the freely drained Ferralsols under the forest to the Hydromorphic Podzols of the depressions or inundated plains under tree or shrub savannahs (units 1 to 5 in Fig. 4c,d,e). One major difference is however reported and assigned to the incisions of the podzolic areas by brook and rivers that drained these areas and enable the development of an open forest (*Caatinga*) (unit 6 in Fig. 4c,d,e).

5.4.3 Detailed soil distributions along transect and catena

Pre-weathering processes along transects: Iron and clay-depletion

In both study sites (Jaú and Curicuriari), the freely drained, reddish-yellow, low activity clay soils (Ferralsols) turn yellow and become progressively depleted in fine particles (Acrisols), before to be podzolised in waterlogged depressions or large inundated plains (Figs 3c,d and 4c,d). Clay-depletion thus appears to be as a pre-existing and necessary process for soil podzolisation (Lucas et al., 1989; Bravard & Righi, 1990; Do Nascimento et al., 2004). Mineralogical, geochemical investigations and mass balance calculations carried out in 5 selected profiles of a 1.6 km long transect (Bueno et al. submitted) illustrating these gradual colorimeric and textural changes in the Curicuriari site (P1 to P5 in Fig. 4e) first indicate a total loss of alkali and alkaline earth elements at the base of the profiles and the residual accumulation of Si, Fe and Al in clay and oxide minerals, mainly kaolinite, gibbsite and Fe-oxides (data not shown). The losses in Fe and Al are enhanced vertically between the saprolite (> 2.2 m) and the overlying soil (0 - 2.2 m) and laterally from P1 to P5. They are mostly assigned in the field to colorimeric (for Fe speciation and content) and textural (for Al

contents) changes. The lack of sedimentary structures, geochemical and mineralogical unconformities and the gradual losses in Fe and Al let us to assign these changes to chemical erosion.

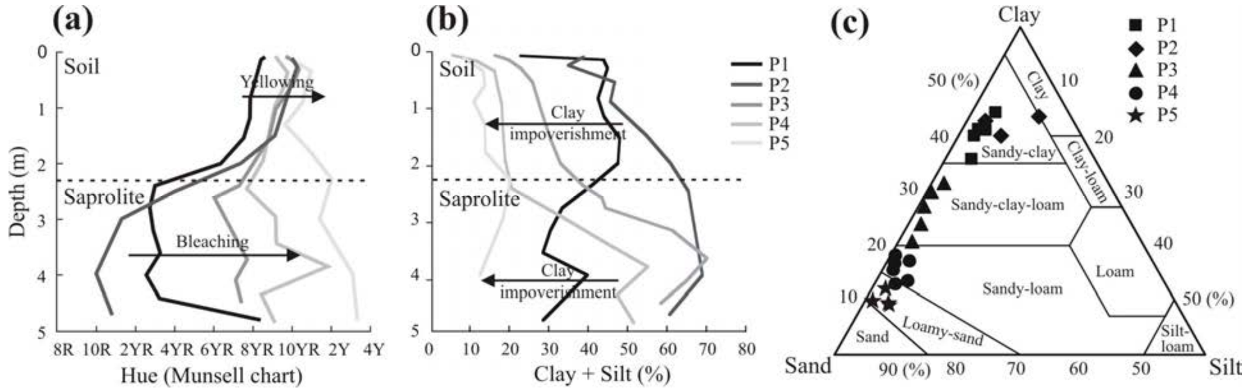


Figure 5. *(a) Hue of the Munsell colour chart calculated from spectroscopic data in the visible range (H) versus depth, (b) clay + silt (< 50µm) weight percent versus depth, and (c) ternary representation of the percentage of clay, silt and sand in soil samples (B horizons) of the five profiles (from P1 to P5) selected in the transect of the Curicuriari site (see (e) in Fig. 4).*

Colorimeric (Fig. 5a) and textural (Fig. 5b,c) changes affect separately soils and saprolites. Soil yellowing (increase of Hue value in Fig. 5a) and Fe losses first affects the upper part of the weathered profiles that conserve the same type of texture (between P1 and P2 in Fig. 5b). Significant losses of clay minerals occur later on in soils and are related to gradual changes of texture from sandy-clay to loamy-sand (P2 to P5 in Fig. 5c). Soil yellowing first results from selective dissolution of Fe-oxides, first hematite than goethite (Fritsch et al., 1989, 2004; Peterschmitt et al. 1996), whereas the ultimate clay depletion is mostly assigned to the dissolution of Al-bearing minerals, mostly kaolinite and gibbsite (Chauvel, 1977; Fritsch et al., 1989; Bravard & Righi, 1990). Such processes indicate greater water activity and soil leaching in Acrisols than in Ferralsols due to larger periods of soil wetting and reduction in unsaturated soils.

At greater depth, the bleaching of red saprolites (between P2 and P4 in Fig 5a) is mainly assigned to a massive dissolution of Fe-oxides and exportation of ferrous iron by groundwater in waterlogged and strongly reduced environment. Close to the podzolic area (P5), the upper part of the saprolite, bleached by the groundwater, becomes also strongly clay-depleted (Fig. 5b). Clay depletion could either be due to the dissolution or the eluviation of clay minerals and associated with greater trough flows in groundwater (Bueno et al. submitted).

Accordingly the gradual lateral losses of matter from Ferralsols to Podzols, via the intermediate Acrisols, increase at two levels in highly weathered laterites: (i) in the soil from the soil surface (unsaturated zone) and at depth in the upper part of the saprolite (saturated one). They favor at macro-scale the formation of a double tongue-like transition and the development at micro-scale of macrovoids between adjacent quartz (Fritsch et al., 1989) that will favor the migration of humus compounds in soils and thus allow the formation of Podzols in waterlogged environments.

Weathering fronts along soil catena: Podzolisation

Structural and mineralogical investigations were carried out along soil catena at the transition between Acrisols and Podzols in both study sites (Jaú and Curicuriari) (Do Nascimento *et al.* 2004 ; Bueno *et al.* submitted). The soil catena of the Jaú site (Fig. 6a) belongs to a waterlogged depression of a plateau partly drained by small brooks (Fig. 3c). It presents a concave sloping side and extends from a small remnant of a forest on a hill-top to a periodically inundated shrub savannah (*Campina*) in a low-lying position. It is 120 m long and the depression is about 2 m lower than the hill-top. The soil catena of the Curicuriari site (Fig. 6b) marks the transition between the inundated podzolic plain and the upslope well-drained Acrisols. It is close from the Curicuriari River and is incised by a brook in low-lying positions (Figure 4c). It presents a convex sloping side and extends from a forest on a hill-top to a *Caatinga* in the midslope position and an inundated riparian forest close to the brook. This soil catena is 80 m long and the hill-top is 5 m higher than the brook. Many similarities exist for both soil catena suggesting highly representative structures and bio-chemical patterns, assigned to soil podzolisation, that could be extended to the whole upper Amazon basin. However remarkable differences are also reported between each site. They will be attributed to brook incisions that have altered the hydrological regime of Podzols.

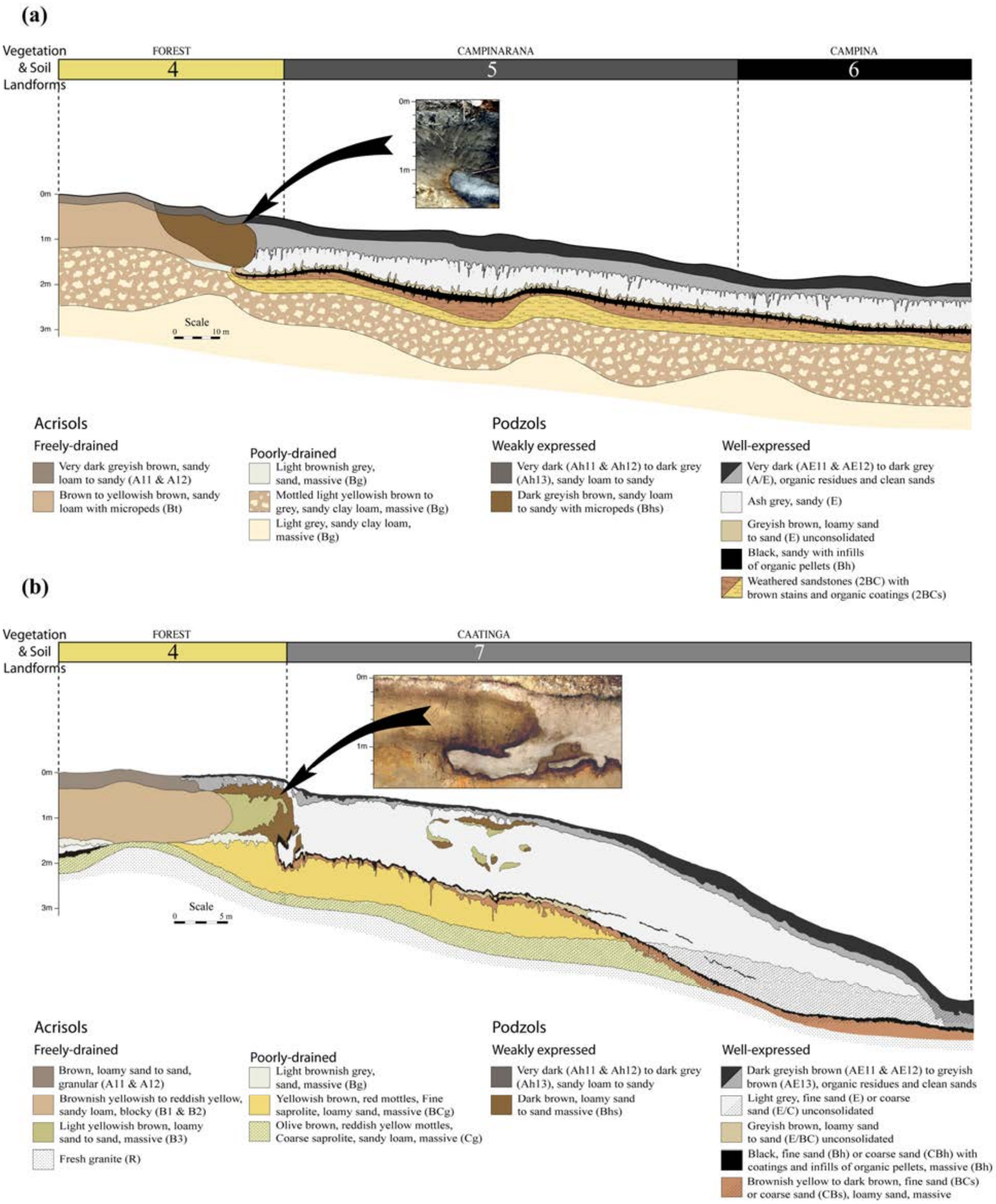


***Figure 6**. Soil catena of the (a) Jaú site in a depression of a plateau (see star in Fig. 3c for catena location) and (b) Curicuriari site at the margin of an incised inundated plain (see star in Fig. 4c for catena location) showing the main types of vegetation and soil horizons according to topographic gradient.*

In both study sites, a double tongue-like shaped transition marks the transition between the upslope Acrisols and the downslope Podzols. This kind of transition has been systematically observed elsewhere at the margin of podzolic areas (Lucas et al., 1989; Bravard & Righi, 1990; Veillon 1990; Dubroeucq et al., 1999; Do Nascimento et al., 2004). The upper tongue is associated with shallow and weakly expressed humus Podzols, which form on top of Acrisols. In such a place, the organic compounds accumulate and deeply impregnate the clay-depleted soils, which contain predominantly quartz but also residual kaolinite, gibbsite and goethite. The organic acids enhance the weathering of clay minerals and contribute to the downward accumulation of organo-metallic complexes (mainly Al and Fe). This first weathering step forms topsoil eluviated A horizons with numerous plant remains and clean sands over subsoil illuviated (or spodic) Bhs horizons with organic coatings (Bardy et al. 2008). In the Curicuriari site, a thin and discontinuous bleached E horizon is also formed between the A and Bhs. The lower tongue is related to the downward but also upslope expansions of Podzols into subsoil B-horizons of Acrisols. This second weathering step marks the almost total loss of clay minerals in AE and E horizons of better-expressed podzols and therefore the residual accumulation of bleached sands as well as the accumulation at greater depths of a second generation of organo-metallic complexes in well-differentiated Bh and BCs spodic horizons (Bueno et al. submitted). By expanding upslope into the clay-depleted and hydromorphic B-horizons of Acrisol, the eluviated E horizon forms the lower tongue of the transition. This horizon may even expand on more than 10 m upslope, at the favor of twisted channels (one of them is cut perpendicularly upslope in the Curicuriai catena, see Fig. 6b). It locally establishes a remarkable structural discontinuity in the vertical differentiation of horizons in Acrisols. This lateral soil differentiation is due to greater through flow in the upper part of the groundwater. Accordingly the convoluted shape of the transition between Acrisols and Podzols and the occurrence in the latter of remnants of B-horizons of Acrisols or Bhs horizons of weakly expressed Podzols (see midslope profiles in Fig. 6b) provide strong evidences of the upslope expansion of the latter into the former.

In both study sites, the development of Podzols is impeded vertically as soon as a more compact and less permeable material is reached. In the Jaú site, this is assigned to a thin slab of weakly weathered sandstones seated on top of a mottled sandy clay loam and loose subsoil. Such kind of material corresponds to the upper part of the saprolitic mantle developed on a granitic basement for the Curicuriari site. Accordingly, textural and structural contrasts in the vertical differentiation of weathered profiles seem to play a major control in the deepening of

Podzols. As soon as a less permeable layer is reached, the lateral development of Podzols will then start to become predominant. The most active weathering front will no longer act at the base of the podzolic areas but at their periphery (Do Nascimento *et al.* 2008). Podzolisation will then be considered as a soil change process (Faning and Faning, 1989) that expands laterally in the landscape (e.g. Sommer et al. 2000). Moreover, the textural contrast at the periphery and base of these podzolic areas will favor the physical fractionation of humus compounds during the spatial differentiation of Podzols, with the accumulation of the smallest fractions (mostly the dissolved organic carbon) in the outer and less permeable materials (respectively the B-horizons of the upslope Acrisols and the top of the underlying saprolitic layer) and the accumulation of coarser fractions (i.e. black organic colloids) at the periphery and base of the inner sandy horizons of Podzols (Fritsch et al. in review). This physical fractionation of humus compounds thus forms on one hand the dark brown Bhs and BCs horizons of Podzols and on another hand their black Bh horizons. Both types of organic accumulation will also reduce the hydraulic conductivity of the soil at the periphery of the podzolic areas and thus favor the development of reducing and acidic conditions in perched groundwaters. This led Do Nascimento et al. (2008) and Fritsch et al. (submitted) to link the formation of Podzols in the lateritic landscape of the upper Amazon basin to the development and dynamics of perched groundwaters. Perched groundwaters rise very quickly in sandy horizons of Podzols. They become enriched in dissolved and suspended organic loads (black waters) and rapidly feed the brooks and rivers of the region. In semi confined environments such as that investigated in the Jaú site (Do Nascimento et al. 2008), the perched groundwater seeps at the margin of the podzolic area and fluctuate in the upper tongue of weakly expressed Podzols during periods of major rainfalls of the wet season. It fluctuates at greater depth, within the lower tongue of better-expressed Podzols, in the early dry or wet seasons and exports large amounts of organic carbon and associated metals to the rivers.

In the Jaú site, Podzols are weakly incised by the river network and systematically observed in open depressions with concave sloping sides (Figs 3c and 6a). By contrast, the highly podzolised plain of the Curicuriari site appears deeply incised by major brooks and rivers. Highly podzolised lands then exhibit convex sloping sides with the river network (Figs 4c and 6b). Comparison of both soil catena (Fig. 6a,b), reveal that physical denudation of the downslope Podzols may have significant consequences on soil differentiation and vegetation cover. Two major differences are reported in soils (Bueno et al. submitted).

First of all, physical denudation of Podzols in low-lying positions may reactivate the deepening of Podzols and contribute to the formation of a second generation of eluviated and illuviated (or spodic) horizons. Indeed, as the slope gradient slowly increases toward the brook incision, a new bleached E horizon is formed just beneath the Bh horizon of the upslope Podzols (Fig. 6b). This sandy horizon expands downward in the saprolitic mantle. It first develops in a clay-depleted and strongly weathered fine saprolite (BC) and ultimately in a coarser, sandier and less weathered saprolite (C). The Bh horizon of the upslope Podzols is partly preserved in bleached E horizons, as a discontinuous line, and a second generation of spodic horizons is formed at greater depth on top of the fine and then of the coarse saprolite (CBh and CBs). Although eroded, the thickness of the Podzols then remains unchanged, or slightly increases donwslope, except in low-lying positions where greater incisions lead to rock outcrops in river beds. Soil survey in other parts of the landscape also shows that podzolisation is not reactivated when brook incisions cut deeper and more abruptly in the landscape (Figs 4c and 7a). Spodic horizons that sustain the perched groundwater on top of saprolitic materials then outcrop in major incisions of the low elevation plateau and numerous springs can be observed on the edges of these newly formed flat surfaces (Fig. 7b). GPR survey clearly reveals the soil organization with a dominant horizontal distribution of podzolic horizons on these incised plateaux as well as the position of the sustained groundwater in the early rainy season (Fig. 7c).

By lowering the local base-level, soil denudation has also significant impacts on the transient accumulation of organic compounds in Podzols. This accumulation of organic matter is much less in upslope positions, at the lateral weathering front between Acrisols and Podzols, and by contrast very important in downslope positions, in the newly formed Podzols. Indeed both the topsoil AE horizons and subsoil Bhs horizons of weakly expressed Podzols appear much thinner in the Curicuriari catena (Fig. 6b) than in the Jaú catena (Fig. 6a). By contrast, the thicknesses of the eluviated topsoil AE horizons and subsoil spodic horizons of better-differentiated Podzols increase significantly toward downslope positions (Fig. 6b). Such changes must be related to better drained environments in the upslope Podzols and the maintenance of waterlogged and reducing conditions in the downslope Podzols. Indeed shorter periods of waterlogging in the upslope Podzols will enhance the turnover of organic compounds whereas longer ones in low-lying positions will increase the residence time of organic compounds and thus favour their accumulation in soils. These changes have also major consequences on the physiognomy and dynamics of the vegetation cover. Indeed the

development of better-drained Podzols in the highly podzolised landscapes of the Curicuriari site enables the return of an open forest (*Caatinga*), which replaces the much denser forest (*Campinarana*) and shrub savannah (*Campina*) of the waterlogged Podzols observed in the weakly podzolised landscapes of the Jaú site.

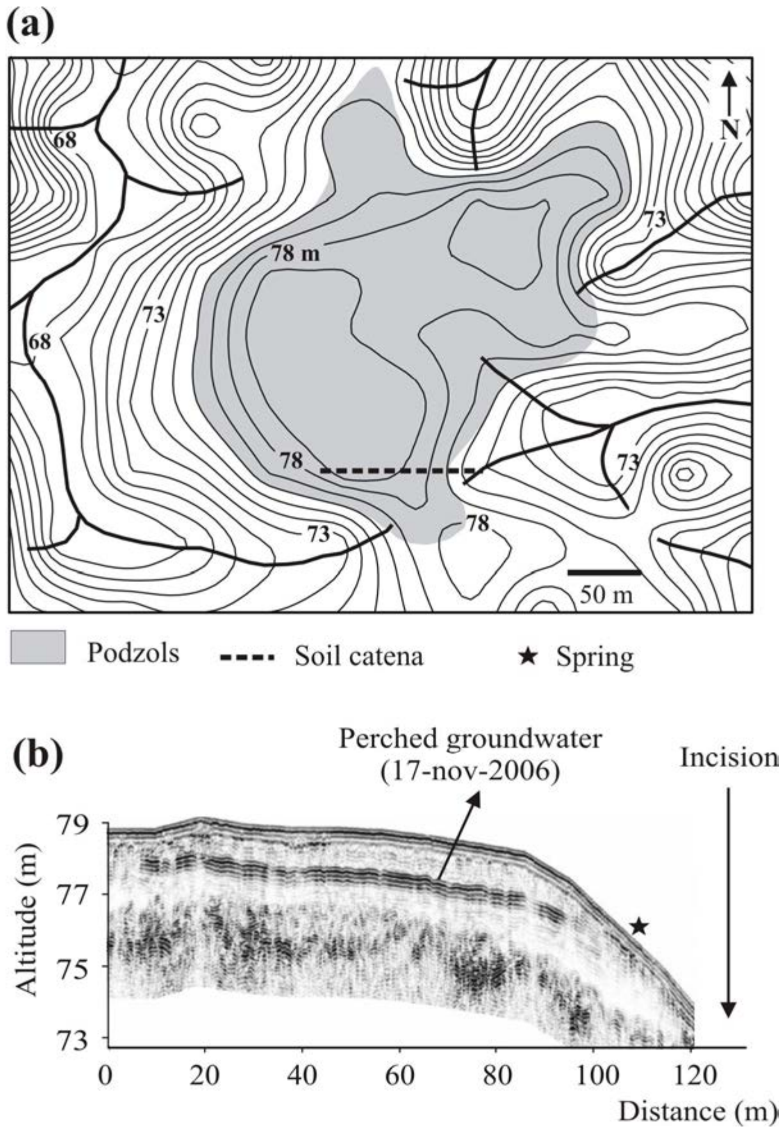


Figure 7*. (a) Small spot of Podzols on a low elevation plateau (see arrow in Fig. 4c for site location) deeply incised by brooks, (b) soil catena (see dashed line in (a)) showing a deep incision in the vertical differentiation of Podzols and groundwater seepage (spring) on the plateau edge in the early rainy season, and corresponding ground penetrating radar (GPR) image (from J. Porsani).*

5.5. Discussion

Pedo-geomorphic investigations carried out at three different scales, from the global scale to the very detailed field surveys, have permitted to recognize major landforms and processes associated with the development of highly degraded lands (mainly Podzols) in waterlogged environments of the Negro River catchment. Regional and detailed field surveys and related soil characterizations led us to propose a schematic model of soil landscape evolution that incorporate, in a sequence of block diagrams, major chemical and physical erosion processes and dominant trends in their spatial expansion (Fig. 8). The development of such processes in the different landforms recognized at regional and global scales are discussed in the frame of the most recent interpretations on the geological history of that part of the Amazon Basin to reveal the main sedimentary, tectonic and climatic controls in the development of these degraded lands.

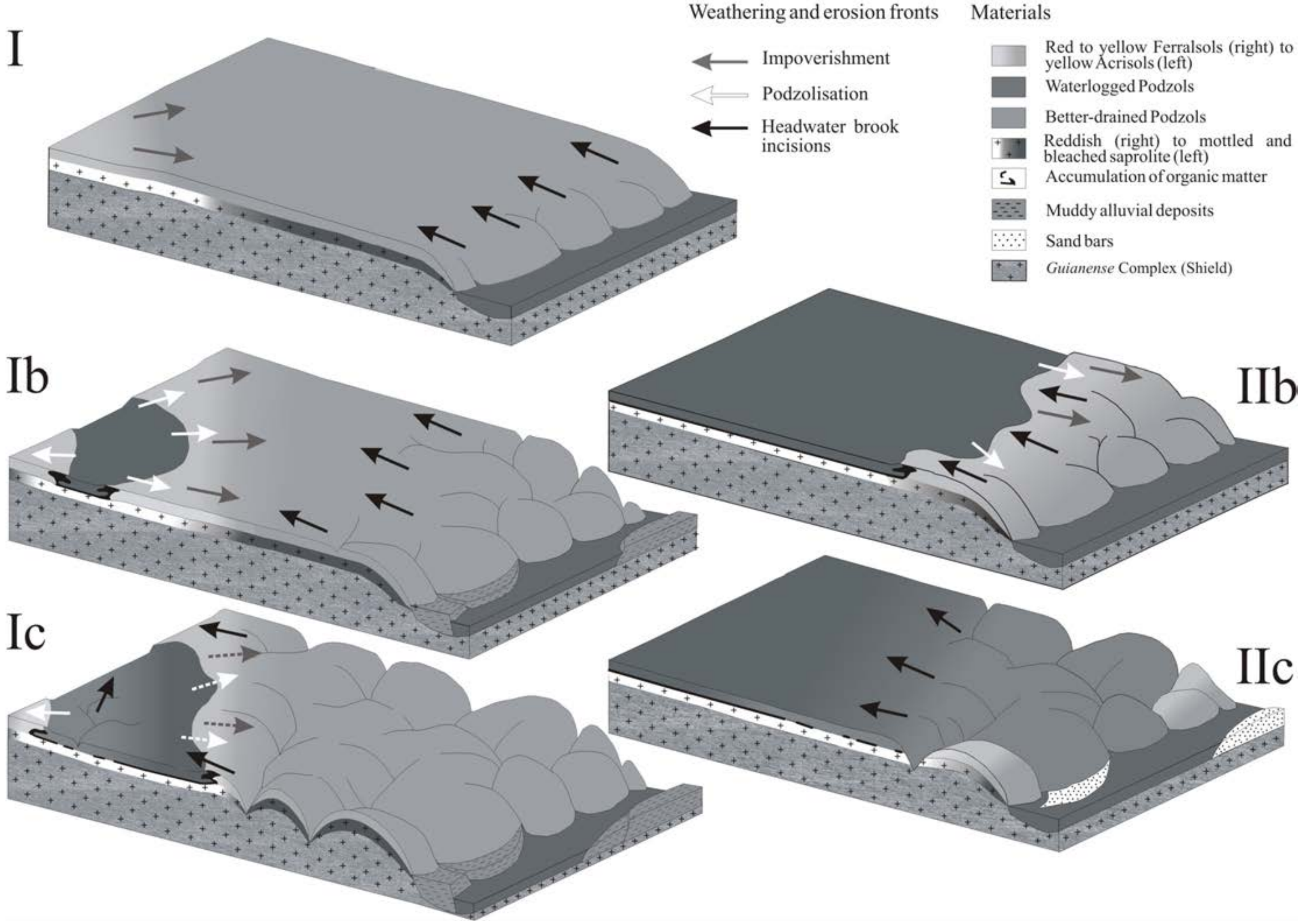


Figure 8. *Schematic model of soil landform dynamics with their three major weathering and erosion processes: from the waterlogged podzols of the low elevation plateaux), iron and clay impoverishment (grey arrows) and podzolisation (white arrows); and from the river network, headwater brook incisions (black arrows), adapted for the lower and middle (Ia, Ib and Ic sequence), and for the upper (Ia, IIb, IIc sequence) Negro River catchment.*

The model opposes dominant weathering processes, which have first acted in the Amazon lowlands to major phases of incision and deposition associated with the birth of the modern Amazon River system, which has formed the low elevation plateaux and built up the alluvial terraces in the upper Amazon basin. According to Fanning and Fanning (1989) and Fritsch et al. (1994), weathering of continental surfaces is either ascribed to soil forming processes commonly observed in freely drained environments (i.e. lateritisation in tropical regions) or to soil change processes, which mainly result from altered water regimes, leading to the individualization of waterlogged environments. In the upper Amazon Basin, broad scale soil maps suggest that lateritisation has either acted on very long geological times or on shorter ones. Indeed, deeply weathered lateritic materials (Ferralsols also known as *Latosols* in Brazil) developed on different geological formations (rocks and sediments) were likely formed prior to the implementation of the Pan-Amazonian Ucayali Peneplain, i.e. before 15 Ma (Campbell et al., 2006). From the early Paleocene, they likely result from the intense weathering under warm and hot climate of rock basements of the *Guianense* and Brazilian shields and the erosion of weathered products at a period where the drainage system of the Amazon basin discharged sediments into a Pacific embayment and built up most of the continental deposits of the basin (mainly Alter do Chão and Solimões formations). This interpretation is in agreement with results of Balan et al. (2005) who provide an age ranging from 65 to 20 Ma for kaolinite of deeply weathered continental deposits of the Manaus region. It is also consistent with paleomagnetic results of Théveniaut and Freyssinet (2002) who attributed a Paleocene-Eocene age to the “Sul Americano” laterization cycles of paleo-surfaces from Guyana, with average relative ages of 60, 50 and 40 Ma. Such lateritic products either *in situ* (paleo-surfaces) or transported (sediments) were deeply faulted in the Amazon trough (Fritsch et al. 2004) during major Andean orogenic events (Quecha I and II) and partly washed out by erosion during the Ucayali Peneplanation. By contrast, less weathered lateritic materials (Cambisols or Acrisols also known as *Podzólicos* in Brazil) have formed on the Late Tertiary sediments accumulated in a huge lacustrine environment in the middle region of the upper Amazon basin (Içá formation), at a period were the Andean Cordillera was formed and at the beginning of the implementation of the modern Amazon River system, i.e. ~ 2.5 Ma (Campbell et al., 2006). This leads us to admit that deposits of the Içá formation came mainly from the erosion of weakly weathered soils of the Andes.

Soil change processes in the Negro River catchment are mostly assigned to: (1) iron and clay impoverishment, and (2) soil podzolisation. They have acted in the Tertiary Amazon

lowlands, including different geological formations of the Ucayali Peneplain and the late Tertiary sediments of the Içá formation. Iron impoverishment has acted alone in some parts of the catchment, leading to the formation of waterlogged clayey soils, namely Gleyic Plinthosols (Fritsch et al., 2007). It has been closely followed by clay impoverishment in podzolic environments. Both iron and clay impoverishment (i.e. development of Acrisols) are thus pre-existing and necessary steps to the ultimate formation of waterlogged sandy soils (i.e. Hydromorphic Podzols) in the Negro River catchment (Bueno et al., submitted) (see grey and white arrows in Fig. 8). Waterlogged Podzols have expanded in the Amazon lowlands in a Northwestern direction according to a major climatic gradient established following the definitive formation of the Andean cordillera. In the lower and middle Negro River catchment (I and II in Fig. 8), they have explored the most confined areas of the Içá formation, which were attributed to former drainage patterns by Fritsch et al. (2007). Podzols have expanded in a huge inundated area of the Pan-Amazonian Ucayali Peneplain in the upper catchment (III in Fig. 8). Development of these Podzols in the Amazon lowlands is related to geochemical erosion, which has contributed to the development of depressions, drains or inundated plains in the most confined areas of the landscapes.

Major incisions associated with the birth of the modern Amazon River system have formed low elevation plateaux in the upper Amazon basin and built up alluvial terraces during the Quaternary. Headwater incisions in the ramified brook networks of the tributaries of the Negro River have strongly reworked the edges of the incised plateaux in numerous hills. The rates of soil denudation on plateau edges and sedimentation in major river corridors was mostly controlled by difference in altitude between the plateau surface and the regional base-level, which was optimum in the early Quaternary during the first major glaciations. Nowadays, the difference of altitude from the plateau surface to the regional base-level increases gradually from upstream (20 m at the Curicuriari site) to downstream positions (40 m at the Jaú site and 50 m at Manaus), suggesting greater rates of soil denudation in the same direction. However, higher stage heights in the lowermost reaches of the Solimões River strongly reduced water discharge of the Negro River at the confluence (Meade et al., 1991). Moreover eroded lands on the plateau edges are actually covered by evergreen forest and most of the suspended clays in rivers most likely result from the rework of alluvial terraces. Suspended clays from major downstream tributaries (e.g. Jaú River) have accumulated in the *Anavilhanas* Archipelago, the major sediment trap recognized in the lower course of the Negro River. Incisions has also generated freely drained conditions in the soils of the plateau

edges and thus favoured the vertical development of laterites. Besides, such incisions (arrow 3 in Fig 8) have acted in an opposite direction that soil change processes (arrows 1 and 2 in Fig 8).

In the lower and middle Negro River catchment, iron and clay impoverishment (arrow 1) closely followed by soil podzolisation (arrow 2) has led to the formation of hydromorphic Podzols in depressions and drains of the plateaux (I in Fig. 8). Regional soil maps suggest that Hydromorphic Podzols have replaced Gleyic Plinthosols from the lower to the middle Negro River catchment (from I to II in Fig. 2c). The weak expansion of Podzols on these landforms must be related to the nature of their underlying geological substrate (i.e. the Içá formation) and the relatively youngest ages of the soils on which they have formed (less than 2.5 MA). Accordingly, the greater rates of soil denudation on plateau edges and the smaller rates of geochemical erosion in more confined areas of the Içá formation thus restrict the lateral expansion of Podzols on the plateaux and therefore their drainage by the river network (I in Fig. 8). Podzols thus remain strongly waterlogged and become deeply impregnated by organic acids, more specifically at the lateral weathering front with their clay-depleted, lateritic upslope counterpart (Acrisols).

The reverse trend can be reported for the upper Negro River catchment. Podzols there have predominantly formed on deeply weathered materials of the Ucayali Peneplain. This kind of materials is highly prone to podzolisation, more specifically in the low elevation plateaux (small water storage capacity in soils) and high rainfall regions of that part of the catchment. Geochemical erosion then acts on a much greater scale and forms huge inundated plains of Podzols that become drained by the brooks and tributaries of the Negro River (II in Fig. 8). Physical erosion of the unconsolidated topsoil horizons of Podzols then provides bleached sands to river systems in periods of high water stages, leading with time to the formation and displacement of wavy sandy bars in major river corridors. This transfer has built up the major sandy repository of the Mariuá Archipelago (MA in Fig. 2b), the second major sediment trap of the Negro River just downstream of the largest podzolised and incised area of the upper catchment. In the lower section of the trap, input of sands from the Branco River has built an internal delta that largely contributes to the accretion of sands in the upper trap. We also reveal that freely-drained Podzols can form from waterlogged ones close to major river incisions. By lowering the groundwater table in Podzols, this will in return restrict the lateral expansion of the podzolised plain but enhance the exportation of organic colloids and associated metals in rivers. Podzolisation will no longer act efficiently at the margin of the

podzolised plain but in low-lying positions and close to major river incisions, expanding then vertically in less permeable weathered materials such as saprolites.

The almost lack of Podzols in the incised landforms of the Quaternary, particularly in the middle and lower Negro River catchment is an additional argument to reveal the great age of the Podzols observed on the low elevation plateaux, which could have started to form on strongly weathered materials at the end of the Ucayali Peneplaination, i.e. 9.5 Ma ago. However and contrary to geological formations, soil change process such as podzolisation, which might have been initiated some Ma ago, could also have been reactivated more recently in some part of the landscapes. This process is also still on-going nowadays, as indicated by the large amount of organic colloids and associated metals transferred to the black waters of the Negro River. This points out the difficulty or impossibility to date weathering processes. Nevertheless, we have also some strong evidences that podzolisation has been reactivated at some times in the past. This led to the formation of Podzols in foot slope positions of Quaternary incised landforms or alluvial terraces. This second generation of Podzols is widely spread downstream of the Negro River, more specifically in footslope positions of the deeply incised plateaux of the Manaus Region (Lucas et al., 1984; 1988; Righi 1990). As reported in this paper, it has also been initiated on incised landforms of the inundated plains of the upper Negro River catchment.

At least, the study also highlights that the development of waterlogged and acidic conditions and the ultimate return to better-drained conditions in podzolic and incised landforms have also a remarkable effect on the dynamics of the vegetation cover. Indeed the first trend will favours the development in the forest of shrub savannah on inundated Podzols (*Campina*), whereas the second one will, on the opposite, lead to the development of an open forest (*Caatinga*) in better-drained Podzols. Soils and vegetations have therefore similar dynamics in the Negro River catchment, which not necessary result from climatic changes during the Quarternary, as stated by some authors (Haffer, 1969).

5.6. Conclusion

The major weathering and erosion processes were replaced in the frame of the main geomorphic surfaces implemented during the Cenozoic history of the Amazon Basin. The detailed mineralogical and structural approach applied in this study has been used in the past on small landscape units to reveal major processes and hydro-geochemical cycles in degraded

landscapes (e.g. Fritsch et al. 1992, 1994). Fritsch et al. (2007) have recently used this approach with detailed and broad scale soil maps to interpret the formation of waterlogged soils on the the Içá formation, which is commonly related to the implementation in the past of a giant lascustrine area (*Lago Amazonas*) and to the switch of the Amazon river drainage system. We used in this paper the same procedure at continental scale, on different geomorphic surfaces, which have formed in the past and are still forming highly degraded landforms in waterlogged and acidic environments, i.e. in the podzolic lands of the Negro River catchment.

We bring new insights on the formation and development of these degraded lands. In particular, we reveal the main controls of geomorphic surfaces and associated geological formations in the development of weathering and erosion processes, which are driving processes in our study site to (1) lateritisation, (2) iron and clay impoverishment, (3) podzolisation, and (4) headwater incisions or regressive erosion in freely-drained and waterlogged lands. We also highlight the contribution of climatic and tectonic factors, closely related to the formation of the Andean Cordillera during the Tertiary, in the development of these processes. We are conscientious of the restrictions imposed by the lack of detailed cartographic documents and believe that integration of major soil patterns in geological and geomorphic maps would greatly improve our understanding on the formation and evolution of the continental surfaces of the Amazon Basin. On this regards, we suggest to restrict the extend of the Içá formation to low elevation plateaux with shallow (~1m deep), weakly weathered soils developed on near horizontal, mottled and compact deposits as well as to occurrence on the plateaux of ramified drains and depressions with waterlogged soils (Fritsch et al. 2007). Indeed, this soil pattern is consistent with an Andean origin of the sediment (weakly weathered), a deposition in lacustrine environment and the relatively young age of the soils (< 2.5 Ma). It is easily recognised in the field and is assigned on all Brazilian soil maps (Radam Brazil, 1972-78; EMBRAPA, 1981; IBGE, 2001) to a vast area in the central part of the upper Amazon Basin. This definition led us to revise the geomorphic map presented in Figure 2c and restrict the extent of the Içá formation to the right bank of the Negro River (Fig. 9).

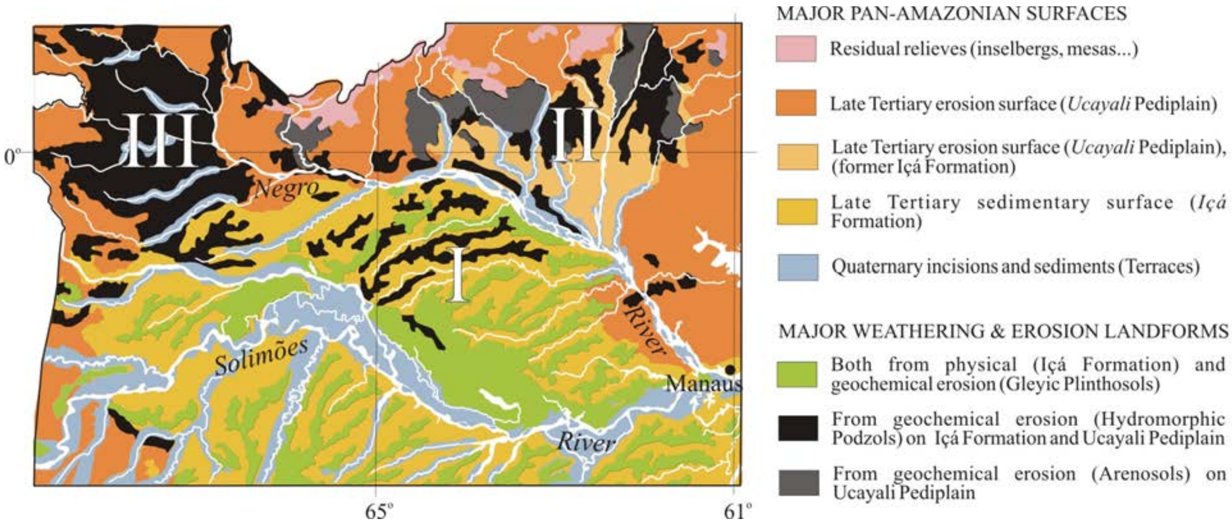


***Figure 9**. Re-interpretation of the major geomorphic landform units presented in Figure 2b for the Northwestern part of the Brazilian upper Amazon Basin from results and interpretations given in this study.*

Figure 9 reveals thee major land surfaces with hydromorphic Podzols (I, II and III). The first one in the South (I in Fig. 9) corresponds to the Içá formation. Podzols less than 2.5MA old are weakly present and lying in the ramified drains and depressions of the formation. They are replacing other waterlogged soils (Gleyic Plinthosols) in higher rainfall areas of the Negro River catchment. By contrast, Podzols are widely spread on the two other land surfaces (II and III in Fig. 9). They have formed on much older and deeply weathered materials (either *in situ* or transported) exposed at the surface after the late Pan-Amazonian Ucayali Peneplaination. Unit II is easily differentiated from unit III, as it comprises large and elongated regions of Podzols alternating with wide strips of deep sands (Arenosols), closely related in the North to residual relieves (inselbergs) of the crystalline rocks of the Guyana Shield. This unit, with its characteristic strip river pattern, comprises most of the giant Podzols of the Negro River catchment. It most likely results from exposure and podzolisation of coarse grained saprolitic materials of old lateritic formations following the Ucayali Peneplaination. Accordingly, weathering processes enhance on continental surfaces geological and geomorphic patterns acquired on geological times. They also contribute by intense chemical weathering to the development of eroded landforms (depressions, plains), which are abundant in the highly degraded podzolic regions of the Negro River catchment (Fig. 9). These eroded landforms are much widely expressed on old lateritic land surfaces (II and III in Fig. 9) than on younger ones (I in Fig. 9) and may also explore structures acquired

during sedimentary processes (e.g. Içá formation). Further remote sensing and field investigations are required to better reveal these structures and the contribution of weathering and erosion processes in the redistribution of major and trace elements in river systems, more specifically in key areas of units I and II.

Acknowledgements

This work benefits from the financial support of CAPESCOFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l'Univers du CNRS), through the "Ecosphère continentale" programme: "Podzolisation des latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)". We gratefully acknowledge J. Porsani who performed the ground penetrating radar (GPR) survey in our study site.

CONCLUSIONS GENERALES ET PERSPECTIVES

Cette étude contribue à une meilleure connaissance des environnements podzoliques amazoniens. Ces environnements extrêmes (engorgements prolongés, résidus sableux peu fertiles, forte acidité des eaux, faible activité et diversité biologique) associés à des paysages insolites d'une grande beauté mais d'un intérêt économique plus limité sont particulièrement bien développés dans la partie nord du haut bassin amazonien qui reçoit les plus fortes précipitations du bassin. Ils couvrent un tiers de la superficie du bassin du Rio Negro. Ce bassin d'une superficie de 600.000 km2 présente la plus grande concentration de rivières à eaux noires et exporte de ce fait des quantités considérables de matières organiques et de métaux à l'océan. Nous nous sommes dès lors intéressés aux processus et fonctionnements associés à la dynamique évolutive de ces podzols dans les paysages. Nous avons étudié ces processus et fonctionnement à la fois aux échelles locales dans des positions clés de ces paysages et à des échelles régionales afin de resituer cette évolutive dynamique des podzols dans un contexte géodynamique plus global, associé à la formation des Andes et aux grandes surfaces d'érosion du bassin sédimentaire attenant. Cette démarche multi-échelle et fortement pluridisciplinaire nous a amené à utiliser des approches très variées pour acquérir nos données. Ces approches débutent avec les outils spectroscopiques pour la caractérisation des phases minérales du sol et s'achèvent avec les outils de la télédétection pour l'identification des principales facettes des paysages et des grands ensembles structuraux du bassin du Rio Negro, sans oublier bien sûr l'approche structurale essentielle pour la reconnaissance des organisations pédologiques sur le terrain que nous avons utilisée lors des nombreuses missions sur nos sites d'étude. Comme nous l'avons déjà signalé en introduction, les documents cartographiques du projet RadamBrasil ont été décisifs dans le choix de ces sites et la reconnaissance des grandes unités structurales du bassin. À l'échelle des profils d'altération et des séquences de sols, des approches géochimiques couplées à des calculs des fonctions de transfert ont permis d'apprécier l'importance des pertes de matières lors de la transformation ou dégradation des couvertures latéritiques.

Les travaux présentés dans ce mémoire apportent une contribution majeure à la compréhension des dégradations successives qu'ont subi ces couvertures latéritiques au court du temps. Ces dégradations sont essentiellement attribuées à des pertes de matières (principalement Fe et Al en régions tropicales) qui peuvent être sélectives, conjointes, très progressives ou brutales. Elles témoignent des changements des conditions d'altération et de

drainage qui se relayent dans l'espace et se succèdent aussi dans le temps. Dans le bassin amazonien, ces dégradations suivent deux grandes voies. Dans la première voie, les pertes de matières sont ménagées et concernent essentiellement Fe. Elles sont de ce fait attribuées à des engorgements et au développement de conditions réductrices provisoires ou plus permanentes dans les profils d'altération (oxydo-réduction). La caractérisation de ces systèmes (Latosols-Gleysols) sort des objectifs de cette étude. Elle a toutefois été abordée de façon très détaillée dans des études antérieures de séquences de sols à la fois sur des formations latéritiques très épaisses (sur la surface d'érosion de Manaus) ou beaucoup plus minces et moins altérées (sur les sédiments de la Formation Içá au Nord de Porto Velho).

La deuxième voie est celle que nous avons abordée et étudiée dans le cadre de cette thèse. Elle est associée à des pertes de matières beaucoup plus importantes et se réalise en deux grandes étapes (appauvrissement et podzolisation). Dans le cadre de l'appauvrissement (cf article du Chapitre 3), les pertes de matières s'expriment différemment suivant qu'on se situe en milieu non saturé (partie supérieure des profils latéritiques) ou en milieu saturé (partie inférieure de ces profils). Dans la partie inférieure des profils latéritiques, les pertes de matières liées à la fluctuation et aux écoulements de nappes sont brutales. Elles sont d'abord attribuées à l'exportation massive du fer (dissolution des oxydes de fer) puis de minéraux argileux (vraisemblablement par soutirage ou lessivage latéral) lorsque les conditions de drainage de la partie supérieure des nappes est accrue. Dans la partie supérieure de ces profils latéritiques, les pertes de matières sont à l'inverse très progressives. Elles sont saisonnières et vraisemblablement attribuées à des périodes d'hydratation plus prolongées. Elles sont sélectives et affectent d'abord l'hématite (jaunissement du sol) puis les minéraux argileux (kaolinite et goethite) vraisemblablement par des mécanismes de dissolution et lixiviation dominants. Ces exportations de matière en surface mais aussi en profondeur aboutissent à l'individualisation à l'aval des versants de réservoirs sableux dont la bordure latérale présente une forme caractéristique en double langue. Le développement de ces réservoirs très poreux et perméables est propice à la migration des matières organiques et de ce fait à la podzolisation ultime des latérites (cf article du Chapitre 4 et aussi articles en annexe). Cette étape ultime marque le colmatage de la bordure des réservoirs sableux par les substances organiques acides qui altèrent les minéraux résiduels argileux et forment des complexes organo-métalliques. Elle est de ce fait étroitement associée à la mise en place de nappes perchées et de conditions réductrices qui favorisent l'accumulation de matières organiques dans ces sols et leur exportation au réseau hydrographique. Le calcul des fonctions de transfert dans ces systèmes

montre que les exportations de matières (Fe et Al) sont minimes lors de la podzolisation et à l'inverse bien plus importantes lors de l'étape préalable d'appauvrissement des latérites en minéraux argileux. Toutefois, la podzolisation marque un changement de spéciation drastique pour les métaux, qui deviennent alors étroitement liés aux matières organiques.

Nous avons également étudié l'effet des incisions linéaires sur la morphologie et dynamique des podzols (rabattement des nappes perchées, érosion des matériaux sableux des podzols). Cette étude minéralogique et structurale réalisée dans la région de São Gabriel da Cachoeira (cf article du Chapitre 4) a de ce fait été comparé à celle entreprise antérieurement sur des systèmes podzoliques à nappe non incisés (région du Jaú). Dans ces podzols drainés par les incisions du réseau hydrographique, le rabattement des nappes à l'amont des systèmes podzoliques favorise la minéralisation des matières organiques dans les fronts latéraux de podzolisation et de ce fait la libération des métaux préalablement accumulés. Cette minéralisation accrue, liée à une oxygénation plus marquée de ces sols, entraîne une nette réduction de l'épaisseur des horizons organiques de ces podzols, en surface (dans les horizons éluviés à résidus organiques) mais aussi en profondeur dans les fronts de podzolisation (horizons illuviés à complexes organo-métalliques). Cette oxygénation du sol peut aussi favoriser la formation d'oxydes de fer mal cristallisé dans les systèmes hydromorphes qui jouxtent les podzols de l'amont. Enfin l'érosion régressive des bas de versants, qui alimente en sables blancs les lits des rivières, peut favoriser la descente des fronts de podzolisation dans niveaux altéritiques moins perméables et de ce fait initier la formation d'une nouvelle génération d'horizons illuviés (ou spodiques) à l'aval. A ce niveau, le maintien de conditions anoxiques en milieu faiblement acide est propice à une grande accumulation de complexes organo-métalliques. Les métaux initialement présents à l'amont de ces systèmes podzoliques s'accumulent à l'aval dans une seconde génération d'horizons spodiques. Cette étude comparative montre aussi que les podzols sont associés à des systèmes de nappe et que le drainage de ces podzols marque une étape ultime dans leur évolution qui permet aussi (soit de façon naturelle soit de façon artificielle) de limiter leur expansion dans l'espace.

Dans une dernière et ultime étape, nous avons resitué ces processus et fonctionnement à l'échelle du bassin amazonien, plus particulièrement dans la région où les podzols sont les plus abondants : le bassin versant du Rio Negro (cf article du Chapitre 5). Cette étape décisive dans la compréhension de la mise en place de ces formations et de leur expansion dans les paysages s'est avérée très riche d'informations. Nous avons ainsi pu montrer que leur expansion dans l'espace était à la fois contrôlée par la nature du support sur laquelle elles se

forment et par les apports pluviométriques. Leur expansion est en effet très nettement accrue dans la partie Nord et Nord Ouest, c'est-à-dire dans les zones les plus pluvieuses et sur la surface d'aplanissement *Ucayali* qui exposent localement les latérites les plus altérées et anciennes du bassin. A l'inverse, elles sont beaucoup moins abondantes dans la partie sud du bassin, plus particulièrement sur la Formation Içá où elles occupent, comme les sols hydromorphes plus classiques (les Gleysols), les parties déprimées des plateaux. La grande expansion des systèmes podzoliques sur ces surfaces Tertaires et leur bien moindre abondance sur les surfaces d'incision et de dépôt du Quaternaire suggèrent fortement que ces systèmes aient pu être mis en place sur le bassin avant la naissance du réseau modern de drainage du fleuve Amazone, il y a prêt de 2.5 Ma. Par ailleurs, l'incision des surfaces basses du bassin par ce réseau de drainage a permis de drainer les aires les plus podzolisées situées au Nord Ouest de ce bassin, de stopper l'expansion de ces podzols ou limiter fortement leur expansion dans les paysages et d'alimenter en sables les lits des rivières.

Suite aux travaux réalisés dans le cadre de cette étude, deux incertitudes majeures subsistent. En effet, nous montrons qu'il existe deux voies possibles dans l'érosion chimique des couvertures latéritiques qui sont toutes deux associées, lors de leur évolution ultime, à la mise en place de systèmes de nappes dans les paysages. Dans la première voie, l'érosion chimique est sélective (dissolution des oxydes de fer) et les sols blanchissent mais restent argileux et peu perméables (formations des Gleys à nappes). Dans la deuxième voie, l'érosion chimique beaucoup plus importante (dissolution de l'ensemble des minéraux argileux) est propices à l'appauvrissement des latérites et ultérieurement à leur podzolisation (formations des Podzols à nappes). Sur la Formation Iça, les deux types de sols (Gleys et Podzols) occupent les mêmes positions topographiques (dépressions et chenaux des plateaux) et se relayent du Sud Est (Gleys) vers le Nord Ouest (Podzols). Quels sont les facteurs qui permettraient d'expliquer l'évolution vers l'une ou l'autre de ces voies à partir d'un même matériau parental ? N'y aurait-il pas içi l'influence de structures sédimentaires (e.g. dépôts plus sableux) qui pourrait favoriser l'une de ces voies plutôt que l'autre (e.g. podzolisation) ? La seconde incertitude correspond aux principaux processus à l'origine de la formation des nombreuses dépressions et chenaux de la Formation Içá. Faut-il y voir içi la marque d'anciennes structures fluvio-lacustres comme ça semble être le cas lorsqu'on les observe à petites échelles ou le résultat d'une fonte géochimique dans les parties centrales les moins bien drainées de ces plateaux, avec l'individualisation ultime de sols à nappes (Gley et Podzols) ?

L'ensemble de ces données permet également de dégager quelques perspectives dans l'optique d'une meilleure connaissance de ces systèmes. La première consisterait à mieux dissocier à méso-échelles les structures sédimentaires de celles attribuées à l'altération et la pédogenèse sur des sites clés de la Formation Içá de façon à mieux répondre aux précédentes incertitudes. La seconde viserait à mieux caractériser les matières organiques et leur charge en métaux dans les podzols drainés du site de São Gabriel da Cachoeira de façon à faire également une étude comparative avec ce qui a été établi au Jaú pour des podzols à nappe. En effet, il serait bon d'attribuer à ces changements de régime hydrique des facies pédologiques différents et des signatures spectrales tranchées pour la matière organique et les métaux, ce qui a encore jamais été réellement fait à notre connaissance. Enfin, il serait aussi souhaitable d'aborder le problème de l'age et de la dynamique de ces systèmes podzoliques par datation (^{14}C) et par des approches isotopiques (^{13}C, ^{15}N) et ce dans les différents ensembles structuraux reconnus aux échelles locales (séquence de sols) et régionales (eaux, sédiments). Des travaux dans ce sens sont en cours. Ils montrent des temps de résidence très contrastés des matières organiques dans les horizons des podzols et des fractionnements isotopiques opposés par rapport à ceux attribués aux environnements minéraux, comme les latérites (pour C, N mais aussi pour les métaux tels que Fe).

CONCLUSÕES GERAIS E PERSPECTIVAS

Este estudo vem contribuir para um melhor conhecimento dos meios podzolizados amazônicos. Estes meios extremos (encharcamentos prolongados, resíduos arenosos pouco férteis, forte acidez das águas, fraca atividade e diversidade biológicas) associados a paisagens insólitas de grande beleza, mas de interesse econômico limitado, são particularmente bem desenvolvidos na parte norte da alta bacia amazônica, que recebe os maiores volumes de precipitação pluviométrica da bacia. Eles cobrem um terço da superfície da bacia do Rio Negro. Essa bacia, com uma superfície de 600.000 km^2, apresenta a maior concentração de rios de águas negras e exporta por isso quantidades consideráveis de matéria orgânica e metais para o oceano. Os processos e funcionamentos associados à dinâmica evolutiva destes podzóis na paisagem nos chamaram a atenção. Estes processos e funcionamentos foram estudos tanto nas escalas locais, em posições-chave destas paisagens, quanto em escalas regionais, visando reconstituir a evolução dinâmica dos podzóis em um contexto geodinâmico mais global, associado à formação dos Andes e às grandes superfícies de erosão da bacia sedimentar. Essa ***démarche*** multiescalar e fortemente pluridisciplinar nos conduziu a utilizar abordagens diversificadas para obtenção dos dados. Essas abordagens se iniciaram pelas análises espectroscópicas para a caracterização das fases minerais do solo e terminaram com o estudo de produtos do sensoriamento remoto para a identificação das principais unidades de paisagem e dos grandes conjuntos estruturais da bacia do Rio Negro, sem deixar de lado, é claro, a abordagem estrutural, essencial para o reconhecimento das organizações pedológicas na escala de campo. Como já assinalado na Introdução, os documentos cartográficos do Projeto RadamBrasil foram decisivos para a escolha dos sítios de estudos e para o reconhecimento das grandes unidades estruturais da bacia. Na escala dos perfis de alteração e das seqüências de solos, abordagens geoquímicas acopladas a cálculos de funções de transporte permitiram a constatação de importantes perdas de matéria durante a transformação ou degradação das coberturas lateríticas.

Os trabalhos aqui apresentados contribuem para a compreensão das degradações sucessivas que as coberturas lateríticas sofreram ao longo do tempo. Estas degradações são essencialmente atribuídas a perdas de matéria (principalmente Fe e Al na região tropical) que podem ser seletivas, conjuntas, progressivas ou brutais. Elas testemunham mudanças das condições de alteração e drenagem que variam no espaço e se sucedem no tempo. Na bacia amazônica estas degradações seguem duas vias. Na primeira via as perdas de matéria são

menos intensas e afetam essencialmente o Fe. Elas são, por isso, atribuídas à saturação hídrica e ao desenvolvimento de condições redutoras provisórias ou mais permanentes nos perfis de alteração (óxido-redução). A caracterização destes sistemas (Latossolos-Gleissolos) vai além dos objetivos deste estudo. Ela foi realizada de forma bastante detalhada em estudos anteriores de seqüências de solos, tanto sobre formações lateríticas espessas (da superfície de erosão da região de Manaus) quanto sobre formações lateríticas delgadas e menos alteradas (sobre os sedimentos da Formação Içá, na região de Porto Velho). A segunda via é aquela que abordamos e estudamos nesta tese. Ela é associada a perdas de matéria muito mais importantes e acontece em duas grandes etapas (empobrecimento e podzolização). Quanto ao empobrecimento (tratado no Capítulo 3), as perdas de matéria se exprimem diferentemente segundo a posição no perfil: na parte inferior, em meio saturado, as perdas associadas à flutuação e ao escoamento dos lençóis são intensas. Elas são inicialmente atribuídas à exportação maciça do ferro (dissolução dos óxidos e lixiviação) e depois dos minerais de argila (aparentemente por lessivagem lateral), desde que aumentem os fluxos na parte superior dos lençóis. Na parte superior dos perfis lateríticos, não saturadas, as perdas são menos progressivas. Elas são sazonais e aparentemente associadas a períodos de hidratação mais prolongados. Elas são seletivas e afetam inicialmente a hematita (amarelecimento do solo) e depois a goethita e os minerais de argila, provavelmente por mecanismos de dissolução e lixiviação. Estas exportações de matéria na superfície, mas também em profundidade, conduzem à individualização, na parte de jusante das vertentes, de reservatórios arenosos cujos limites têm a forma de “dupla língua”. O desenvolvimento destes reservatórios bastante porosos e permeáveis é propício à migração da matéria orgânica e, assim, à podzolização última dos solos lateríticos (tratadas no Capítulo 4 e também em artigos no Anexo). Esta última etapa marca a colmatação da borda dos reservatórios arenosos por substâncias organo-metálicas. Ela é, assim, estreitamente associada ao aparecimento de lençóis suspensos e de condições redutoras que favorecem a acumulação de matéria orgânica nos solos e sua exportação para a rede hidrográfica. O cálculo das funções de transporte nestes sistemas mostra que as exportações de matéria (Fe e Al) são mínimas durante a podzolização, mas são muito mais importantes durante a etapa antecedente, de empobrecimento dos solos lateríticos em minerais argilosos. Entretanto, a podzolização marca uma mudança drástica na especiação dos metais, que passam a se associar à matéria orgânica.

Foram também estudados os efeitos das incisões lineares sobre a morfologia e a dinâmica dos podzóis (rebaixamento dos lençóis suspensos, erosão dos materiais arenosos dos podzóis).

Este estudo mineralógico e estrutural realizado na região de São Gabriel da Cachoeira (apresentado no Capítulo 4) foi comparado àquele feito anteriormente sobre sistemas podzolizados com lençol suspenso e pouco afetados pelas incisões dos canais de drenagem (região do Jaú). Nestes podzóis drenados pelas incisões, o rebaixamento dos lençóis na parte de montante dos sistemas podzólicos favorece a mineralização da matéria orgânica nas frentes laterais de podzolização e, conseqüentemente, a liberação dos metais previamente acumulados. Esta mineralização mais intensa, ligada a uma maior oxigenação destes solos, conduz a uma clara redução da espessura dos horizontes orgânicos destes podzóis, em superfície (nos horizontes eluviais com resíduos orgânicos), mas, também, em profundidade, nas frentes de podzolização (horizontes iluviais com complexos organo-metálicos). Esta oxigenação do solo pode também favorecer a formação de óxidos de ferro mal cristalizados nos sistemas hidromórficos que afetam os podzóis de montante. Enfim, a erosão regressiva na base das vertentes, que alimenta com areias brancas os leitos dos rios, pode favorecer o aprofundamento das frentes de podzolização sobre os saprolitos menos permeáveis e, assim, iniciar a formação de uma nova geração de horizontes iluviais (ou espódicos). Neste nível, a permanência de condições anóxicas em meio fracamente ácido é propícia a uma grande acumulação de complexos organo-metálicos. Os metais inicialmente presentes na parte de montante dos sistemas podzólicos se acumulam na parte de jusante, em uma segunda geração de horizontes espódicos. Este estudo comparativo mostra, também, que os podzóis estão associados a sistemas de lençol e que a drenagem destes podzóis marca uma etapa última na sua evolução, podendo, de forma natural ou artificial, limitar sua expansão no espaço.

Numa última etapa, os processos e funcionamentos foram discutidos na escala da bacia amazônica, particularmente na região onde os podzóis são mais abundantes: a bacia do Rio Negro (Capítulo 5). Esta etapa, decisiva para a compreensão da gênese destas formações e de sua expansão nas paisagens, trouxe importantes informações. Foi possível, assim, mostrar que sua expansão espacial é condicionada tanto pela natureza do substrato sobre o qual se formam quanto pela pluviometria. Sua expansão é, de fato, claramente mais importante nas partes norte e noroeste, isto é, nas zonas mais pluviosas e sobre a superfície de aplanamento *Ucayali*, coberta pelos perfis lateríticos mais alterados e antigos da bacia. Ao contrário, elas são muito menos abundantes na parte sul da bacia, particularmente sobre a formação Içá, onde ocupam, ao lado dos solos hidromórficos mais clássicos (Gleissolos), as partes deprimidas dos platôs. A grande expansão dos sistemas podzólicos sobre estas superfícies terciárias e sua menor incidência sobre as superfícies mais recentes, do Quaternário, sugerem fortemente que estes

sistemas podem ter se desenvolvido na bacia antes da instalação da rede de drenagem moderna do Rio Amazonas, há aproximadamente 2.5 Ma. Além disso, a incisão desta rede fluvial sobre as superfícies baixas foi responsável pela drenagem das áreas mais podzolizadas da parte noroeste da bacia, pela interrupção ou a limitação da expansão destes podzóis nas paisagens e pelo fornecimento de areias brancas para os canais fluviais.

Após os trabalhos realizados no âmbito deste estudo, duas incertezas maiores persistem. De fato, foi mostrado que existem duas vias possíveis para a erosão química das coberturas lateríticas. Estas duas vias estão associadas, na sua evolução final, ao aparecimento de sistemas de lençóis na paisagem. Na primeira via, a erosão química é seletiva (dissolução dos óxidos de ferro) e os solos se tornam mais brancos, mas permanecem argilosos e pouco permeáveis (formação de Gleissolos com lençóis). Na segunda via, a erosão química mais importante (dissolução do conjunto dos minerais argilosos) é propícia ao empobrecimento dos solos lateríticos e posteriormente à sua podzolização (formação de Podzóis com lençol). Sobre a Formação Içá, os dois tipos de solos (Gleissolos e Podzóis) ocupam as mesmas posições topográficas (depressões e canais mal drenados dos platôs) e se alternam do sudeste (Gleissolos) para noroeste (Podzóis). Quais são os fatores que permitiriam explicar a evolução rumo a uma ou outra destas duas vias a partir de um mesmo material de origem? Não haveria aqui a influência de estruturas sedimentares (ex: depósitos mais arenosos) que poderiam favorecer uma destas vias em detrimento da outra (ex: podzolização)? A segunda incerteza corresponde aos principais processos que explicam a origem das inúmeras depressões e canais mal drenados dos platôs da Formação Içá. É necessário verificar se se trata de antigas estruturas flúvio-lacustres, associadas a antigas redes de drenagem, como parece ser o caso quando observadas em pequena escala, ou o resultado de uma perda geoquímica mais acentuada nas partes centrais de pior drenagem destes platôs, seguida da individualização última de solos com lençóis (Gleissolos e Podzóis).

O conjunto destes dados permitiu igualmente apontar algumas perspectivas na ótica de um melhor conhecimento destes sistemas. A primeira consistiria em melhor dissociar, em meso-escala, as estruturas sedimentares daquelas atribuídas à alteração e à pedogênese sobre sítios-chave da Formação Içá, para melhor responder às referidas incertezas. A segunda visaria uma melhor caracterização das matérias orgânicas e de sua carga em metais nos podzóis drenados do sítio de São Gabriel da Cachoeira, para fazer um estudo comparativo com aquele realizado no sítio do Jaú sobre os podzóis com lençol. De fato, seria bom atribuir, a estas mudanças de regime hídrico, diferentes fácies pedológicas e assinaturas espectrais para a matéria orgânica e

para os metais, o que não foi ainda feito segundo nosso conhecimento. Enfim, seria também desejável abordar o problema da idade e da dinâmica destes sistemas podzólicos por datação (^{14}C) e por abordagens isotópicas (^{13}C, ^{15}N), isto para os diferentes conjuntos estruturais identificados nas escalas locais (seqüências de solos) e regionais (águas e sedimentos). Trabalhos neste sentido estão em curso. Eles indicam tempos de residência da matéria orgânica muito contrastados nos horizontes dos podzóis e fracionamentos isotópicos muito diferentes daqueles atribuídos aos meios minerais, como os solos lateríticos (para C, N, mas, também, para metais como o Fe).

BIBLIOGRAFIA

Anderson H.A., Berrow M.L., Farmer V.C., Hepburn A., Russel J.D., Walker A.D. (1982). A reassessment of podzol formation processes. *J. Soil Sci*. **33**, 125-136.

Allard T., Ponthieu M., Weber T., Filizola N., Guyot J.L., and Benedetti M. (2002). Nature and properties of suspended solids in the Amazon Basin. *Bull. Soc. Géol. France* **173**, 67-75.

Allard T., Menguy N., Salomon J., Calligaro T., Weber T., Calas G., Benedetti M.F. (2004). Revealing forms of iron in river-borne material from major tropical rivers of the Amazon Basin (Brazil). *Geochimica et Cosmochimica Acta* **68**, 3079-3094.

Aubert G. (1954). Les sols latéritiques. *Actes et Comptes Rendus du V^e^ Congrès International de la Science du Sol.* Léopoldville **1**, 103-118.

Balan E., Allard T. Boizot B., Morin G., Muller J.P. (1999). Structural Fe^{3+} in natural kaolinites: new insights from electron paramagnetic resonance spectra fitting at X and Q-band frequencies. *Clays and Clay Minerals* **47**, 605-616.

Balan, E., Trocellier , P., Jupille, J., Fritsch, E., Muller, J.-P., Calas, G. (2001). Surface chemistry of weathered zircons. *Chemical Geology* **181**, 13-22.

Balan E., Allard T., Fritsch E., Sélo M., Falguères C., Chabaux F., Pierret M.C., Calas G. (2005). Formation and evolution of lateritic profiles in the middle Amazon basin: Insights from radiation-induced defects in kaolinite. *Geochimica et Cosmochimica Acta* **69**, 2193-2204.

Bardy M., Bonhomme C., Fritsch E., Maquet J., Hajjar R., Allard T., Derenne S., Calas G. (2007). Al speciation in tropical Podzols of the upper Amazon basin : a solid-state ^{27}Al MAS and MQMAS NMR study. *Geochimica et Cosmochimica Acta* **71**, 3211-3222.

Bardy M., Fritsch E., Derenne S., Allard T., Do Nascimento N.R., Bueno G.T. (2008). Micromorphology and spectroscopic characteristics of organic matter in waterlogged Podzols of the upper Amazon basin. *Geoderma* **14**, 222-230.

Beaudou A.G. & Chatelin Y. (1972). Les mouvements d'argile dans certains sols ferrallitiques centrafricains. ORSTOM, 9p.

Bedidi, A., Cervelle, B., Madeira, J., Pouget, M. (1992). Moisture effects on visible spectral characteristics of lateritic soils. *Soil Science* **153**, 129-141.

Bezerra P.E.L., (2003). Compartimentação morfotectônica do Interflúvio Solimões-Negro. Tese de doutorado, 335p**.**

Bish D.L. & Reynolds J. (1989): Sample preparation for X-ray diffraction. *Reviews in Mineralogy : Modern Powder Diffraction*, Vol. 20, Mineralogical Society of America, Washington, 73-99.

Benedetti M.F., Mounier S., Filizola N., Benaim J., Seyler P. (2003a). Carbon and metal concentrations, size distributions and fluxes in major rivers of the Amazon Basin. *Hydrological Processes* **17**, 1363-1377.

Benedetti M.F., Ranville J.F., Allard T., Bednar A.J., Menguy N. (2003b). The iron status in colloidal matter from the Rio Negro, Brasil. Colloids and Surfaces A. *Physicochem. Eng. Aspects* **217**, 1-9.

Bigarella J.J. & Andrade G.O. (1965). Contribution to the study of the Brazilian Quaternary. In: WRIGHT H.E. Jr., FREY D.G. (eds.). *International Studies on the Quaternary. Geological Society of America Special Papers* **94**, 433-451.

Blancaneaux P. (1981). Essai sur le milieu naturel de la Guyane Française. Travaux et Documents de l'ORSTOM, 137, 126p.

Bocquier G. (1971). Genèse et évolution de deux toposéquences de sols tropicaux du Tchad – Interprétation biogéodynamique. *Cah. ORSTOM* **9**, 509-515.

Boulet R. (1974). Toposéquences de sols tropicaux en Haute-Volta. Equilibres dynamiques et bio-climatiques. Thèse Sci. Strasbourg, Mémoire ORSTOM, 85, 1978, 272p.

Boulet R., Bocquier G., Millot G., (1977). Géochimie de la surface et formes du relief : 1. Déséquilibre pédobioclimatique dans les couvertures pédologiques de l'Afrique tropicale de l'Ouest et son rôle dans l'aplanissement des reliefs. *Sciences Géologiques Bulletin* **30** (4), 235-243.

Boulet R., Chauvel A., Humbel F.X., Lucas Y. (1982). Analyse structurale et cartographie en pédologie: I - Prise en compte de l’organisation bidimensionnelle de la couverture pédologique: les études de toposéquences et leurs principaux apports à la connaissance des sols. *Cah. ORSTOM* **19**, 309-321.

Boulet R., Lucas Y., Fritsch E., Paquet H. (1993). Géochimie des paysages : le rôle des couvertures pédologiques. *In* Coll. "Sédimentologie et Géochimie de la Surface" à la mémoire de Georges Millot. H. Paquet et N. Clauer eds., Les colloques de l'Académie des Sciences et du Cadas, Paris, 55-76.

Boulet R., Lucas Y., Fritsch E., Paquet, H. (1997). Geochemical processes in tropical landscapes: role of the soil covers. In: Paquet, H. & Clauer N. (Eds). Soils and Sediments - Mineralogy and Geochemistry, Springer-Verlag, Heidelberg, 67-96.

Bousserrhine N, Gasser U.G., Jeanroy E., Berthelin J. (1998). Bacterial and chemical reductive dissolution of Mn-, Cr- and Al-substituted goethithes. *Geomicrobiology Journal* **16**, 245-258.

Bravard S. & Righi D. (1989). Geochemical differences in an oxisol-spodosol toposéquence of Amazonia, Brazil. *Geoderma* **44**, 29-42.

Bravard S. & Righi D. (1990). Podzols in Amazonia. *Catena* **17**, 461-475.

Brimhall G.H. & Dietrich W.E. (1987). Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis. *Geochimica et Cosmochimica Acta* **51**, 567-587.

Braun, J.J., Pagel, M., Herbillon, A., Roisin, C. (1993). Mobilization and redistribution of REEs and thorium in a syenitic lateritic profile. A mass balance study. *Geochimica et Cosmochimica Acta* **57**, 4419-4434.

Braun J.J., Ngoupayou J.R.N., Viers J., Dupre B., Bedimo J.P., Boeglin J.L., Robain H. Nyeck B., Freydier R., Nkamdjou L.S., Rouiller J., Muller J.P. (2005). Present weathering rates in a humid tropical watershed : Nsimi, South Cameroon. *Geochimica et Cosmochimica Acta* **69**, 357-387.

Bravard, S. & Righi, D. (1989). Geochemical differences in an Oxisol-Spodosols Toposequence of Amazonia, Brazil. *Geoderma* **44**, 29-42.

Bravard S. & Righi D. (1990). Podzols in Amazonia. *Catena* **17**, 461-475.

Brewer R. (1964). Fabric and mineral analysis of soils. J. Wiley and Sons, N.Y., Sydney, 470p.

Brimhall, G.H., Lewis, C.J., Ford, C., Bratt, J., Taylor, G., Warin O. (1991). Quantitative geochemical approach to pedogenesis: importance of parent material reduction, volumetric expansion, and eolian influx in lateritization. *Geoderma* **51**, 51-91.

Brinkman R. (1970). Ferrolysis, a hydormorphic soil forming process. *Geoderma* **3**, 199-206.

Bruand A., Braudeau E., Fritsch E. (1990). Evolution de la géométrie de l'espace poral des sols lors du passage du domaine ferrallitique au domaine ferrugineux et hydromorphe : exemple du bassin de Booro Borotou. *In* Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, Paris, 90-96.

Büdel J. (1957). Die “Doppelten Einebnungsflächen” in den feuchten Tropen. *Z. Geomorphol*. **1**, 201-228.

Buurman P. (1987). pH-dependent character of complexation in podzols. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 191-186.

Buurman P. & Jongmans A.G. (2005). Podzolisation and soil organic matter dynamics. *Geoderma* **125**, 71-83.

Campbell K.E. Jr., Frailey C.D., Romero-Pittman L. (2006). The Pan-Amazonian Ucayali Peneplain, late Neogene sedimentation in Amazonia, and the birth of the modern Amazon River system. *Palaeogeography, Palaeoclimatology, Palaeoecology* **239**, 166-219.

Chadwick O.A., Brimhall G.H., Hendricks D.M. (1990). From a black to a grey box: a mass balance interpretation of pedogenesis. *Geomorphology* **3**, 369-390.

Chauvel A., Bocquier G., Pedro G. (1977). Géochimie de la surface et formes du relief III. Les mécanismes de la disjonction des constituants des couvertures ferrallitiques et l’origine de la zonalité des couvertures sableuses dans les régions intertropicales de l’Afrique de l’Ouest. *Sci. Géol., Bull*. **30**, 255-263.

Chauvel A., & Pedro G. (1978). Genèse de sols beiges (ferrugineux tropicaux lessivés) par transformation des sols rouges (ferrallitiques) de Casamance (Sénégal) – Modalités de leur propagation, *Cah. ORSTOM* **16**, 231-249.

Chauvel A., Lucas Y., Boulet R. (1987). On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. *Experientia* **43**, 234-241.

Colin F., Vieillard P., Ambrosi J.P. (1993). Quantitative approach to physical and chemical old mobility in equatorial rainforest lateritic environment. *Earth Planet. Sci. Let.*, **114**, 269-285.

Cornu S., Lucas Y., Lebon E., Ambrosi J.P., Luizão F, Rouiller J, Bonnay M, Neal, C. (1999). Evidence of titanium mobility in soil profile Manaus, central Amazonia. *Geoderma* **91**. 281-295.

Costa R C.R., Natali Filho T., Oliveira A.A.B. (1978). Projeto RADAMBRASIL – Geomorfologia. Manaus, 18, 165-244.

De Coninck F. (1980). Major mechanisms in formation of spodic horizons. *Geoderma* **24**, 101-128.

DNPM. (1981). Mapa geológico do Brasil, Brasília, escala 1:2.500.000.

Dubroeucq D. & Volkoff B. (1988). Évolution des couvertures pédologiques sableuses à podzols géants d'Amazonie (Bassin du Haut rio Negro). *Cahiers ORSTOM, Série Pédologie* **26** (3), 191-214.

Dubroeucq D. & Volkof B. (1998). From Oxisols to Spodosols and Histosols: evolution of the soil mantles in the Rio Negro basin (Amazonia). *Catena* **32**, 245-280.

Dubroeucq D., Volkoff B., Faure P. (1999). Les couvertures pédologiques à Podzols du Bassin du Haut Rio Negro. *Étude et Gestion des Sols* **6**, 131-153.

Duchaufour P. (1972). Processus de formation des sols. Biochimie et Géochimie. Nancy : Editions CRDP, Coll. Etudes et Recherches, 182 p.

Duchaufour P. (1982). Pedology: Pedogenesis and Classification. London: George Allen and Unwin, 481p.

EMBRAPA. (1981). Mapa de Solos do Brasil. Brasília. escala 1:5.000.000.

Fanning D.S. & Fanning M.C. (1989). Soil, morphology, genesis and classification. John Wiley & Sons, New York, 395p.

FAO. (1998). World Reference Base for Soil Resources. World Soil Resources Report n° 84. Rome, 172p.

Farmer V.C., Russel J.D., Berrow M.L. (1980). Imogolite and proto-imogolite alophane in spodic horizons: evidence for a mobile aluminium silicate complex in podzol formation. *J. Soil Sci.* **31**, 673-784.

Farmer V.C. (1987). The role of inorganic species in the transport of aluminium in podzols. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 187-194.

Fauck R. (1972). Les sols rouges sur sables et sur grès d'Afrique Occidentale. Mémoires ORSTOM, 261p.

Fernandes P.E.C.A, Pinheiro S.S., Montalvão R.M.G., Issler R.S., Abreu A.S.; Tassinari C.C.G. (1977). Geologia. Içá, 14. DNPM/Projeto Radambrasil, 19-123.

Fitzpatrick, E.A., (1970). A technique for preparation of large thin sections of soils and unconsolidated materials. In: Osmond, D.A. & Bullocck, P. (Eds.), Soil Survey of England and Wales, Harpenden, Technical Monograph. Micromorphological Techniques and Applications, vol. 2, 3-13.

Franco E.M.S., Moreira M.M.M.A, Barbosa G.V. (1977). Projeto RADAMBRASIL – Geomorfologia. Içá, 14, 127-180.

Fritsch E., Bocquier G., Boulet R., Dosso M., Humbel F.X. (1986). Les systèmes transformants d'une couverture ferrallitique de Guyane française. Analyse structurale d'une formation supergène et mode de représentation. *Cah. ORSTOM* **22**, 361-395.

Fritsch E., Herbillon A.J., Jeanroy E., Pillon P., Barres O. (1989). Variations minéralogiques et structurales accompagnant le passage "sols rouges - sols jaunes" dans un bassin versant caractéristique de la zone de contact forêt-savane de l'Afrique occidentale (Booro-Borotou, Côte d'Ivoire). *Sci. Géol. Bul.* **42**, 65-89.

Fritsch E., Valentin C., Morel P., Leblond P. (1990a). La couverture pédologique : interactions avec les roches, le modelé et les formes de dégradation superficielles. In : Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 31-57.

Fritsch E., Chevallier P., Janeau J.L. (1990b). Le fonctionnement hydrodynamique du bas de versant. In : Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 185-206.

Fritsch E, Peterschmitt E., Herbillon A.J. (1992). A structural approach to the regolith: Identification of structures, analysis of structural relationships and interpretations. *Sci. Géol. Bul.* **45** (2), 77-97.

Fritsch E. & Fitzpatrick R.W. (1994). Interpretation of Soil Features Produced by Ancient and Modern Processes in Degraded Landscapes. I. A new method for constructing conceptual soil-water-landscape models. *Aust. J. Soil Res.* **32**, 889-907.

Fritsch E., Montes-Lauar C.R., Boulet R., Melfi A.J., Balan E., Magat Ph. (2002). Lateritic and redoximorphic features in a faulted landscape near Manaus, Brazil. *European Journal of Soil Science* **53**, 203-218.

Fritsch E., Morin G., Bedidi A., Bonnin D., Balan E., Caquineau S., Calas G. (2005). Transformation of haematite and Al-poor goethite to Al-rich goethite and associated yellowing in a ferralitic clay soil profile of the middle Amazon basin (Manaus, Brazil). *European Journal of Soil Science* **56**, 575-588.

Fritsch E., Herbillon A. J., Nascimento Do N. R., Grimaldi, M., Melfi M. J. (2007). From Plinthic Acrisols to Plinthosols and Gleysols : iron and groundwater dynamics in the tertiary sediments of the upper Amazon basin. *European Journal of Soil Science* **58**, 989-1006.

Fritsch E., Allard T., Benedetti M.F., Bardy M., Nascimento Do N. R., Li, Y., Calas G. (2009). Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. *Geochimica et Cosmochimica Acta*, (doi: 10.1016/j.gca.2009.01.008).

Fritsch E., Allard T., Benedetti M.F., Bardy M., Do Nascimento N. R., Li, Y., Calas G. Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. *Geochimica et Cosmochimica Acta*, (submitted).

Gombeer R. & D'Hoore H. (1971). Induced migration of clays and other moderately mobile soil constituents. III. Critical soil/water dispersion ratio, colloid stability and electrophoretic mobility. *Pedologie* **21**, 311-342.

Grybos M., Davranche M., Gruau G., Petitjean P. (2007). Is trace metal release in wetland soils controlled by organic matter mobility or Fe-oxyhydroxides reduction? *Journal of Colloid and Interface Science* **314**, 460-501.

Gouveia S.E.M., Pessenda L.C.R. Aravena, R. Boulet R., Roveratti R., Gomes B.M. (1997). Dinâmica de vegetações durante o Quaternário recente no sul do Amazonas, indicada pelos isótopos do carbono (^{12}C, ^{13}C, ^{14}C) do solo. *Geochimica Brasiliensis* **11**, 355-367.

Gustafsson J.P., Bhattacharya P., Karltun E. (1999). Mineralogy of poorly crystalline aluminium phases in the B horizon of Podzols in southern Sweden. *Applied Geochemistry* **14**, 707-718.

IBGE. (2001). Mapa de solos do Brasil, Rio de Janeiro, escala 1: 5.000.000.

Jansen B., Nierop K.G.J., Verstraten J.M. (2003). Mobility of Fe(II), Fe(III) and Al in acidic forest soils mediated by dissolved organic matter: influence of solution pH and metal/organic carbon ratios. *Geoderma* **113**, 323-340.

Jeanroy E., Rajot J.L., Pillon P., Herbillon A.J. (1991). Differential dissolution of hematite and goethite in dithionite and its implication on soil yellowing. *Geoderma* **50**, 79-94.

Jenny H. (1941). Factors of soil formation. New York: McGraw-Hill, 109p.

King L.C. (1953). Canons of landscape evolution. *Bull. Geol. Soc. Am.* **64**, 721-752.

Klinge H. (1965). Podzol soils in the Amazon Basin. *Journal of Soil Sci.* **16**, 95-103.

Kronberg B. & Melfi,A. J. (1987). The geochemical evolution of lateritic terranes. *Z Geomorph N F Suppl Bd.* **64**, 25-32.

Kosmas, C.S., Curi, N., Bryant, R.B. & Franzmeier, D.P. (1984). Characterization of iron oxide minerals by second derivative visible spectroscopy. *Soil Science Society of America Journal* **48**, 401-405.

Latrubesse E.M., Franzinelli E., (2005). The Late Quaternary evolution of the Negro River, Amazon, Brazil : Implications for island and floodplain formation in large anabranching tropical systems. *Geomorphology* **70**, 372-397.

Linton D.L. (1955). The problem of tors. *Geogr. Journal.* **121**, 470-487.

Lucas, Y. (1989). *Systèmes pédologiques en Amazonie brésilienne. Equilibres, déséquilibres et transformations*. Thèse de Doctorat, Université de Poitiers, 157p.

Lucas Y., Chauvel A., Boulet R., Ranzani G., Scatolini F. (1984). Transição latossolos-podzóis sobre a Formação Barreiras na região de Manaus, Amazônia. *Revista Brasileira de Ciência do Solo* **8**, 325-335.

Lucas, Y., Boulet, R., Veillon, L. (1987). Systèmes sols ferrallitiques – podzols en région amazonienne. In: *Podzols et Podzolisation* (eds D. Righi & A. Chauvel), Association Française pour l'Etude du Sol, INRA, 53-65.

Lucas Y., Boulet R., Chauvel A. (1988). Intervention simultanée des phénomènes d'enfoncement vertical et de transformation latérale dans la mise en place des systèmes de sols de la zone tropicale humide. Cas des systèmes sols ferrallitiques-podzols de l'Amazonie Brésilienne. *C. R. Academie des Sciences de Paris* **306**, 1395-1400.

Lucas Y., Nahon D., Cornu S., Eyrolle F. (1996). Genèse et fonctionnement des sols en milieu équatorial. *C. R. Acad. Sci. Paris* **322**, 1-16.

Lundström U.S. (1993). The role of organic acids in soil solution chemistry in a podzolized soil. *J. Soil Sci.* **44**, 121-133.

Lundström U.S., van Breemen N., Bain, D. (2000). The Podzolisation process. A review. *Geoderma* **94**, 91-107.

Macias-Vasquez F, Fernandez-Marcos M.L., Chesworth W. (1987). Transformations minéralogiques dans les podzols et les sols podzoliques de Galice (NW. Espagne). In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 163-177.

Magnago H., Barreto R.A.A., Pastore U. (1978). Vegetação. Manaus, Projeto RadamBrasil, 18, 413-530.

Maurin J.C., Gilbert F., Robert M., Churlaud C. (2005). L'érosion chimique et l'érosion mécanique à long terme du substrat granitique (Vendée, France). *C. R. Geosciences* **337**, 841-848.

Malengreau, N., Beddidi A., Muller, J.P., Herbillon, A.J. (1996). Spectroscopic control of iron oxide dissolution in two ferralitic soils. *European Journal of Soil Science* **47**, 13-20.

Meade R., Rayol J.M., Da Conceição S.C., Natividade J.R., (1991). *Environmental Geologic Water Science* **18** (2), 105-114.

Mehra, O.P. & Jackson, M.L. (1960). Iron oxide removal from soils and clays by a dithionite-citrate buffered with sodium bicarbonate. *Clays and Clay Minerals* **7**, 317-327.

Melfi A.J. & Pedro G. (1977). Estudo geoquímico dos solos e formações superficiais do Brasil. Parte 1 - Caracterização e repartição dos principais tipos de evolução pedogeoquímica. *Revista Brasileira de Geociências* **7**, 271-286.

Middelburg J.J., Van der Weijden C.H., Woittiez J.R.W. (1988). Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks. *Chemical Geology* **68**, 253-273.

Millot G. (1983). Planation of continents by intertropical weathering and pedogenetic processes. In: Melfi A.J. & Carvalho A. Lateritisation Processes – Proceedings of the II International Seminar on lateritisation processes, 53-64.

Montes C.R., Lucas Y., Melfi A.J., Ishida D.A. (2007). Systèmes sols ferrallitiques–podzols et genèse des kaolins / Ferralsols–podzols soil systems and kaolin genesis. *C. R. Geosciences* **339**, 50-56.

Mortland M.M. (1968). Protonation of compounds at clay minera1 surfaces. *Transactions IX Int. Cong. Soi1 Sciences*, Adelalde (Australie) 1, 691-699.

Nahon, D.B. (1991). *Introduction to the Petrology of Soils and Chemical Weathering*. New York: John Wiley & Sons, 313p.

Nascimento Do N.R., Bueno G. T., Fritsch E., Herbillon A.J., Allard Th., Melfi A.J., Astolfo R., Boucher H., Y. Li. (2004). Podzolisation as a deferralitization process. A study of an Acrisol-Podzol sequence derived from Paleozoic sandstones in the northern upper Amazon Basin. *European Journal of Soil Science* **55**, 523-538.

Nascimento Do N.R., Fritsch E., Bueno G.T., Bardy M., Grimaldi C., Melfi A.J. (2008). Podzolization as a deferralitisation process: dynamics and chemistry of ground and surface waters in an Acrisol–Podzol sequence of the upper Amazon Basin. *European Journal of Soil Science* **59**, 911-924.

Oliva P., Viers J., Dupré B., Fortuné J.P., Martin F., Braun J.J., Nahon D.B., Robain H. (1999). The effect of organic matter on chemical weathering : Study of a small tropical watershed : Nsimi-Zoétélé site, Cameroon. *Geochimica et Cosmochimica Acta* **63**, 4013-4035.

Patel-Sorrentino N., Lucas Y., Eyrolle F., Melfi A.J. (2007). Fe, Al and Si species and organic matter leached off a ferrallitic and podzolic soil system from Central Amazonia. *Geoderma* **137**, 444-454.

Pedro G. (1987). Podzols et Podzolisation: un problème pédologique fort ancien, mas toujours d'actualité. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 1-10.

Peterschmitt E., Fritsch E., Rajot J.L., Herbillon A.J. (1996). Yellowing bleaching and ferritization in a hydrotoposequence of the Western Ghâts, South India. *Geoderma* **74**, 235-253.

Petersen L. (1984). The Podzol concept. In: Buurman, P. (Ed.), Podzols. New York: Van Nostrand Reinhold Company, 12-19.

Plaisance G. & Cailleux A. (1958). Dictionnaire des Sols. Paris: La Maison Rustique, 604 p.

Planchon O., Fritsch E., Valentin C. (1987). Rill development in a wet savannah environment. *Catena sup.* **8**, 55-70.

Projeto Radam (or Radam Brazil) (1972-78). *Levantamento de Recursos Naturais.* Vol. 1 - 15. Ministério das Minas e Energia. Departamento Nacional da Produção Mineral. Rio de Janeiro, Brazil.

Rinder G.E., Fritsch E., Fitzpatrick R.W. (1994). Computing procedures for mapping soil features at sub-catchment scale. *Aust. J. Soil Res.* **32**, 909-913 (colour figs 886-887).

Robinson G.W. (1949). *Soils, their origin, constitution and classification.* London: Thomas Murby and Co., 573p.

Sampaio, A. & Northfleet, A. (1973). Estratigrafia e correlação das bacias sedimentares brasileiras. In: Ann. 27 Congr. Soc. Bras. Geol., Aracajú, 3, 189-206.

Schwartz D. (1987). Les podzols tropicaux sur sable Batéké en R.P du Congo:description, caracterisation et genèse. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 25-36.

Ségalen P. (1966). Le processus de ferrallitisation et ses limites. ORSTOM s.n., 15-20.

Silva F.C.F., Jesus R.M., Ribeiro A.G. (1977). Vegetação. Içá, 14. DNPM/Projeto Radambrasil, 229-396.

Simonson, R.W. (1959). Outline of a generalized theory of soil genesis. *Soil Sci. Soc. Am. Proc.* **23**, 152-156.

Soil Survey Staff. (1975). Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S. Dept. of Agric. Handb. 436p.

Taboada T., Cortizas A. M., García C., García-Rodeja E. (2006). Particle-size fractionation of titanium and zirconium during weathering and pedogenesis of granitic rocks in NW Spain. *Geoderma* **131**, 218-236.

Tardy Y. (1993). *Pétrologie des latérites et des sols tropicaux.* Paris : Masson, 459p.

Théveniaut, H. & Freyssinet, Ph. (2002). Timing of lateritzation on the Guiana Shield: synthesis of paleomagnetic results from the French Guiana and Suriname. *Palaeogeography, Palaeoclimatology, Palaeoecology* **178**, 91-117.

Thompson C.H. (1992). Genesis of Podzols on Coastal Dunes in Southern Queensland. I. Field Relationships and Profile Morphology. *Australian Journal of Soil Research,* **30**, 593-613.

Torrent J., Schwertmann U., Barron V. (1987). The reductive dissolution of synthetic goethite and hematite in dithionite. *Clay Miner.* **22**, 329-337.

Trescases J.J. (1975). L'évolution géochimique supergène des roches ultrabasiques en zone tropicale. Formation des gisements nickélifères de Nouvelle-Calédonie. *Mém. ORSTOM* 78, 259p.

Turenne, J.F. (1975). *Modes d'humification et différenciation Podzolique dans deux toposéquences guyanaises.* Thèse de Doctorat, Université Nancy I, 185p.

Turenne J.F. (1977). Modes d'humification et différenciation podzolique dans deux toposéquences Guyanaises. *Mém. ORSTOM* 84, Paris, 174p.

Ugolini F.C. & Dahlgren R. (1987). The mechanism of podzolisation as revealed by soil solution studies. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 195-203.

Valentin C. & Fritsch E. (1990). Un résumé des processus pédologiques ouest-africains. *In* Structure et fonctionnement hydropédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 227-232.

Van Breemen N. (1985). Effects of seasonal redox-processes involving Fe on the chemistry of periodically reduced soils. In: Stucki J. W., Goodman A., Schwertmann O. (Eds.) Iron in soils and clay minerals. Bad Windsheim: Nato Advanced Study Institute, 858-875.

Van der Weijden C.H. & Van der Weijden R. (1995). Mobility of major, minor and some redox-sensitive trace elements and rare-earth elements during weathering of four granitoids in central Portugal. *Chemical Geology* **125**, 149-167.

Van Hees P.A.W. & Lundström U.S. (2000). Equilibrium models of aluminium and iron complexation with different organic acids in soil solution. *Geoderma* **94**, 201-221.

Van Ranst F. & De Coninck F. (2002). Evaluation of ferrolysis in soil formation. *European J. Soil Science* **53**, 513-520.

Viers J., Dupré B., Polvé M., Schott J., Dandurand J.L., Braun J.J. (1997). Chemical weathering in the drainage basin of a tropical watershed (Nsimi-Zoetele site, Cameroon): comparison between organic poor and organic rich waters. *Chem. Geol.*, **140**, 181-206.

Wesemael B., Verstraten J.M., Sevink J. (2005). Pedogenesis by clay dissolution on acid, low-grade metamorphic rocks under mediterranean forests in southern Tuscany (Italy). *Catena*, **24**, 105-125.

Wyszecki, G. & Stiles, W.S. (1982). Color science: Concepts and Methods, Quantitative Data and Formulae. John Wiley & Sons, New York, 950p.

Yamazaki D.R., Costa A.M.R., Azevedo W.P. (1978). Projeto RADAMBRASIL – Pedologia. Manaus, 18, 245-410.

UNIVERSIDADE ESTADUAL PAULISTA

Instituto de Geociências e Ciências Exatas

Campus de Rio Claro

EMPOBRECIMENTO E PODZOLIZAÇÃO DE SOLOS LATERÍTICOS DA BACIA DO RIO NEGRO E GÊNESE DOS PODZÓIS NA ALTA BACIA AMAZÔNICA

GUILHERME TAITSON BUENO

Orientadores: Nádia Regina do Nascimento (UNESP-Brasil)
Emmanuel Fritsch (IPGP-França)

Tese elaborada junto ao Programa de Pós-Graduação em Geografia, Área de Concentração em Análise Espacial (UNESP-Brasil), e ao Programa de Pós-Graduação em Ciências da Terra, Área de Concentração em Geoquímica Fundamental e Aplicada (IPGP-França) (regime de co-tutoria, convênio CAPES-COFECUB) para obtenção do título de Doutor em Geografia e em Ciências da Terra

Rio Claro (SP)
2009

551.41 B928e

Bueno, Guilherme Taitson

Empobrecimento e podzolização de solos lateríticos da bacia do Rio Negro e gênese dos podzóis na alta Bacia Amazônica / Guilherme Taitson Bueno. - Rio Claro : [s.n.], 2009

157 f. : il., gráfs., tabs., fots., mapas

Tese (doutorado) - Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas

Orientador: Nádia Regina do Nascimento

Orientador: Emmanuel Fritsch

1. Ciência do solo. 2. Podzóis da Amazônia. 3. Podzolização. 4. Mineralogia. 5. Geoquímica. 6. Evolução da paisagem. I. Título.

Ficha Catalográfica elaborada pela STATI - Biblioteca da UNESP
Campus de Rio Claro/SP

Comissão Examinadora

Profa. Dra. Nádia Regina do Nascimento (orientadora)

Dr. Emmanuel Fritsch (orientador)

Dr. Marc Benedetti

Prof. Dr. Antônio José Teixeira Guerra

Dr. Georges Calas

Dr. Ary Bruand

Prof. Dr. Adolpho José Melfi

Dra. Sylvie Derenne

Guilherme Taitson Bueno
Aluno (a)

Paris, 6 de maio de 2009

Resultado: aprovado

RESUMO

Os podzóis (espodossolos) apresentam horizontes arenosos sobre níveis pouco permeáveis enriquecidos em matéria orgânica e metais. Ocupam grandes superfícies da alta bacia amazônica, sob influênica de lençóis suspensos e meios redutores e ácidos. Este trabalho trata da: (i) pré-podzolização, ou empobrecimento prévio dos solos lateríticos (latossolos); (ii) formação de podzóis sobre platôs, posteriormente dissecados pelos rios; (iii) dinâmica dos podzóis na escala da bacia do Rio Negro. Integra abordagens geoquímicas, petrográficas e mineralógicas, estudos de solos e de unidades de paisagem. A erosão química, mas, também, particulada, dos solos lateríticos, crescente da borda ao centro podzolizado dos platôs, afeta, separadamente, solos e saprolitos. O amarelecimento e o empobrecimento do solo devem-se à dissolução dos óxidos de Fe (hematita e depois goethita), e da caolinita. O desenvolvimento de lençóis suspensos no saprolito favorece o empalidecimento dos materiais e, os escoamentos laterais, a eluviação. Produzem reservatórios arenosos, explorados pela podzolização. A posterior incisão dos podzóis hidromórficos ativa a mineralização da matéria orgânica, a oxidação do Fe, e o aporte de areias aos rios. O desenvolvimento dos podzóis na bacia pode ser anterior à rede de drenagem moderna do Amazonas (2,5 Ma BP). Sua posterior incisão posterior teria limitado sua expansão lateral e fornecido areias brancas ao Rio Negro.

Palavras-chave: Amazônia, podzolização, mineralogia, geoquímica, evolução da paisagem

ABSTRACT

Podzols present spectacular morphology, with sandy horizons over less permeable and organo-metallic compartments. They occupy important surfaces of the upper Amazon basin, under the influence of perched watertables and reducing/acidic environments. This work focuses on: (i) lateritic soils impoverishment before podzolisation; (ii) hydromorphic podzol development on the plateaux and their latter incision; and (iii) podzol dynamics in the Rio Negro catchment scale. It associates geochemical, petrographic and mineralogical approaches, with investigations of soil catena and landscapes units. The increasing chemical but also particulate erosion of lateritic soils from the edge to the podzolised plateaux centre affect, separately, soils and saprolites. Selective dissolution of iron oxydes (hematite, then goethite), and ultimately of kaolinite, are associated with soil yellowing and impoverishment. In the saprolites, the groundwater promotes the material bleaching, and lateral flows, close to podzols, its eluviation. Chemical and physical erosions generate sandy horizons explored by podzolisation. River incisions into podzols enhance organic matter mineralisation, iron oxidation and the sand transport to the rivers. The apparition of podzols may preceed the formation of modern Amazon River system (2,5 Ma BP). Ultimate incisions of podzols restrict their spatial expansion and fill with white sands the Rio Negro sediment traps.

Keywords: Amazônia, podzolisation, mineralogy, geochemistry, landscape evolution

RÉSUMÉ

Les podzols sont des sols à morphologie spectaculaire présentant des horizons sableux sur des niveaux peu perméables, enrichis en matière organique et métaux. Ils occupent de grandes surfaces dans le haut bassin amazonien. Leur formation est attribuée à l'existence des nappes propices à des accumulations organo-métalliques en milieu réducteur et acide. Le travail traite: (i) de la pré-podzolisation (appauvrissement préalable des latérites); (ii) de la formation des podzols sur plateaux, posterieurement incisés par le reseau hydrographique; (iii) de la dynamique de ces podzols dans le bassin du Rio Negro. Il intègre des approches géochimiques, pétrographiques et minéralogiques, des études de séquences de sols et d'unités de paysages (terrain et traitement d'images). L'érosion chimique mais aussi particulaire des latérites, accrue depuis la bordure vers le centre des plateaux à podzols affecte séparément sols et saprolites. Le jaunissement et l'appauvrissement des sols sont attribués à la dissolution des oxydes de fer (hématite puis goethite) puis des kaolinites. Le développement des nappes dans les saprolites favorise le blanchiment et, leurs écoulements latéraux, l'éluviation. Ces érosions génèrent des réservoirs sableux en "double langue" qui vont être exploités par la podzolisation. L'incision posterieure de ces podzols hydromorphes par le reseau hydrographique active la minéralisation des matières organiques, l'oxydation du fer et l'apport de sable aux rivières. La distribution des podzols est fortement controlée par la pluviometrie et la géologie. Leur apparition peut être antérieure à l'établissement du réseau moderne de drainage de l'Amazone (2,5 Ma BP). L'incision posterieure des aires podzolisées aurait limitée leur expansion et alimentée en sable blanc le Rio Negro.

Mots-clés: Amazônia, podzolisation, mineralogie, géochimie, évolution du paysage

SUMARIO

Página

INTRODUCTION

Le bassin amazonien est l'un des plus grands bassins des surfaces émergées de la planète, avec une superficie totale d'environ 6,5 millions de km^2. Situé dans la zone tropicale forestière et en grande partie protégé des activités anthropiques, ce bassin contrôle les principaux cycles biogéochimiques de la planète (dont le cycle du carbone). Il constitue de ce fait une région emblématique pour aborder l'étude de ces cycles, et révéler d'une part les processus majeurs qui contrôlent la dynamique des métaux et des matières organiques et d'autre part l'impact du forçage anthropique (déforestation, effets de serre et changement climatique) sur la dynamique de ces processus et sur les re-mobilisations de matières aux interfaces atmosphère, biosphère, hydrosphère et lithosphère. Le fleuve Amazone exporte par ailleurs des quantités considérables de matières à l'océan (13,5 t/sec). Si les quantités de matières exportées par l'Amazone à l'océan Atlantique sont essentiellement attribuées à la surrection et érosion des Andes, des études récentes tendent à montrer que d'importantes quantités de matières ont pu également être remobilisées au sein des couvertures latéritiques du bassin et être exportées par érosion chimique au réseau hydrographique. Les processus associés à de telles exportations agissent essentiellement dans les régions amont les plus pluvieuses du bassin et la podzolisation marque le stade ultime de cette "fonte géochimique". La diversité des processus d'altération et d'érosion mis en jeu dans ce bassin est illustrée par la très célèbre "rencontre des eaux" ("*encontro das águas*") de la région de Manaus (partie centrale et amont du moyen basin amazonien) (Fig. 1a). Sur plusieurs kilomètres se rejoignent sans se mélanger les eaux brunes issues de l'érosion physique des sols andins et les eaux noires qui, comme nous le verrons par la suite, sont étroitement reliés à une érosion chimique et interne du sol et au développement de podzols au sein des paysages latéritiques du haut bassin amazonien.

Sur les 6,5 millions de km^2 du bassin, 4 millions de km^2 appartiennent au Brésil, ce qui représente prêt de la moitié de la surface de ce pays. Si les connaissances sur le milieu naturel des régions Sud, Sud Est et Nord Ouest du Brésil, qui regroupent la majeure partie de la population et des activités économiques du pays, sont très détaillés, celles portant sur les milieux amazoniens restent encore éparses. Le premier inventaire systématique des ressources naturelles de cette immense région forestière, souvent difficile d'accès, a été programmé dans les années 1970 par le gouvernement brésilien dans le cadre du Projet RadamBrasil. Ce projet a nécessité des moyens logistiques importants (dont avions et hélicoptères) et a mobilisé un nombre considérable de chercheurs de toutes disciplines (botanistes, géologues, pédologues,

géomorphologues, hydrologues…). Il a permis d'évaluer les ressources de cette grande région naturelle, où prédominent des plateaux de faibles altitudes associés à d'immenses réserves d'eau, et de révéler par la même occasion toute la diversité et complexité d'organisation de ses différentes composantes (roches, sédiments, végétations, sols et paysages) (Figs 2a et b).

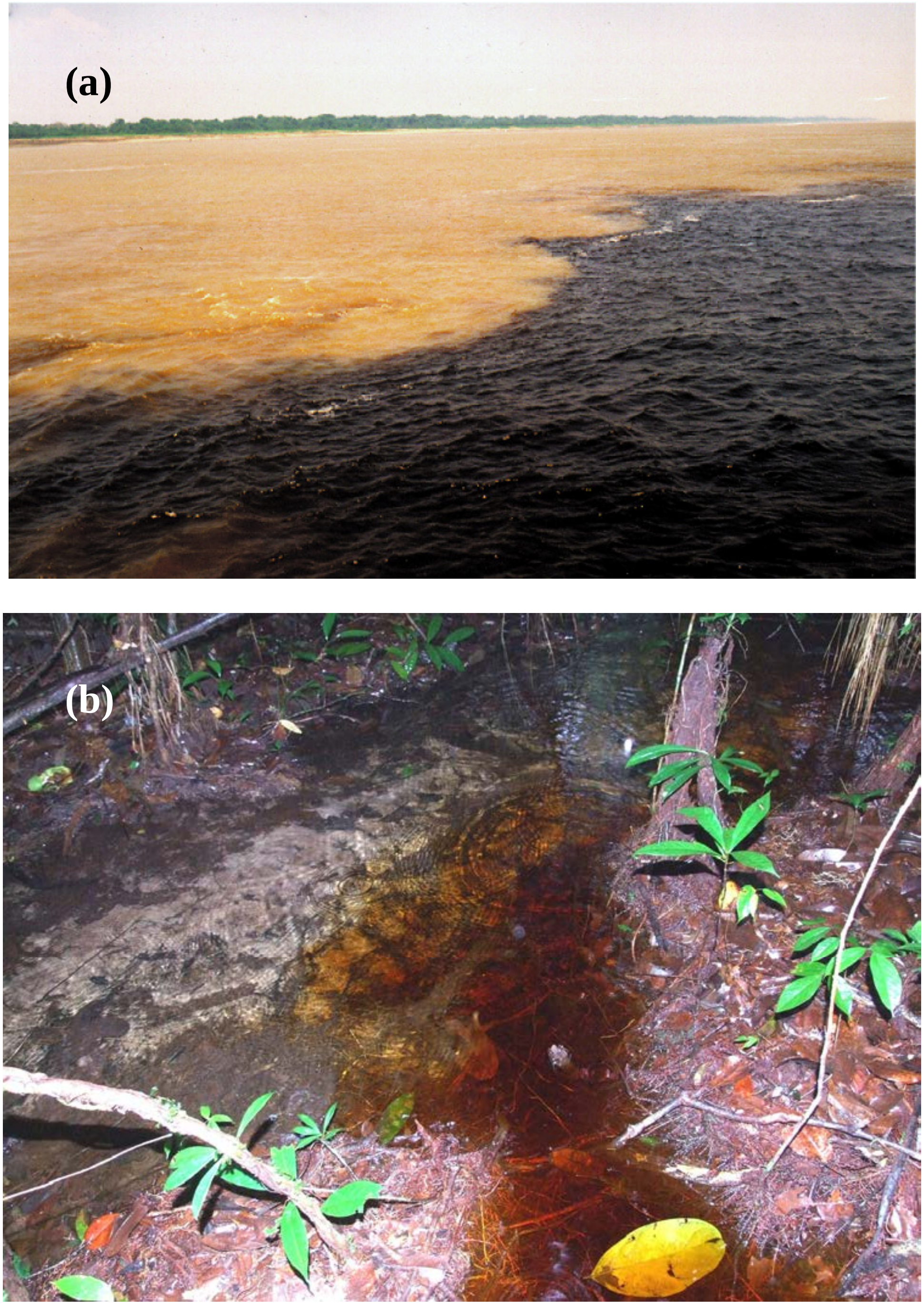


Figure 1*. La rencontre des eaux (a) à l'amont du fleuve Amazone et à l'aval de la ville de Manaus où les eaux noires du Rio Negro (à droite) rejoignent les eaux brunes du Rio Solimões (à gauche) (provenance Th Allard) et (b) au niveau d'une confluence de ruisseaux dans les bas plateaux (région de São Gabriel da Cachoeira) où les eaux noires des aires podzoliques (à droite) rejoignent les eaux claires des latérites (à gauche).*

La diversité des structures et ressources de cet écosystème est illustrée par les nombreux documents cartographiques et légendes élaborés dans le cadre de ce projet. La carte, établie à l'échelle 1 :2.500.000, permet d'avoir une perception d'ensemble du milieu physique et biologique du bassin. Des cartes plus détaillées à l'échelle 1 :1.000.000 donnent une vision plus précise des organisations régionales. Comme nous allons le voir dans ce mémoire, ces documents riches d'informations très variées sont à l'origine de travaux plus détaillés, en particulier sur les sols. Ces dernières entreprises sur des sites pilotes comprenant petites unités de paysages (ou bassin versants élémentaires) et séquences de sols, orientées sur des axes de plus forte pente (le plus souvent d'un pôle haut et bien drainé vers un pôle bas et mal drainé), sont de plus en plus nombreuses (Lucas *et al.,* 1984; 1988; 1996; Bravard & Righi, 1989; 1990; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1998; Nascimento *et al.,* 2004; Montes *et al.,* 2007). Elles ont révélé les processus associés à la mobilité des éléments majeurs et en traces dans différents types d'écosystèmes, mais ont également montré, dans certains cas, l'inexactitude des documents RadamBrasil dans la caractérisation de certaines structures ou les interprétations qu'on en donne. Cela a en particulier amené le Département National de Recherche Minérale (Departamento Nacional de Pesquisa Mineral : DNPM) à réviser la carte géologique du bassin en différentiant au sein de la formation Solimões une nouvelle formation plus récente : la formation Içá. Cette dernière marque l'un des derniers épisodes sédimentaires du Tertiaire. Comme nous le verrons par la suite, elle aura une importance considérable sur la compréhension de la genèse des sols du bassin.

Les documents du Projet RadamBrasil et les images satellitaires de plus en plus nombreuses et variées montrent que l'idée d'une Amazonie couverte par une forêt homogène et monotone est fausse. La forêt sempervirente, qui recouvre sur de très grandes surfaces les bas plateaux et les versants creusés par le réseau de drainage, est localement associée à des couverts végétaux plus bas, quelquefois étonnamment ouverts, où les sols sont exposés à l'érosion hydrique et éolienne. A ce titre, des paysages tout à fait insolites ont été reconnus dans le haut bassin du Rio Negro où de vaste étendues dépourvues de végétation font apparaître des dunes de sables blancs. La comparaison des différents documents cartographiques du Projet RadamBrasil suggère que la diversité du couvert forestier reflète des hétérogénéités lithologiques, des gradients pluviométriques mais surtout et aussi, une grande diversité d'altérites et de sols. Les cartes du projet RadamBrasil et les études plus ponctuelles sur séquence de sols montrent en effet qu'il existe une distribution ordonnée des sols à l'échelle des paysages et également une distribution ordonnée de ces paysages à l'échelle du bassin amazonien (Fig. 3).

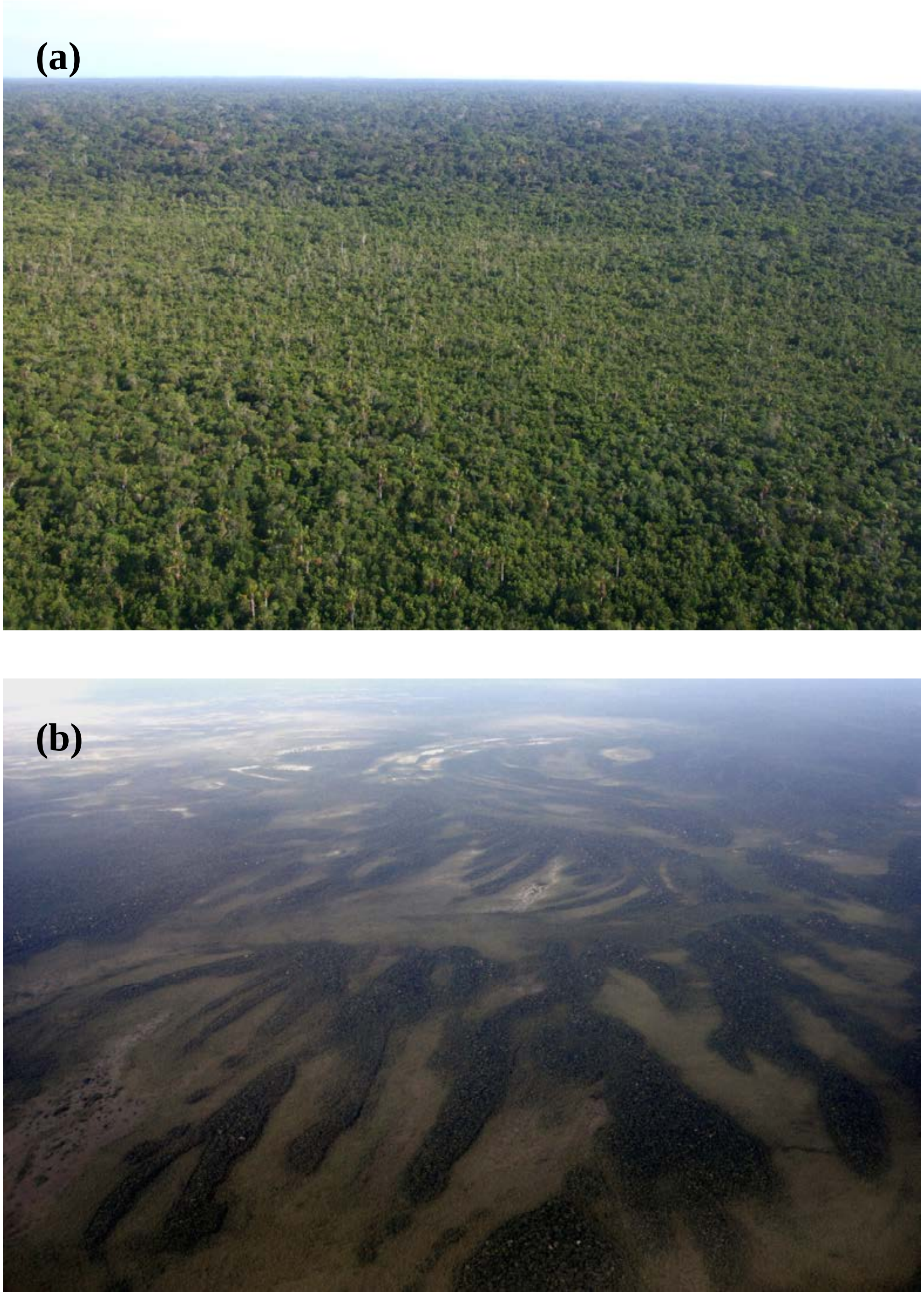


***Figure 2**. Diversité des paysages amazoniens : (a) Végétations de caatinga sur podzols (premier plan) et de fôret sur latérites (arrière plan), bas plateaux de la région de São Gabriel da Cachoeira ; (b) Bandes végétales en concordance avec les structures sédimentaires fluvio-lacustres de la formation Içá, région de Barcelos.*

Les sols latéritiques les plus typiques (Latosols ou Ferralsols rouges, argileux et bien drainés) sont essentiellement présents à la périphérie du bassin et sont associés à des sols

hydromorphes (Gleys) dans les principaux axes de drainage et plaines alluviales. Ces latérites épaisses ont tendance à jaunir dans la partie centrale du bassin.

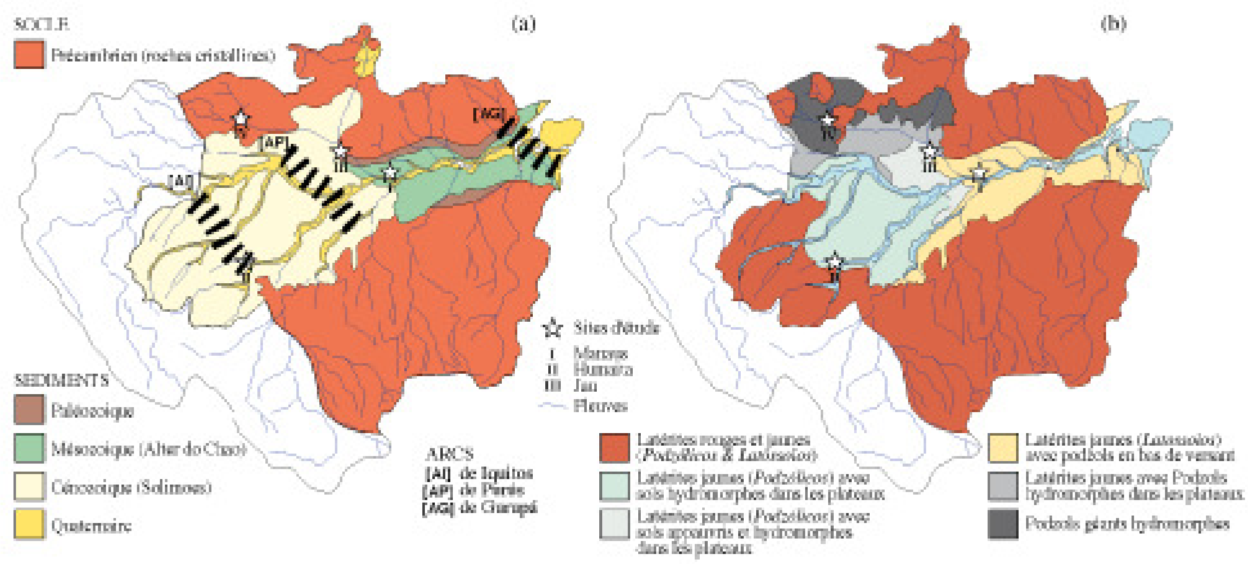


Figure 3*. Les roches (a) et les sols (b) du bassin amazonien brésilien (documents réduits et simplifiés à partir des cartes RadamBrasil au 1 :2.500.000) montrant l'extension des formations sédimentaires, la distribution des latérites rouges et jaunes et l'extension des zones hydromorphes et podzoliques dans la partie amont et centrale du bassin. (Fritsch et al., 2002).*

Sur des formations continentales plus récentes du haut bassin amazonien (Formation Içá), les formations latéritiques moins épaisses des bas plateaux amazoniens sont étroitement associées à des sols hydromorphes (Plinthosols, Gleys). Plus au nord dans le bassin du Rio Negro, les latérites s'appauvrissent en éléments fins (Ultisols) et se podzolisent (Podzols hydromorphes). Les podzols sont généralement situés sur les bas plateaux amazoniens. Dans la partie médiane du bassin du Rio Negro, ces podzols sont peu développés et s'observent, comme les sols hydromorphes (Gleys), dans les dépressions de ces plateaux (région du Jaú). Dans sa partie amont et plus pluvieuse (région de São Gabriel da Cachoeira), les podzols ont une extension beaucoup plus importante et sont directement connectés aux axes de drainage principaux du bassin du Rio Negro. Ils occupent alors de vastes pénéplaines inondées et les sols latéritiques n'apparaissent plus que sous la forme de collines résiduelles ou de reliques de rebords de plateaux. Dans la partie aval du bassin du Rio Negro (région de Manaus), les podzols sont généralement absents des plateaux. Ils sont par contre identifiés dans les bas de versants de ces plateaux. Ces distributions relatives de sols dans les paysages montrent ainsi que la mise

en place et la dégradation ultérieure des latérites du bassin amazonien peuvent être reliées à quatre processus majeurs : (1) la latéritisation, (2) l'appauvrissement, (3) l'oxydo-réduction et (4) la podzolisation.

Dans l'optique d'une meilleure connaissance de ces processus, des sols et des fonctionnements hydro-biogéochimiques qui leur sont associés, des projets scientifiques conjoints entre chercheurs brésiliens et français ont été élaborés. Ces projets étaient engagés de longue date dans les régions de Manaus et São Gabriel da Cachoeira (Lucas *et al.,* 1984, 1988, 1996; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1999). Ils ont été étendus en 1996 à l'ensemble du haut bassin amazonien dans le cadre d'un accord de coopération CNPq/IRD associant le Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera de l'Université de São Paulo et l'Unité de Recherche 12 "Géoscience de l'Environnement Tropical" du Département TOA de l'IRD (ex ORSTOM) sur un projet de recherche intitulé "Organisation et fonctionnement hydro-biogéochimique des couvertures latéritiques d'Amazonie" (Dylat Amazonie). Ils ont été ultérieurement financés par des projets FAPESP, PRONEX, et ECCO, et ont aussi reçu l'appui de l'Institut de Minéralogie et de Physique des Milieux Condensés (IMPMC) de Paris dans le cadre de la caractérisation minéralogique et spectroscopique des échantillons de sols. En 2004, ces travaux se sont progressivement focalisés sur l'étude des systèmes podzoliques d'Amazonie plus particulièrement dans le cadre d'un projet CAPES-COFECUB intitulé : "Podzolisation des latérites du haut bassin amazonien : Etudes des mécanismes et facteurs contrôlant la dynamique évolutive des podzols et les exportations de matières dans les têtes de rivières du bassin versant du Rio Negro et des dépôts de kaolins associés".

Les travaux, engagés dans le cadre de ces projets, correspondent essentiellement à des études multi-échelles de quatre sites pilotes (étoiles dans Fig. 3) : (1) région de Manaus, (2) région de Porto Velho, (3) région du Jaú et (4) région de São Gabriel da Cachoeira. Les sites (1) et (2) ont permis de mieux caractériser les processus de latéritisation et d'oxydo-réduction (Fritsch *et al.,* 2002, 2007). Dans le site (1) (région de Manaus), la latéritisation a été attribuée à des paragenèses affectant les principales phases minérales de ces sols, i.e. les kaolinites (Balan et al. 2005) et les oxydes de fer (Fritsch *et al.,* 2005). Cette latérisation a transformé des formations sédimentaires très anciennes (formation Alter do Chão, fin Crétacé – début Tertiaire) en latérites très épaisses (Latosols). Les latérites montrent de nombreuses failles normales liées à la réactivation de failles plus profondes, elles-mêmes associées à la mise en place du graben amazonien. Ces latérites sont localement affectées par l'hydromorphie

(développement au sein de ces latérites de poches réduites au-dessus de raies ferrugineuses) (Fritsch *et al.,* 2002). Dans le site (2) (région de Porto Velho), les latérites se sont formées sur des formations sédimentaires beaucoup plus récentes (Formation Içá) et sont de ce fait beaucoup moins épaisses (< 1m). A l'inverse, l'hydromorphie est beaucoup plus développée, en particulier dans les dépressions des bas plateaux amazoniens (Fritsch *et al.,* 2007). Les sites (3) et (4) ont par ailleurs permis d'étudier plus en détail l'appauvrissement et la podzolisation des couvertures latéritiques. L'étude du site (3) (région du Jaú), à laquelle j'ai contribué, a permis dans un premier temps de définir les grandes étapes dans la mise en place des "îlots" podzoliques des bas plateaux amazoniens (Nascimento *et al.*, 2004). La mise en place de ces podzols a pu être reliée au développement de nappes perchées en milieu réducteur et acide et la caractérisation géochimique de ces nappes a permis de mieux comprendre les mécanismes associés à la mobilisation des matières organiques et des métaux au sein des sols et des eaux noires qui les drainent (Nascimento *et al.*, 2008). Cette compréhension dans le fonctionnement hydro-biogéochimique de ces podzols hydromorphes a été fortement améliorée dans le cadre de la caractérisation des principaux groupements fonctionnels des matières organiques du sol (Bardy *et al.,* 2008) et dans l'étude de leur aptitude à complexer l'aluminium (Bardy *et al.*, 2007) et le fer (Fritsch *et al.*, 2009).

Figure 4*. Les eaux noires et les sables blancs (région de Barcelos) issus de l'érosion chimique et physique des vastes étendues podzolisées de la partie amont du bassin du Rio Negro (région de São Gabriel da Cachoeira).*

Les travaux présentés dans ce mémoire traitent essentiellement du site (4) (région de São Gabriel da Cachoeira). Ces travaux sont de ce fait complémentaires de ceux engagés dans le site (3) (région du Jaú). Comme nous l'avons déjà signalé, le site 4 est caractérisé par une extension optimale des podzols dans les paysages. Ces podzols sont alors directement reliés au réseau hydrographique principal du Rio Negro. Ils alimentent ce dernier en eaux noires mais aussi en sables blancs (Fig. 4). L'étude de ce quatrième site a permis de mieux comprendre les interactions entre les deux moteurs principaux de la morphogenèse des paysages dans cette partie du bassin amazonien : (1) la transformation des modelés en réponse à l'érosion chimique due à l'expansion latérale des systèmes podzoliques dans les paysages latéritiques, et (2) le processus d'incision des bas plateaux par le réseau hydrographique qui a de ce fait tendance à drainer ces formations hydromorphes. Nous avons par ailleurs étudié les mécanismes associés à l'appauvrissement préalable des couvertures latéritiques, comme processus majeur de pré-podzolisation. Enfin nous avons resitué ces processus d'appauvrissement et de podzolisation à l'échelle du haut bassin amazonien et ceci en relation avec l'histoire géodynamique de ce bassin. Cette étape ultime nous a amené à regrouper l'ensemble des travaux obtenus sur deux site-clés du bassin du Rio Negro ((3) et (4)), en associant études régionales (documents cartographiques) et études plus ponctuelles (de transects et séquences de sols sur des unités représentatives des paysages).

INTRODUÇÃO

A bacia amazônica é uma das maiores bacias hidrográficas da superfície emersa do planeta, com uma área total de cerca de 6,5 milhões de km^2. Situada na zona das florestas tropicais e em grande parte protegida das atividades antrópicas, essa bacia controla os principais ciclos biogeoquímicos do planeta (dentre eles o ciclo do carbono). Ela constitui, por isso, uma região emblemática para abordar o estudo destes ciclos e revelar, por um lado, os processos maiores que controlam a dinâmica dos metais e da matéria orgânica e, por outro, o impacto da pressão antrópica (desmatamento, efeito estufa e mudança climática) sobre a dinâmica destes processos e sobre a remobilização de matéria na interface atmosfera, biosfera, hidrosfera e litosfera. O rio Amazonas exporta quantidades consideráveis de matéria para o oceano (13,5 t/s). Se as quantidades de matéria exportadas pelo Amazonas para o oceano Atlântico são atribuídas essencialmente à orogênese e à erosão dos Andes, estudos recentes tendem a mostrar que importantes quantidades de matéria são também remobilizadas a partir das coberturas lateríticas da bacia e exportadas por erosão química para a rede hidrográfica. Os processos associados a estas exportações agem essencialmente nas regiões mais chuvosas da parte de montante da bacia e a podzolização marca o último estágio desta perda geoquímica. A diversidade de processos de alteração e de erosão que atuam nesta bacia é ilustrada pelo célebre “encontro das águas”, na região de Manaus (parte central da bacia amazônica) (Fig. 1a). Por mais de 60 km, as águas provenientes da erosão física dos Andes se encontram sem se misturar com as águas “negras” que, como veremos a seguir, estão estreitamente associadas à erosão química e interna do solo e ao desenvolvimento de podzóis nas paisagens lateríticas da alta bacia amazônica.

Dos 6,5 milhões de km^2 da bacia, 4 milhões de km^2 pertencem ao Brasil, o que corresponde a quase a metade da área deste país. Se o conhecimento dos meios naturais das regiões Sul, Sudeste e Nordeste do Brasil, que concentram a maior parte da população e das atividades econômicas do país, pode ser considerado satisfatório, o conhecimento dos meios amazônicos é ainda esparso e pouco detalhado. O primeiro inventário sistemático dos recursos naturais desta imensa região de florestas, quase sempre de difícil acesso, foi realizado nos anos 1970 pelo governo brasileiro no âmbito do Projeto RadamBrasil. Este projeto exigiu importantes meios de logística (como aviões e helicópteros) e a mobilização de uma vasta equipe de pesquisadores de diferentes áreas de conhecimento (botânicos, geólogos, pedólogos, geomorfólogos, hidrólogos...). Ele permitiu avaliar os recursos desta imensa região natural,

onde predominam platôs de baixas altitudes associados a imensas reservas de água, e revelar toda a diversidade e a complexidade de organizações de seus diferentes componentes (rochas, sedimentos, vegetações, solos e paisagens) (Fig. 2a e b). A diversidade das estruturas e recursos destes ecossistemas é ilustrada por numerosos documentos cartográficos e legendas elaborados por este amplo projeto. As cartas à escala 1:2.500.000 permitiram uma percepção do conjunto do meio físico e biológico da bacia. Cartas mais detalhadas, à escala 1:1.000.000 fornecem uma visão mais precisa das organizações regionais. Estes documentos, ricos em informações bastante variadas, serviram de base para trabalhos mais detalhados, particularmente sobre os solos. Estas investigações, realizadas em sítios-chave em pequenas unidades de paisagem (bacias elementares) e seqüências de solos ao longo de vertentes (frequentemente partindo de um pólo de montante, bem drenado, rumo a um pólo de jusante, mal drenado), são cada vez mais numerosas (Lucas *et al.*, 1984, 1988, 1996; Bravard & Righi, 1989, 1990; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.*, 1999; Nascimento *et al.,* 2004; Montes *et al.,* 2007). Elas revelaram os processos associados à mobilidade de elementos maiores e em traços nos diferentes ecossistemas, mas mostraram, ainda, em alguns casos, as imprecisões dos documentos do Projeto RadamBrasil na caracterização ou na interpretação de certas estruturas. Este último fato justifica posteriores revisões destes documentos, como a realizada pelo Departamento Nacional de Pesquisa Mineral (DNPM) sobre a carta geológica da bacia, que propôs a diferenciação de uma nova formação, mais recente, no interior da formação Solimões: a formação Içá. Esta formação marca os últimos episódios sedimentares do Terciário. Como será visto adiante, ela tem grande importância para a compreensão da gênese dos solos da bacia.

Os documentos do Projeto RadamBrasil e as imagens de satélite cada vez mais numerosas e detalhadas mostram que a idéia de uma Amazônia coberta por uma floresta homogênea e monótona é falsa. A floresta sempervirente, que cobre amplas superfícies dos baixos platôs e das vertentes abertas pela rede de drenagem, é associada a coberturas vegetais mais baixas, algumas vezes surpreendentemente abertas, onde os solos são expostos à erosão hídrica e eólica. Campos de dunas de areias brancas sem cobertura vegetal (região de Santa Isabel do Rio Negro, por exemplo), em meio à floresta constituem paisagens insólitas da alta bacia do Rio Negro. A comparação de diferentes documentos cartográficos do Projeto RadamBrasil sugere que a diversidade da cobertura vegetal reflete as heterogeneidades litológicas, os gradientes pluviométricos mas, sobretudo, uma grande diversidade de materiais de alteração e de solos.

As cartas do Projeto RadamBrasil e os estudos pontuais sobre sequencias de solos mostram que existe uma distribuição ordenada dos solos na escala da paisagem e, igualmente, uma distribuição ordenada destas paisagens na escala da bacia amazônica (Fig. 3). Os solos lateríticos mais típicos (Latossolos ou Ferralsols vermelhos, argilosos e bem drenados) são presentes essencialmente na periferia da bacia e estão associados aos solos hidromórficos (Gleissolos) ao longo dos principais eixos de drenagem e planícies aluviais. Estes solos lateríticos espessos tendem a ficar mais amarelos na parte central da bacia. Sobre as formações continentais mais recentes da alta bacia amazônica (Formação Içá), as formações lateríticas menos espessas dos baixos platôs amazônicos estão estreitamente associadas a solos hidromórficos (Plintossolos e Gleissolos). Mais ao norte, na bacia do Rio Negro, os solos lateríticos se empobrecem em elementos finos (Ultisols) e se podzolizam (Podzóis hidromóficos). Os podzóis se encontram geralmente sobre os baixos platôs amazônicos. Na parte média da bacia do Rio Negro estes solos são pouco desenvolvidos e ocupam, como os solos hidromórficos (Gleissolos), zonas deprimidas sobre estes platôs (região do Jaú). Na parte de montante e mais chuvosa (região de São Gabriel da Cachoeira), os podzóis têm uma extensão muito mais importante e estão diretamente conectados aos eixos de drenagem principais da bacia do Rio Negro. Eles ocupam vastos peneplanos inundados onde os solos lateríticos aparecem apenas como colinas residuais ou faixas relictuais nas bordas dos platôs. Na parte de jusante da bacia do Rio Negro (região de Manaus), os podzóis geralmente não aparecem sobre os platôs. Eles existem nas partes baixas e médias de vertentes elaboradas pelas incisões da rede de drenagem nestes platôs. Esta distribuição relativa de solos na paisagem mostra que a elaboração e a degradação posterior dos solos lateríticos da bacia amazônica pode ser associada a quatro processos maiores: (1) lateritização, (2) empobrecimento, (3) óxido-redução e (4) podzolização.

Na ótica de um melhor conhecimento destes processos, dos solos e dos funcionamentos hidro-biogeoquímicos a eles associados, foram elaborados projetos científicos em que colaboram pesquisadores brasileiros e franceses. Estes projetos têm início a partir dos anos 80 para a região de Manaus (Lucas et al., 1984; 1988; 1996) e dos anos 90 para a região de São Gabriel da Cachoeira (Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1999). Eles foram estendidos em 1996 ao conjunto da alta bacia amazônica no âmbito de um acordo de cooperação BNPq/IRD associando o Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera de l'Université de São Paulo e a Unidade de Pesquisa 12 (Unité de Recherche 12 "Géoscience de l'Environnement Tropical") do Departamento TOA do IRD (ex-ORSTOM) em um projeto de

pesquisa intitulado “Organização e funcionamento hidro-bioquímico das coberturas lateríticas da Amazônia (Dylat Amazonie). Eles foram posteriormente financiados por projetos FAPESP, PRONEX e ECCO e receberam também o apoio do Instituto de Mineralogia e Física dos Meios Condensados de Paris (IMPMC) para a caracterização mineralógica e espectroscópica de amostras de rocha e solo. Em 2004 estes trabalhos passaram a focalizar particularmente o estudo dos sistemas podzólicos da Amazônia, mais particularmente no âmbito de um projeto intitulado “Podzolização das lateritas da alta bacia amazônica: estudos dos mecanismos e fatores que controlam a dinâmica evolutiva dos podzóis e as exportações de matéria nas cabeceiras de drenagem da bacia do Rio Negro e os depósitos de caolim associados”.

Os trabalhos desenvolvidos nestes projetos correspondem essencialmente a estudos em várias escalas de quatro sítios-chave (estrelas na Fig. 3): (1) região de Manaus, (2) região de Porto Velho, (3) região do Jaú e (4) região de São Gabriel da Cachoeira. Os sítios (1) e (2) permitiram melhor caracterizar os processos de lateritização e de óxido-redução (Fritsch *et al.,* 2002, 2007). No sítio (1) (região de Manaus), a lateritização foi associada às paragêneses que afetam as principais fases minerais destes solos, i.e. as caolinitas (Balan *et al.,* 2005) e os óxidos de Fe (Fritsch *et al.,* 2005). Esta lateritização transformou formações sedimentares muito antigas (Formação Alter do Chão, do final do Cretáceo-começo do Terciário em coberturas lateríticas muito espessas). Essas coberturas lateríticas móveis (ou solos lateríticos) apresentam numerosas falhas normais ligadas à reativação de falhas profundas, associadas ao estabelecimento do graben amazônico. Estes solos lateríticos são localmente afetados pela hidromorfia (desenvolvimento de zonas redutoras na forma de bolsas sobre camadas finas ferruginosas). No sítio (2) (região de Porto Velho), os solos lateríticos se formam sobre formações sedimentares muito mais recentes (Formação Içá) e são muito menos espessas (< 1 m). Inversamente, a hidromorfia é muito mais desenvolvida, particularmente nas depressões dos baixos platôs amazônicos (Fritsch *et al.,* 2007). Os sítios (3) e (4) permitiram o estudo mais detalhado do empobrecimento e da podzolização das coberturas lateríticas. O estudo do sítio (3) (região do Jaú), em que participei como colaborador, permitiu definir as grandes etapas da elaboração das “ilhas” podzolizadas dos baixos platôs amazônicos (Nascimento *et al.,* 2004). A instalação destes podzóis pôde ser associada ao desenvolvimento de lençóis suspensos em meio redutor ácido e a caracterização geoquímica destes lençóis permitiu uma melhor compreensão dos mecanismos associados à mobilização da matéria orgânica e dos metais nos solos e nas águas negras que os drenam (Nascimento *et al.,* 2008). Esta

compreensão do funcionamento hidro-biogeoquímico destes podzóis hidromórficos foi aprofundada com a caracterização das principais funções estruturais da matéria orgânica do solo (Bardy *et al.,* 2008) e com o estudo da aptidão das mesmas para a complexação do alumínio (Bardy *et al.,* 2007) e do ferro (Fristsch *et al.,* 2009).

Os resultados apresentados neste trabalho tratam essencialmente do sítio (4) (região de São Gabriel da Cachoeira). Estes trabalhos são complementares daqueles desenvolvidos no sítio (3) (região do Jaú). Como já assinalado, este sítio se caracteriza pela extensão máxima dos podzóis na paisagem. Estes podzóis estão diretamente ligados à rede de drenagem principal do Rio Negro. Eles alimentam este rio não somente em águas negras, mas, também, em areias brancas (Fig. 4). O estudo deste quarto sítio permitiu compreender melhor as interações entre os dois principais motores da morfogênese das paisagens nesta parte da bacia amazônica: (1) a transformação dos relevos em resposta à erosão química e à expansão lateral dos sistemas podzólicos nas paisagens lateríticas e (2) o processo de incisão dos baixos platôs pela rede hidrográfica, que tem como conseqüência a drenagem das formações hidromórficas. Foram estudados, ainda, os mecanismos associados ao empobrecimento dos solos lateríticos, como processo maior de pré-podzolização. Finalmente, os processos de empobrecimento e de podzolização foram situados espacialmente na escala da alta bacia amazônica e temporalmente na história geodinâmica desta bacia. Esta última etapa nos conduziu a reagrupar o conjunto dos trabalhos produzidos nestes dois sítios-chave da bacia do Rio Negro (3) e (4) associando estudos regionais (documentos cartográficos) e estudos pontuais (estudos de transeções e de seqüências de solos em unidades representativas das paisagens).

OS CINCO CAPITULOS DA TESE

Les résultats de cette étude sont regroupés dans cinq chapitres :

Le **Chapitre 1** est une brève revue bibliographique qui présente les podzols (distribution et horizons diagnostiques) et les mécanismes le plus souvent invoqués dans la mise en place de ces sols.

Le **Chapitre 2** présente le cadre naturel de cette étude. Il traite des grands ensembles structuraux du bassin amazonien, de ses sols et des processus majeurs (latérisation, appauvrissement, oxydo-réduction, podzolisation et incision du modelé) impliqués dans l'érosion chimique et physique des paysages.

Le **Chapitre 3** traite de l'appauvrissement des latérites comme étape préalable à la podzolisation. Cette étude a été réalisée dans la région de São Gabriel da Cachoeira (site (4)) à la bordure des aires fortement podzolisées du bassin versant du Curicuriari (bassin versant podzolisé sur prêt de 95% de sa superficie).

Le **Chapitre 4** présente les résultats d'une étude minéralogique et structurale d'une séquence de sols entreprise dans la même région (site 4) au niveau d'une relique de sols latéritique, dans un paysage fortement podzolisé et incisé par le réseau hydrographique. Cette étude a pour objectif de montrer les effets de ces incisions sur la morphologie des podzols et sur la dynamique de ces sols (rabattement des nappes perchées). Elle traitera en particulier des analogies et différences par rapport à ce qui a déjà été étudié sur le site (3) du Jaú.

Le **Chapitre 5** est un essai de reconstitution de la dynamique des podzols dans le bassin du Rio Negro à partir des études ponctuelles obtenues sur des séquences de sols (sites 3 et 4), de documents cartographiques obtenues à des échelles régionales et des connaissances actuelles sur l'histoire géodynamique et géologique du bassin amazonien.

VALORIZAÇÃO DOS RESULTADOS

Les résultats présentés dans cette thèse ont donné lieu à l'écriture de trois articles destinés à paraître dans des revues internationales. Ces articles constituent l'ossature de cette thèse. Ils sont brièvement introduits en début des Chapitres 3, 4 et 5 :

Chapitre 3

Yellowing, bleaching and clay depletion of laterites in the Negro River Catchment (upper Amazon Basin). Preliminary steps to Podzolisation. G. Bueno, E. Fritsch, N.R. DO Nascimento, M.E. Almeida & B.S. Arenare.

Chapitre 4

Podzolisation of clay depleted laterites and physical denudation of Podzols in the high rainfall region of the upper Negro River watershed. G. Bueno, E. Fritsch, N.R. DO Nascimento & A.J. Melfi.

Chapitre 5

Weathering and erosion in major Cenozoic land surfaces and genesis of waterlogged Podzols in the Negro River Catchment (upper Amazon Basin). G. Bueno, E. Fritsch, N.R. DO Nascimento, A.J. Melfi & G. Calas.

CAPITULO 1. PODZOIS E PODZOLIZAÇÃO

1.1. Définition

Le nom "Podzol" vient du russe "pod" pour sous et de "zola" pour cendre et caractérise de ce fait des sols présentant des horizons de sub-surface cendreux ou blanchis par des agents organiques acides (FAO, 1998). Ces sols sont vraisemblablement les plus connus de la planète du fait de leur morphologie spectaculaire avec la présence d'horizons éluviés, blanchis (aussi connu sous le terme d'horizons albiques) qui recouvrent plus en profondeur des horizons illuviés, brun foncé à brun rouge, enrichis en humus et parfois aussi en sesquioxydes (horizons également qualifiés de spodiques) (Fig. 5).

Le terme "Podzol" est utilisé dans la plupart des systèmes de classification des sols, en Russie bien sûr, mais aussi en Europe et par la FAO. La "Soil Taxonomy" américaine préfère néanmoins parler de "Spodosols" en référence aux horizons spodiques qui, comme nous le verrons, sont les horizons diagnostiques des podzols.

1.2. Morphologie et concept

Les podzols présentent deux catégories d'horizons : (1) des horizons supérieurs éluviés comprenant le plus souvent des horizons organiques de type Mor enrichis en résidus organiques (L, O, AE) et des horizons minéraux albiques (E), sans cohésion, essentiellement constitués de résidus quartzeux et minéraux lourds, et (2) des horizons inférieurs illuviés (Bh et Bs) enrichis en substances humiques acides susceptibles d'altérer les minéraux argileux du sol et de former des complexes organo-métalliques. Cette distribution relative indique ainsi des mécanismes de transfert (“chéluviation”) et d’accumulation (“chilluviation”). L’illuviation de substances organiques en profondeur est confirmée par la présence de revêtements ou cutanes qui coiffent les quartz ou remplissent les interstices ménagés par ces derniers (Bardy *et al.,* 2008). Ces revêtements sont très fins, brun rouge, souvent craquelés sur lames minces dans les horizons Bs les plus profonds des podzols. Ils sont noirs, plus grossiers (fibres ou boulettes), dans les horizons Bh qui les surmontent, à la base des réservoirs sableux (Buurman & Jongmans, 2005; Bardy *et al.,* 2008). Ces horizons illuviés, aussi qualifiés d’horizons spodiques, sont riches en humus et en métaux (Duchaufour, 1982; Petersen, 1984; Macias-Vasquez, 1987). Deux critères géochimiques majeurs sont généralement requis pour les horizons spodiques des podzols (FAO, 1998): (1) des teneurs en carbone organique supérieures à 6 g/kg et (2) des rapports Al_o+1/2Fe_o supérieurs à 5, où “Al_o” et “Fe_o” réfèrent respectivement aux quantités d’aluminium et de fer extraites par le traitement oxalate (c.a.d. aux formes complexées aux matières organiques et aux oxydes mal cristallisés). Ces horizons peuvent de ce fait être considérés comme des zones d’accumulation de métaux (principalement Al mais aussi Fe), qui sont majoritairement chélatés à des groupements organiques (formation de complexes organo-métalliques).

Les associations entre substances organiques et phases minérales résiduelles du sol sont très tranchées entre horizons éluviés et illuviés. Dans les horizons éluviés, les résidus organiques sont nettement dissociés des quartz blancs. Dans ces niveaux organo-minéraux de surface ou de subsurface, les horizons présentent alors un aspect “poivre et sel” très caractéristique (horizons humifères ponctués de blanc). Dans les horizons illuviés, les substances organiques, souvent assimilées à des humus de faible ou haut poids moléculaire (e.g. acides fulviques, acides humiques et humine), recouvrent les grains de quartz. En masquant les quartz, ces substances organiques peuvent ainsi nous amener à surestimer visuellement les quantités de matières organiques accumulées dans les horizons spodiques de ces sols (Nascimento *et al.,* 2004).

Figure 5*. Les podzols de la partie médiane des aires podzolisées (profile IV) de la séquence du Curicuriari (site 4) montrant en surface les horizons humifères éluviés (AE), puis l'horizon blanchi ou albique (E) et les horizons spodiques en profondeur: l'horizon noir Bh et les horizons brun rouge BCs (noter entre ces deux horizons la naissance d'un nouvel horizon éluvié, gris clair)*

Dans les horizons éluviés organiques et minéraux (AE et E), les pHs sont généralement bas (< 4), les groupements hydroxyles des composés organiques sont protonés (prédominance de fonctions carboxyliques, faible occurrence de carboxylates), les phases argileuses du sol ont pratiquement disparues et les résidus grossiers organiques et minéraux (surtout quartz mais aussi minéraux lourds, tels que zircon et oxydes de Ti) tendent à s'accumuler. Dans les horizons illuviés ou spodiques, les pHs sont généralement plus élevés (> 4) et les métaux sont complexés (chélatés) aux substances organiques (prédominance de carboxylates). Une partie non négligeable de métaux peut également précipiter sous forme de composés inorganiques faiblement cristallisés, les plus connus correspondant aux ferrihydrites (à deux ou six raies sur spectres DRX) pour Fe et aux produits allophaniques (allophane, proto-imogolite et imogolite) pour Al (Ross, 1980; Buurman, 1987; Macias-Vasquez, 1987; Lundström ***et al.,***

2000). Ces gradients soulignent de ce fait le rôle essentiel du pH dans l'immobilisation ou la remobilisation des métaux lors d'une lixiviation et acidification ultime de ces sols (principalement pour Al) (Nascimento *et al.* 2004, 2008).

1.3. Les deux grands types de podzols

Les horizons spodiques des podzols doivent apparaître sous des horizons éluviés organiques (AE) ou minéraux (E) et montrer des évidences d'accumulation de matières organiques et de métaux pour que le processus central de podzolisation puisse être invoqué (Petersen, 1984 ; Lundström et al., 2000). Dès lors, deux grands types de podzols peuvent distingués suivant l'épaisseur de ces sols et l'absence ou présence d'horizon albique.

Dans les podzols peu évolués, les horizons éluviés et organiques de surface (A, AE) surmontent des horizons spodiques faiblement différenciés (Bhs). Ces sols peu épais, dépourvus d'horizon albique, marquent de ce faite une première étape dans le développement de la podzolisation (Nascimento *et al.*, 2004). Ils ont été qualifiés de sols crypto-podzoliques (Duchaufour, 1972) ou de podzols humiques (Thompson, 1992). Des podzols plus épais et mieux différenciés sont le plus souvent observés dans les paysages. Dans ces podzols, les horizons organiques éluviés et illuviés sont séparés par des horizons blanchis (albiques). D'autre part, les horizons illuviés sont nettement différenciés en deux types d'horizons spodiques : (1) des horizons humiques noirs (Bh) surmontant (2) des horizons brun-rouge riches en sequioxydes (Bs).

Enfin une troisième catégorie de podzols pourrait éventuellement être distinguée. Cette dernière catégorie marque une étape ultime dans le développement vertical des podzols dans les paysages. Elle correspond aux podzols géants, qui ont été identifiés en abondance dans la zone tropicale, plus particulièrement dans le haut bassin amazonien. Ces podzols sont caractérisés par la très grande épaisseur de ces horizons blancs, sableux (albiques) qui rendent de ce fait difficile la reconnaissance à plus grande profondeur des horizons spodiques (les horizons albiques, dépourvus de cohésion, tendent en effet à s'effondrer dans les fosses pédologiques ou lors de sondages). De tels sols ne sont en fait plus considérés comme des podzols dans la plupart des systèmes de classification. Ils ont été qualifiés d'arénosols dans les cartes pédologiques du projet RadamBrasil.

1.4. Régime hydrique et morphologie des podzols

Ils existent très peu de données sur le fonctionnement hydrique des podzols et donc sur les conditions redox qui ont pu contribuer à la mise en place de ces sols. De telles conditions (i.e. alternance aux rythmes des saisons d'épisodes anoxiques et oxiques) sont toutefois reconnues comme l'un des facteurs majeurs dans la différenciation verticale des sols. Il est néanmoins admis qu'il existe des podzols à nappes et des podzols bien drainés sans qu'un lien génétique ait pu être établi entre ces deux types de sols.

Dans les podzols à nappe, les contrastes de couleur entre horizons sont parfois tenus. En effet, les couleurs sont plus fades et sont nettement dominées par l'abondance de composés organiques brun foncé à noirs. La présence d'une nappe à faible profondeur est propice au développement de conditions réductrices et de ce fait à une grande mobilité du fer au sein de ces formations. Cet élément est exporté sous forme dissoute ou en association avec les composés organiques au réseau hydrographique lors d'écoulements hydriques latéraux (Nascimento *et al.,* 2004, Fritsch *et al.,* 2009). Les eaux de nappe baignant ces podzols, mais aussi les eaux de surface qui drainent ces aires podzoliques, ont alors une coloration noire caractéristique (Fig. 1b), attribuée à la présence d'acides fulviques et de colloïdes organiques en suspension dans les eaux (FAO, 1998; Allard et al., 2002; Benedetti *et al*., 2003a).

Dans les podzols bien drainés, les contrastes de couleur entre horizons sont plus forts et la morphologie de ces sols est de ce fait plus spectaculaire. La plus grande minéralisation des composés organiques dans ces sols limite leur accumulation dans les horizons spodiques, plus profonds. Ces composés masquent de ce fait moins les hétérogénéités texturales et structurales de ces sols. Par ailleurs, le développement à certaines périodes de l'année de conditions oxiques est propice à la précipitation du fer qui donne des colorations brun rouge à rouge vif aux horizons spodiques les plus profonds de ces sols (Bs). Des phénomènes d'induration ont parfois été invoqués. Par contre, la nature des agents de cimentation reste incertaine et mal définie (oxydes de fer et de Mn, complexes organo-métalliques …).

1.5. Mécanismes communément invoqués pour la podzolisation

La formation des podzols est généralement attribuée à l'accumulation et migration des substances organiques, à l'altération des phases argileuses résiduelles du sol et à la formation de composés mal cristallisés associés ou non aux phases organiques de ces sols (Gustafsson *et al.*, 1999; Lundström *et al.*, 2000, Van Hees & Lundström, 2000, Nascimento et al., 2004). Il n’existe toutefois pas de véritables consensus sur les zones des profils ou ces mécanismes sont susceptibles d’agir et sur la nature des substances organiques susceptibles de migrer et de fixer les métaux libérés par l’altération. Ceci a amené les scientifiques à proposer plusieurs modèles conceptuels de formation des podzols.

D’après Petersen (1984), de Coninck (1980) et Buurman (1987), les acides organiques à faible poids moléculaire sont des agents de transport du Fe et de l’Al sous forme complexée. Ces complexes organo-métalliques peuvent être immobilisés en profondeur (1) au niveau de discontinuités lithologiques, (2) par la diminution du rapport C/(Al+Fe) au fur et à mesure que les complexes migrent à travers le profil, ce qui conduit à la saturation des sites d’échange de la matière organique, à la neutralisation de leurs charges négatives et à la précipitation des complexes, (3) après la biodégradation de certains complexes organo-métalliques, ce qui libère des cations métalliques qui peuvent saturer d’autres complexes, les faisant moins biodégradables, ou précipiter sous forme inorganique, ou (4) par adsorption des substances organiques à la surface des imogolites dans les horizons spodiques, suivant la diminution de la capacité complexante des groupements carboxyliques après la diminution du pH en profondeur.

D’après Farmer (1980), Anderson et al., (1982) et Farmer (1987), les cations Al et Fe libérés en surface par l’altérations des phases argileuses forment des gels de haut poids moléculaires (formation en particulier de proto-imogolites). Ces gels migrent en profondeur et s’accumulent dans les horizons spodiques sous forme de ferrihydrites et/ou de produits allophaniques (surtout imogolite). La matière organique (principalement les acides fulviques) migre en profondeur et s’adsorbe à la surface des imogolites.

D’après Ugolini & Dahlgren (1987) et Lundström (1993), l’imogolite se forme dans les horizons spodiques après hydrolyse des minéraux argileux dans un milieu à forte pCO_2. Ces imogolites adsorbent des complexes organo-métalliques (acides fulviques + métaux) qui migrent depuis la surface.

1.6. Conditions de formation et répartition géographique

Les conditions propices à la migration et accumulation de complexes organo-métalliques dans les sols sableux des surfaces continentales et de ce fait à la formation de podzols sont grandement favorisées par des climats froids et humides, par des environnements de hautes montagnes, par des matériaux parentaux sableux et des couverts végétaux acides (e.g.

conifères et landes) (FAO, 1998). Les Podzols peuvent se former sur n'importe quel type de matériaux parentaux (Buurman, 1984). Toutefois, les sédiments sableux sont très propices à la formation de ces sols lorsque les autres conditions du milieu s'y prêtent (Pedro, 1987). Ils peuvent également se développer à partir d'autres types de sols qui ont été au préalable appauvris en éléments fins argileux (Turenne, 1977; Lucas *et al.,* 1989). L'influence de systèmes de nappes semble également être un élément prépondérant dans l'accumulation des matières organiques et la mise en place de ces sols.

Les podzols sont les sols zonaux des régions boréales, où ils sont communément associés aux dépôts morainiques des glaciers et aux forets à *Taïga* (Buurman, 1984; Pedro, 1987). Bien que la podzolisation des sols affecte de très grandes superficies dans cette partie émergée des surfaces continentales, ce processus n'est pas limité à ces régions froides et humides. En effet, il est bien connu que ce processus est actif dans toutes les régions humides de la planète (FAO, 1998), plus particulièrement dans les régions tempérées (e.g. Buurman, 1984 ; Righi, 1987), mais aussi dans les régions tropicales (Klinge, 1965; Schwartz, 1987; Bravard & Righi, 1990; Dubroeucq & Volkoff, 1998; Thomas, 1999), où de nombreux exemples de podzols géants ont été décrits (e.g. Klinge, 1965). Les podzols tempérés et tropicaux ont été qualifiés d'intrazonaux par Buurman (1984) et de podzols secondaires par Duchaufour (1982).

Les Podzols des régions tropicales ne figurent pas sur la plupart des cartes pédologiques établis à l'échelle du globe, alors qu'ils semblent occuper des superficies importantes dans les zones les plus pluvieuses de cette partie de la planète (e.g. Amazonie, Afrique centrale et Indonésie). Ces sols, relativement peu connus dans ces régions, n'ont entre autres été décrits qu'assez récemment à partir des années 1960. Ils se forment sur des matériaux beaucoup plus altérés et souvent plus profonds. Ils présentent de ce fait une minéralogie plus simple que celle des podzols boréaux et tempérés. En particulier, les horizons éluviaux (AE et E) de ces podzols sont constitués presque exclusivement de quartz et de quelques minéraux lourds, résistants à l'altération (zircon, rutile, anatase…). Dans les horizons spodiques et à la bordure des aires podzoliques, les matières organiques sont généralement associées aux minéraux secondaires les plus communément rencontrés dans la zone tropicale (i.e. kaolinite, gibbsite et goethite) (Turenne, 1977; Schwartz, 1987, 1988; Lucas *et al.,* 1989; Bravard & Righi, 1990; Dubroeucq & Volkoff, 1998; Nascimento *et al.,* 2004). Comme l'ont souligné Nascimento et al. (2004), la présence de composés allophaniques (imogolite, allophane) dans les horizons spodiques des podzols tropicaux n'a encore jamais été démontrée, probablement du aux

faibles quantités des cations présents dans les nappes perchées de ces podzols hydromorphes (Si, Al et Fe), ainsi qu’à la forte lixiviation et acidification de ces sols.

CAPÍTULO 2. SOLOS E PROCESSOS MAIORES DE ALTERAÇÃO E PEDOGÊNESE NO ALTO RIO NEGRO

2.1. Histoire géodynamique du bassin et principaux ensembles structuraux

Situé sous les tropiques, le bassin forestier amazonien a focalisé l'attention de la communauté scientifique brésilienne et internationale par la diversité des processus mis en jeu et des facteurs qui ont pu contrôler la mise en place de ses principaux ensembles structuraux. Ces facteurs sont étroitement associés à la géodynamique de la plaque sud américaine et les processus à l'altération, l'érosion et la déformation (flexure et fracture) de cette plaque. La formation du graben amazonien a, entre autres, été reliée à l'érosion des socles brésilien et guyanais et à une sédimentation massive dans la partie centrale et ouest du bassin à une époque où les écoulements se faisaient vers le Pacifique (Fig. 3a). La majeure partie des sédiments accumulés dans ce bassin correspond ainsi de nos jours aux vastes pénéplaines à faible gradient topographique du haut bassin amazonien. La subduction de la plaque de Nazca a initié au Tertiaire la formation de la chaîne montagneuse des Andes sur la bordure Ouest du bassin. La surrection de cette chaîne, toujours actuelle, a joué un rôle déterminant sur le climat, l'érosion et changé de façon irréversible le sens des écoulements des eaux dans le bassin (vers l'Atlantique). Les changements climatiques et les variations des niveaux de base au Quaternaire ont favorisé l'incision des pénéplaines et de ce fait formé les bas plateaux qui dominent le modelé du bassin. Le basculement définitif du réseau hydrographique au Pliocène (~ 2,5 Ma) a contribué à l'individualisation de chenaux fossiles et de vastes étendues ennoyées dans les sédiments du haut bassin amazonien (Campbell ***et al.,*** 2006, Fritsch ***et al.,***

2007), dans une région soumise alors à de forts gradients pluviométriques (1,5 m/an à l'Est, jusqu'à 6 m/an au Nord Ouest).

L'histoire géodynamique de ce bassin est ainsi à l'origine de la mise en place de ses principales formations sédimentaires. Les formations les plus anciennes, issues de l'érosion des socles brésilien et guyanais, affleurent de nos jours au nord et au sud du graben central (Formations Prosperança et Trombetas), lui-même comblé par une puissante formation Crétacé (Formation Alter do Chão). Des sédiments plus récents ont recouvert ces dépôts dans le haut bassin amazonien. Ils correspondent à l'une des plus vastes formations Tertiaires de la planète (Fig. 3a). Des travaux récents (Campbell *et al.,* 2006) ont révélé deux grands cycles sédimentaires pan-américains au Tertiaire, séparés par une longue période d'aplanissement qui a tronqué toutes les structures géologiques exposées à la surface ("*the Ucayali Peneplain*"). Ces cycles, reliés à la surrection des Andes, sont associés à deux événements tectoniques majeurs: Quechua I et Quechua II. Le premier événement tectonique (Quechua I) s'est achevé approximativement au Miocène moyen. Il a contribué à la mise en place des épais sédiments de la Formation Solimões. Le second événement (Quechua II) est relié à la surrection définitive des Andes (~ 9,5 Ma) qui a définitivement obturé les écoulements vers le Pacifique. En initiant la formation d'un méga-lac dans la partie centrale et aval du haut bassin amazonien, il marque le début de l'ultime sédimentation Tertiaire (Formaton Içá). Cette sédimentation, essentiellement attribuée à l'érosion des Andes, s'est achevée vers 2,5 Ma avec la naissance du réseau hydrographique actuel, qui a pu explorer les anciens axes de drainage ou en créer de nouveaux en incisant de ce fait profondément les vastes plaines sédimentaires du bassin (Fig. 6).

L'observation de la Figure 3 montre que la distribution actuelle des sols se cale grosso modo sur ces structures géologiques et sédimentaires (N.B. la Formaton Içá, identifiée en 1981 par le DNPM, n'a pas été représentée sur la Fig. 3a, elle correspond toutefois à l'extension des latérites à sols hydromorphes de la Fig. 3b, cf aussi Fritsch *et al.,* 2007). On voit en particulier que les latérites rouges les mieux drainées (en rouge dans la Fig. 3b) se sont essentiellement développées au Nord et au Sud sur les roches cristallines des socles guyanais et brésilien. A l'inverse, les autres sols qui font apparaître soit une tendance plus ou moins affirmée au jaunissement et à l'appauvrissement de la partie supérieure des latérites, soit une tendance plus affirmée à l'hydromorphie et à la podzolisation se développent de préférence sur les formations sédimentaires de ce bassin. Les formations podzoliques (en gris ou noir sur la Fig. 3b) semble néanmoins échapper à cette règle puisqu'on les retrouve de part et d'autre de la

limite entre formations sédimentaires au Sud et cristallines au Nord, dans les zones les plus pluvieuses du bassin. Comme nous le verrons dans ce mémoire, les sols hydromorphes à Gleys ou à Podzols s'observent soit dans les dépressions des bas plateaux amazoniens (cas très fréquents de certaines unités de paysages) soit en positions plus basses, sur les bas de versants et les dépôts alluviaux (sableux ou argileux) du Quaternaire. Les premiers systèmes sont partiellement confinés (drainés par un réseau épars de petits ruisseaux) tandis que les seconds sont ouverts et directement connectés aux principales rivières du bassin. A ces systèmes peuvent être reliées des séquences ordonnées de sols qui partiront soit du rebord vers le centre des plateaux (cas des plateaux à dépressions) soit de l'amont vers l'aval sur les versants du rebord de ces plateaux.

2.2. Les grandes catégories de sols, de végétation et de régimes hydriques

Les sols du bassin Amazonien peuvent être regroupés dans deux grandes catégories suivant la nature des processus d'altération mis en jeu et les régimes hydriques qui leurs sont associés. La première catégorie de sols correspond aux latérites, formations également connues sous les termes de sols ferrallitiques, de Latosols, d'Oxisols ou de Ferralsols. Ces formations occupent généralement les positions hautes les mieux drainées des paysages et sont reliées à des écoulements libres verticaux. Ces écoulements sont propices à une horizonation des sols, et donc à un développement vertical des processus d'altération. Le processus majeur associé à la formation de ces sols argileux et bien structurés est la latéritisation (Melfi & Pedro, 1977; Fanning & Fanning, 1989: Fritsch *et al.,* 2002, 2005). La deuxième catégorie de sols se situe en général dans les zones basses ou déprimées des paysages. Il est de ce fait étroitement lié à des engorgements permanents ou provisoires contrôlés par les apports pluviométriques et la capacité de ces sols à exporter l'eau au réseau hydrographique. L'altération et la pédogenèse sont alors contrôlées par la dynamique des nappes. Les écoulements d'eau et les exportations de matières sont essentiellement latéraux. Les Gleys et les Podzols sont de bons exemples de sols hydromorphes. Ils peuvent se développer verticalement à partir de matériaux sous-jacents, mais aussi latéralement à partir des formations latéritiques amont (Nascimento *et al.,* 2004). En accord avec Fanning & Fanning (1989), cela suggère que des sols puissent se former dans un premier temps (*soil forming processes*) puis se transformer ou se dégrader dans un second temps (*soil change processes*). Ce concept nouveau permet ainsi d'introduire la notion d'équilibre ou déséquilibre géodynamique pour les formations latéritiques et également de systèmes de transformation (Boulet *et al.,* 1982) ou transformants (Fritsch *et al.,*

1986). Dans les paysages latéritiques des régions humides du bassin amazonien, la pédogenèse semble ainsi favoriser l'exportation des éléments préalablement accumulés lors d'une phase d'intense latéritisation.

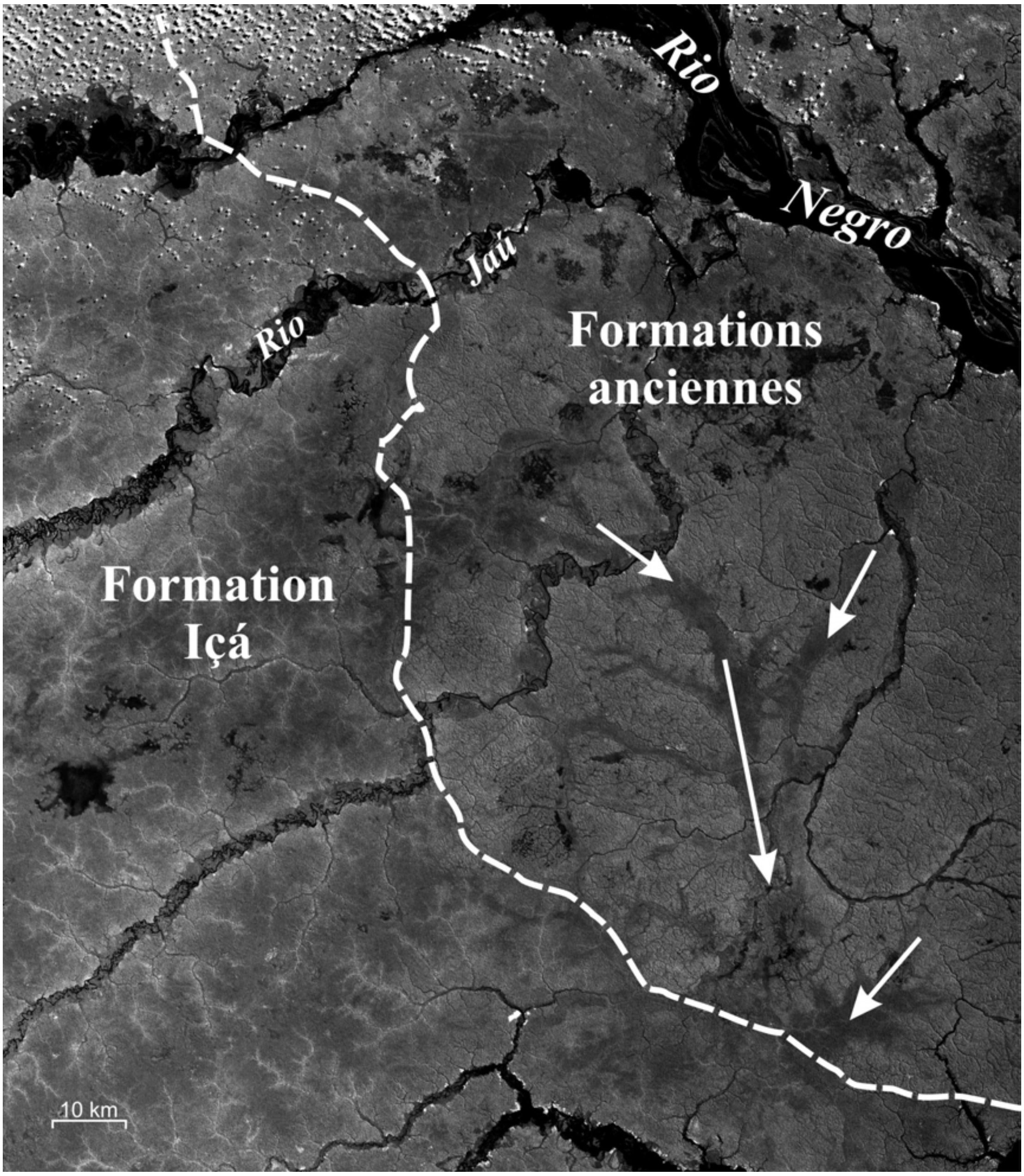


Figure 6*. Image Landsat d'un reseau fluvial fossile (zone foncée sous les fleches) installé sur les formations géologiques anciennes (Prosperança, Trombetas et Alter do Chão). Ce reseau est localement recoupé par le réseau de drainage actuel des bas plateaux de la région du Jaú. Noter des directions opposées pour les écoulements suggérant que les paléo chenals puissent être antérieurs à l'installation du réseau de drainage moderne du fleuve Amazone).*

La distribution de la végétation reflète très généralement cette distinct entre ces deux grandes catégories de sols (Fig. 2a). Par ailleurs, le type de régime climatique et de sol formé en

environnement hydromorphe semble également avoir une incidence notable sur le port du couvert végétal. Ainsi, les sols latéritiques bien-drainés (Ferralsols et Acrisols) soutiennent très généralement la forêt sempervirente (*Floresta de Terra Firme*) (Silva ***et al.***, 1977). Sur les sols périodiquement engorgés (e.g. Gleys ou Podzols hydromorphes) se développent des couverts végétaux plus bas et ouverts que la forêt. Dans les podzols hydromorphes de la partie centrale de certains plateaux (cas par exemple du site (3) du Jaú, Nascimento ***et al.***, 2004), la forêt laisse place à une végétation arbustive dense à la bordure des dépressions à podzols (*Campinarana*) puis à une savane arbustive ouverte (*Campina*) dans la partie saisonnièrement ennoyée de ces dépressions. Ces couverts arbustifs témoignent ainsi de stress hydriques plus marqués à l'aval de ces dépressions (Anderson, 1982), avec des périodes d'ultra-dessiccation en saisons sèches (faible capacité de rétention en eau du sable) et d'engorgements prolongés en saisons pluvieuses. Dans des régions plus pluvieuses à paysages plus fortement podzolisés mais également incisés par le réseau hydrographique (cas du site (4) de São Gabriel da Cachoeira), une forêt arborée plus haute, mais plus claire que la forêt sempervirente peut alors coloniser les aires podzoliques (*Caatinga*) (Fig. 2a). Ces distributions de végétations (Magnago *et al.*, 1978; Chauvel *et al.*, 1987) semblent ainsi être plus attribuables à des régimes hydriques contrastés entre latérites et podzols, voire même entre podzols hydromorphes et podzols drainés, qu'à des oscillations climatiques Quaternaires comme cela est généralement invoqué dans la littérature (Gouveia *et al.*, 1997).

2.3. Les latérites (Ferralsols) et la latéritisation

La latéritisation correspond à l'altération zonale des régions intertropicales humides ou à saisons contrastées du globe. Les latérites meubles ou indurées (e.g. cuirasses) sont les résidus de cette altération (Melfi & Pedro 1977, Fanning & Fanning 1989). Dans ces régions, les conditions de drainage ouvert à semi-ouvert, les températures élevées et les pHs modérément acides sont propices à une exportation totale des bases, partielle de la silice et une accumulation résiduelle du fer et de l'aluminium dans les minéraux secondaires du sol (essentiellement kaolinite, oxydes de Fe et d'Al) (Robinson 1949; Melfi & Pedro, 1977). Des éléments en trace (e.g. Zr, Ti, Th), présents dans des phases minérales peu altérables (e.g. zircon, oxydes de Ti ou de Th) (Balan *et al.*, 2001; Maurin *et al.*, 2005) ont également tendance à s'accumuler de façon relative dans ces profiles d'altération. Ils sont souvent utilisés comme invariants pour les calculs des bilans de masse (Brimhall & Dietrich 1987; Chadwick *et al.*, 1990). Les latérites meubles présentent des horizons organiques de type

mull. Ils sont fréquemment argileux et présentent verticalement de faibles gradients texturaux. Les oxydes de Fe intimement liés aux argiles forment avec ces derniers des structures polyédriques ou micro-agrégées stables (pseudo-particules, Beaudou & Chatelin, 1972) qui rendent les matrices poreuses et perméables.

Des travaux récemment engagés sur des latérites meubles de la zone intertropicale humide d'Amazonie ont également montré que les accumulations résiduelles de matières étaient aussi reliées à une dissolution ménagée des quartz et à des mécanismes de dissolution/recristallisation affectant les principales phases minérales secondaires de ces sols: la kaolinite (Balan *et al.,* 2005) et les oxydes de fer (Fritsch *et al.,* 2005). Ces transformations minéralogiques sont appréhendées sur le terrain par des variations progressives de texture et de couleur. Les variations texturales sont attribuées à une diminution progressive de la taille des particules de kaolinite de la base vers le sommet des profils latéritiques. Elles sont particulièrement marquées en profondeur à la transition entre les altérites et les sols. La diminution de la taille de ces particules a été reliée à un accroissement du désordre cristallin des kaolinites, lui-même attribué à des fautes d'empilement des feuillets de ce minéral (Balan *et al.,* 1999). Ces variations texturales ne peuvent s'expliquer que par des mécanismes de dissolution/recristallisation propices au remplacement d'anciennes populations de kaolinite de grande taille et dépourvu de fautes d'empilement par de nouvelles populations de kaolinite plus petites et fortement désordonnées. Les variations colorimétriques sont attribuées au jaunissement progressif des latérites rouges, particulièrement marquées dans la partie supérieure des profils d'altération. Ces changements, qui peuvent se faire sans perte des teneurs en fer, ont été attribués à la dissolution d'oxydes de fer faiblement substitués en aluminium (hematite et goethite) suivie par la recristallisation d'oxy-hydroxydes plus fortement substitués (goethite alumineuse) (Fritsch *et al.,* 2005). Lorsque l'accumulation d'aluminium dans les structures des oxyhydroxydes de fer est achevée (maximum de 33%), des hydroxydes d'aluminium (gibbsite) sont alors susceptibles d'être produits. Ces transformations témoignent d'une activité en aluminium et en eau plus élevée et, à l'opposé, d'une activité en silicium plus faible dans la partie supérieure de ces profils. Ces conditions d'altération qui restent propices à la dissolution des kaolinites ne sont par contre plus favorables à la recristallisation de nouvelles générations de phyllosilicates. Elles favorisent à l'opposé le piégeage de l'aluminium dans des phases minérales plus hydroxylées (goethite alumineuse puis gibbsite). Ces dernières témoignent d'un début de mobilité de l'aluminium dans ces profils d'altération.

2.4. Les latérites (Acrisols) et l'appauvrissement

Les latérites, précédemment décrites (Ferralsols), sont susceptibles de s'appauvrir en éléments fins et d'acquérir de ce fait des textures de plus en plus sableuses. L'appauvrissement en éléments fins peut se faire soit directement lors de l'altération de la roche (Wesemael *et al.,* 1995) soit par transformation latérale d'un autre sol (des latérites par exemple). Il donne naissance à des sols qui ont reçu différents qualificatifs: « *sandy bleached brown loam* » (Klinge, 1965), « sols ferrallitiques fortement désaturés, lessivés, intergrades » (Turenne, 1977), « sols intermédiaires ferrallitiques lessivés » (Lucas *et al.,* 1988), Ultisols (Bravard & Righi, 1990) ou Acrisols (Nascimento *et al.,* 2004). Ces sols présentent généralement des horizons organiques de type mull et des gradients texturaux avec ou sans évidence de transport particulaire, en particulier des revêtements argileux (cutanes d'illuviation) dans des horizons Bt plus profonds ou situés plus à l'aval dans les paysages. Deux processus majeurs sont généralement invoqués dans la littérature pour expliquer ces pertes de matières: (i) la lixiviation associée à des dissolutions de minéraux et au transport d'ions en solution (Plaisance & Cailleux, 1958) et (2) le lessivage attribué au transport de particules ou colloïdes en suspension (Aubert, 1954; Bocquier, 1971).

La lixiviation peut être relié au processus de latéritisation tel qu'il a été décrit dans le précédent paragraphe, dans la mesure ou les pertes en éléments dissous peuvent être reliées à une nette prédominance des dissolutions par rapport aux recristallisations de minéraux secondaires. Ces dissolutions seraient sélectives et affecteraient d'abord les oxydes de fer puis les kaolinites. Dans les latérites meubles, les pertes de matières associées à une remobilisation du fer sont souvent minimes. Elles ont néanmoins une répercussion importante sur la structuration et perméabilité du sol. En effet, le rôle agrégeant et stabilisant du fer (surtout hématite) sur la fraction fine du sol est reconnu depuis longtemps (Gombeer & D'Hoore, 1971; Van Ranst & De Coninck, 2002). Son exportation est généralement associée à une dissolution sélective des hématites et à un jaunissement du sol (Fritsch *et al.,* 1989; Peterschmitt *et al.,* 1996). Ce processus conduit à la rupture des liaisons fer-argile, à la destruction des agrégats du sol et à la prise en masse des matrices (Chauvel *et al.,* 1977; Fritsch *et al.,* 1989). La dissolution des kaolinites est un processus beaucoup plus lent qui s'opère vraisemblablement sur des temps géologiques (Balan *et al.,* 2005). Un autre processus est parfois invoqué pour expliquer les pertes importantes de minéraux argileux : La ferrolyse (Brinkman, 1970). Ce processus opère en deux grandes étapes: (i) le Fe^{2+} remplace d'abord des cations échangeables des argiles, qui sont lixiviés (phase réductrice), (ii) ce Fe^{2+} est

ensuite oxydé en Fe^{3+} (phase oxydante avec formation d'hydroxydes), et les protons H^+ occupent leur place dans les argiles. Cet environnement acide favorise la dissolution partielle de ces silicates (Brinkman, 1970; Van Breemen, 1985).

Les pertes en éléments fins entraînent une modification du type d'assemblage (de compact à granulaire) propice au développement d'une porosité grossière (Fritsch *et al.,* 1989) et de ce fait au transport de particules fines lors d'écoulements gravitaires (Fritsch *et al.,* 1989; Bravard & Righi 1990; Lucas *et al.,* 1996). Les pertes de matières semblent ainsi se faire en deux étapes. La première étape est attribuée à l'altération ou lixiviation des matériaux (par dissolutions sélectives et détachement des particules). La seconde étape correspond au soutirage ou lessivage des particules fines d'un horizon ou d'un ensemble d'horizons. Ce lessivage peut être mis en évidence soit par des mesures d'éléments en suspension dans les eaux de percolation soit par la reconnaissance de cutanes d'illuviation dans les profils d'altération. Il peut aboutir à l'individualisation de compartiments éluviés (pertes relatives) et illuviés (accumulations absolues) qui peuvent être soit superposés soit distribués latéralement en accord avec des écoulements hydriques latéraux dominants (Bocquier, 1971; Boulet, 1974; Fritsch *et al.,* 1990a; 1990b; Valentin & Fritsch, 1990). Signalons enfin dans certains paysages de savanes, la contribution non négligeable des remontées biologiques de terre et de l'érosion sélective en surface par ruissellement (Fauck, 1972; Fritsch *et al.,* 2007) dans l'appauvrissement des horizons de surface. Ces horizons sableux ne peuvent plus de ce fait contribuer à la reconstruction des profils latéritiques par la base (Lucas *et al.,* 1996).

La contribution respective des processus de lixiviation et de lessivage dans ces pertes de matière reste toutefois délicate à établir. Des tentatives ont été réalisées en utilisant des éléments considérés comme peu mobiles dans les profils d'altération (e.g. Zr, Ti et Th) et en les comparant aux principaux éléments (Fe et Al) présents dans les principales phases minérales de ces sols : oxydes de fer et kaolinites (Lucas *et al.,* 1987, 1996; Bravard & Righi, 1989, 1990). Ainsi une plus grande perte de Fe par rapport à Al et une bonne corrélation de ce dernier élément avec Ti indiquerait une dissolution sélective des oxydes de fer. Par contre, des pertes des trois éléments (Fe, Al et Ti) dans des rapports qui restent constants pris deux à deux indiquerait plutôt un lessivage (Bravard & Righi, 1990).

Les processus de lixiviation et lessivage, impliqués dans la perte en éléments fins peuvent s'observer dans la partie supérieure ou inférieure des profils d'altération, ou encore les deux à la fois. Ils sont identifiés soit en milieu non saturé (dans la partie supérieure de certains profils latéritiques) soit en milieu saturé (dans la partie inférieure de ces profils) et être associés à des

systèmes de nappe. Cela suggère de ce fait que l'hydromorphie prolongée des latérites (ou forte oxydo-réduction) n'est pas forcement une étape préalable à leur appauvrissement.

Les facteurs environnementaux invoqués pour expliquer ces pertes de matières restent encore incertains et parfois contradictoires. Ainsi en régions tropicales à saisons contrastées, elles ont été attribuées principalement à l'ultra-dissecation des sols (Chauvel *et al.,* 1977; Chauvel & Pedro, 1978). Sous conditions de très faible humidité du sol, les films d'eau deviennent polarisés, les taux de dissociation s'élèvent (Mortland, 1968) et les pH aux interfaces s'abaissent (ordre de 2). Ces conditions permettraient alors la mobilisation du fer des sites d'échange des argiles, même en milieu oxydant (Chauvel & Pedro, 1978). En régions tropicales humides, ces pertes de matières ont, à l'inverse, été attribuées à une plus forte hydratation du sol (climats ou pédoclimats plus humides), à des mécanismes d'auto-développement et au vieillissement des latérites (Fritsch *et al.,* 1989, 2005).

2.5. Les sols hydromorphes (Gleysols) et l'oxydo-réduction

Les sols de ces environnements sont associés à des systèmes de nappe. Ce sont des sols intrazonaux et leur distribution relative dans les paysages est de ce fait commandé par le relief et la capacité des nappes à alimenter en eau mais aussi en matériel dissous et particulaire les rivières. En Amazonie, ils occupent de ce fait systématiquement les bas de versants des rebords des plateaux et les plaines alluviales. On les trouve également dans les dépressions de certains plateaux, plus particulièrement dans les nombreuses dépressions anastomosées de la Formation Içá (Fritsch *et al.,* 2007).

Les sols de ces environnements ont généralement des teneurs en argile assez élevées et l'accumulation d'eau va d'une part altéré les flux du cycle du carbone entre lithosphère, biosphère, atmosphère et hydrosphère, et d'autre part favoriser le développement de conditions réductrices propices à la mobilité de certains éléments (en particulier Fe). En milieu saturé et anoxique, la minéralisation réduite des matières organiques va favoriser leur accumulation dans la partie supérieure des sols, ces accumulations de matières organiques pouvant aboutir à la formation d'Histosols en cas de saturation hydrique permanente jusqu'en surface (Fanning & Fanning, 1989). D'autre part, les saturations hydriques temporaires ou permanentes de ces sols sont propices au développement d'une faune microbienne adaptée aux conditions oxydo-réductices qui règnent dans ces sols (Duchaufour, 1982).

En période d'engorgement, le développement de conditions réductrices est propice sous l'action de bactéries à la consommation de l'oxygène de l'eau, puis à la réduction en chaîne de composés minéraux, les plus connus étant les nitrates, les oxydes de Mn, les oxydes de Fe et les sulfates. En milieu tropical où les oxydes de fer sont largement prédominants, cela conduit progressivement au jaunissement et blanchiment des latérites rouges (Fritsch *et al.,* 1989; Peterschmitt *et al.,* 1996). Ce jaunissement et cet éclaircissement des matrices latéritiques constituent très certainement l'un des processus majeurs de la zone intertropicale. Ils ont été reliés à une dissolution préférentielle des hématites, généralement moins substituées en Al, dans le pool des oxydes de fer souvent dominé par la goethite (Jeanroy et al., 1991; Bousserrhine et al., 1999; Torrent *et al.,* 1987; Peterschmitt *et al.,* 1996). Ces dissolutions sélectives sont majoritairement guidées par la taille et les taux de substitution en Al dans les sites octahédriques de ces minéraux. Ils s'expriment de ce fait différemment suivant qu'on se situe dans les altérites ou dans les sols qui les surmontent au sein des profils d'altération.

En période de rabattement des nappes, l'oxygénation temporaire et parfois localisée de ces sols est propice aux re-précipitations des éléments préalablement dissous. Ces re-précipitations de minéraux mal cristallisés (ferrihydrite) ou mieux cristallisés (lepidocrocite, goethite, hématite…) peut dès lors conduire à l'individualisation de taches, de nodules ou concrétions, de raies ferrugineuses ou d'horizons indurés (e.g. plinthites) (Duchaufour, 1982; Fanning & Fanning, 1989; Fritsch *et al.,* 2002, 2007).

Dans les régions tropicales humides, ces re-mobilisations de matières sous l'action des nappes restent limitées puisqu'elles sont essentiellement attribuées à la dissolution des oxydes de fer pris au sens large, et qu'elles préservent les minéraux argileux (kaolinite) généralement très dominant dans les fractions fines de ces sols (Fritsch *et al.,* 2002). Elles aboutissent généralement à la formation de sols à colouration hétérogène en cas d'engorgements provisoires (horizon diagnostique: pseudogleys) ou à des sols entièrement blanchis en cas d'engorgements permanents (horizon diagnostique: gleys) et lorsque les conditions réductrices sont maintenues dans les sols (Fanning & Fanning, 1989). A l'échelle des paysages et comme dans le cas de l'appauvrissement, la redistribution du fer peut aboutir à l'individualisation de compartiments réduits (pertes relatives) et indurés (accumulations absolues) qui peuvent être soit superposés et déconnectés du réseau hydrographique (Fritsch *et al.,* 2002), soit distribués latéralement et reliés au réseau hydrographique (Fritsch *et al.,* 2007). Dans ce dernier cas, des transitions ou structures en "double langue" ont pu être

identifiées entre les compartiments latéritiques les mieux drainés de l'amont et les systèmes hydromorphes aval. De telles structures témoignent d'écoulements hydriques latéraux dominants en accord avec la fluctuation de systèmes de nappe (Fritsch *et al.*, 2007).

2.6. Les podzols hydromorphes et la podzolisation

Comme les Gleysols, les Podzols hydromorphes du bassin amazonien sont associés à des systèmes de nappe. Ils correspondent de ce fait à des sols intrazonaux et leur distribution relative dans les paysages est commandé par le relief et la capacité de ces nappes à exporter les éléments dissous et particulaire aux rivières. Ils occupent sensiblement les mêmes positions topographiques que les Gleysols. Néanmoins et comme nous le soulignons dans cette thèse, la mise place de ces sols nécessite soit des matériaux parentaux à texture sableuse soit des formations latéritiques ayant au préalable perdues une grande partie de leurs constituants fins argileux par appauvrissement. En effet, la migration verticale et latérale des produits de décomposition des matières organiques n'est vraiment efficace que lorsque la porosité du sol devient suffisamment élevée, en dessous d'un seuil de teneur en argile très faible de l'ordre de 2 à 3% (Bravard & Righi, 1989). Dans la mesure où cet appauvrissement des latérites en éléments fins affecte essentiellement les parties déprimées des vastes pénéplaines du bassin amazonien, des podzols d'extension très variable s'observent essentiellement dans les dépressions de ces pénéplaines, qui correspondent de nos jours aux bas plateaux incisés par le réseau hydrographique du fleuve Amazone (Nascimento *et al.*, 2004). Toutefois des podzols, sans doute plus récents, s'observent également sur les incisions (Lucas *et al.*,1988, 1996) et dépôts alluviaux de ce fleuve et de ses tributaires.

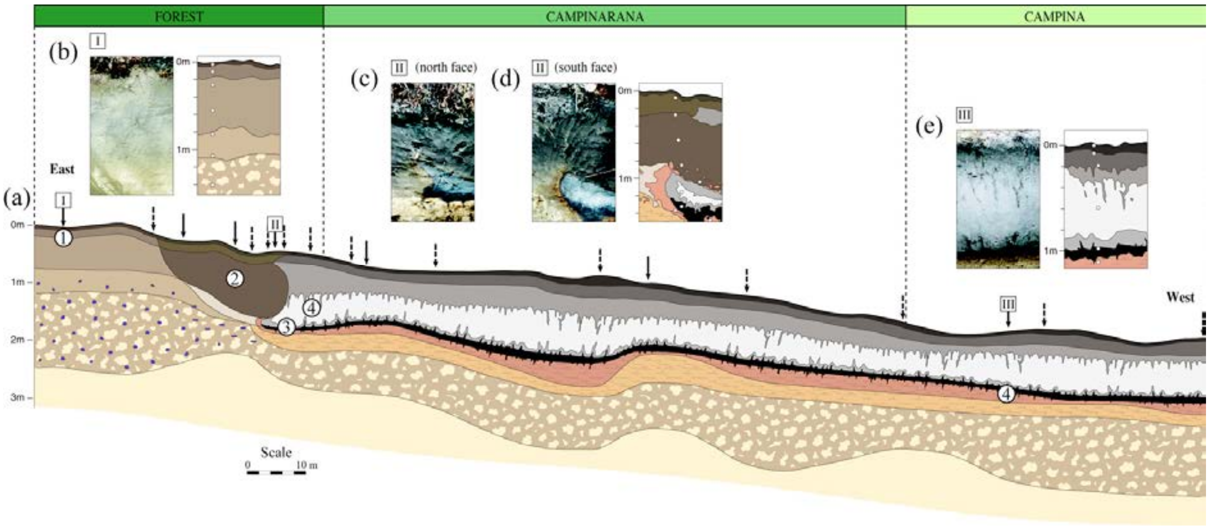


Figure 7*. Séquence de sols étudiée au Jaú (site 3) illustrant la transition latérale entre les latérites (à gauche) et les podzols des dépressions des plateaux (à droite) (d'après Nascimento et al., 2004).*

Dans les dépressions des bas plateaux où les podzols hydromorphes commencent à apparaître (site (3) du Jaú), la caractérisation minéralogique et structurale de séquences ordonnées de sols (Fig. 7) a permis de mieux définir les deux grandes étapes dans la podzolisation des latérites (Nascimento *et al.,* 2004). La première étape marque l'apparition à la bordure de la dépression de podzols faiblement différenciés (ou sols crypto-podzoliques). Ces podzols comprennent des horizons humifères A de type Mor surmontant des horizons spodiques, peu différenciés de type Bhs. La matière organique imprègne de ce fait profondément (sur plus d'1m) les latérites jaunes, appauvries de la bordure de ces dépressions, qui contiennent essentiellement du quartz mais aussi des minéraux argileux résiduels (kaolinite, gibbsite et goethite). Ces substances organiques assurent l'altération de ces minéraux argileux et contribuent à la formation et au transfert vertical de complexes organo-métalliques (principalement à base de Al mais aussi de Fe). La deuxième étape marque la quasi-disparition de ces minéraux argileux dans les horizons AE et E de podzols mieux différenciés et l'accumulation à plus grande profondeur d'une seconde génération de complexes organiques dans les deux horizons spodiques de ces podzols (Bh et Bs). Une étude hydrodynamique et géochimique le long de ces différentiations pédologiques a montré que la seconde étape était étroitement liée au développement de conditions réductrices et acides au sein d'une nappe perchée qui alimente en saisons pluvieuses les ruisseaux à l'aval des dépressions (Nascimento *et al.,* 2008).

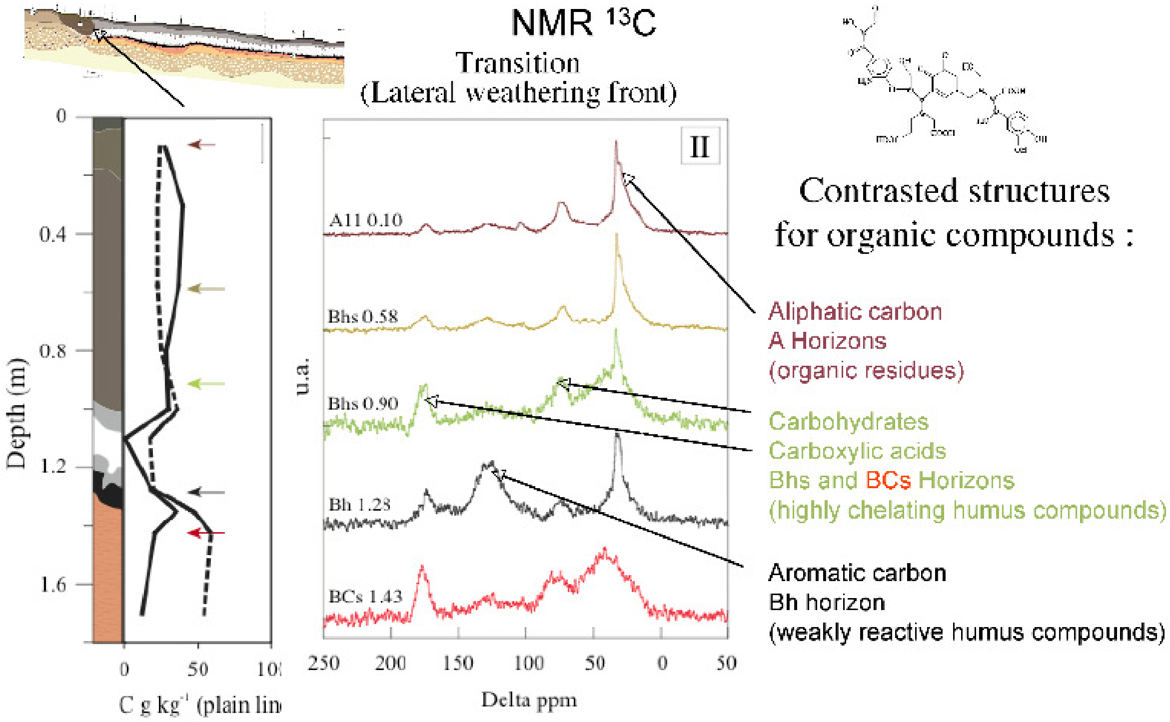


Figure 8*. Spectres RMN des matières organiques dans les horizons éluviés (A) et illuviés (Bhs, BCs et Bh) des podzols à la bordure de la dépression de la séquence du Jaú (d'après Bardy et al., 2008).*

La caractérisation microscopique et spectroscopique (RMN) des matières organiques de ces podzols a par ailleurs révélé des groupements fonctionnels dont l'abondance relative variait de façon significative suivant la nature des principaux composés organiques reconnus dans les horizons identifiés le long d'une séquence de sols (Fig. 8) (Bardy *et al.*, 2008). Ainsi les horizons de surface, éluviés, des podzols (A et AE) à nombreux résidus végétaux présentent essentiellement des groupements aliphatiques sur spectres RMN. Des matières organiques très fines formant des revêtements bruns dans les horizons spodiques Bhs des podzols faiblement différenciés, mais aussi plus en profondeur dans les horizons Bs de podzols mieux différenciés, sont caractérisés essentiellement par des groupements carboxyliques, dont l'aptitude à complexer les métaux est unanimement reconnue. Enfin, les revêtements organiques noirs et plus grossiers qui colmatent la base des horizons sableux de ces podzols et forment des horizons Bh sont essentiellement caractérisés par des groupements aromatiques. Les matières organiques qui alimentent les eaux noires des podzols en colloïdes organiques (Allard *et al.*, 2004, Fritsch *et al.*, 2009) s'observent sous forme de « boulettes », dispersées et peu abondantes dans les horizons de surface et en remplissage entre les quartz ou en

revêtements sur ces derniers dans les horizons Bh (Bardy *et al.,* 2008). Ces différenciations verticales témoignent ainsi d'un fractionnement physique des matières organiques lors de leur migration verticale dans les profiles d'altération. Les éléments les plus fins migrent plus en profondeur ou à la périphérie des aires podzoliques dans des horizons moins poreux (horizons Bhs et Bs) et les plus grossiers tapissent la bordure des réservoirs sableux de ces podzols (horizons Bh) (Duchaufour, 1972). L'aptitude de ces matières à complexer les métaux a été révélée dans un premier temps par des attaques chimiques sélectives (Nascimento *et al.,* 2004). Elle a été ultérieurement confirmée par des approches spectroscopiques à la fois pour l'aluminium qui est abondamment complexé aux matières organiques dans ces environnements (Bardy *et al.,* 2007) et pour le fer qui l'est beaucoup moins du faite des conditions réductrices qui prévalents dans ces podzols hydromorphes (Fritsch *et al.,* 2009). Ces travaux ont également montré qu'au fractionnement physique des substances organiques dans ces podzols pouvait être relié une séparation des formes complexées de l'aluminium et de celles du fer, les complexes alumineux s'accumulant plus en profondeur (Bs) ou plus à la périphérie dans les organisations latéritiques encaissantes (Bhs) que les complexes ferriques qui tapissent la bordure des réservoirs sableux (Bh). L'ensemble de ces travaux montre également que le développement de conditions très acides ($pH < 3.5$) dans les réservoirs sableux de ces podzols est propice à la remobilisation des métaux, principalement de l'aluminium, en accord avec les travaux de Jansen et al. (2003). Ces podzols seraient de ce fait des pièges à métaux dans les fronts latéraux de podzolisation et à l'inverse une source de métaux pour les rivières, à proximité des incisions qui drainent les dépressions de ces podzols (Allard et al., 2004; Benedetti *et al.,* 2003a, 2003b; Nascimento *et al.,* 2004; Bardy *et al.,* 2007; Fritsch *et al.,* 2009).

L'étude de la dynamique et composition chimique des nappes qui drainent ces associations de sols montre par ailleurs que la recharge rapide de la nappe perchée dans les réservoirs sableux de ces podzols est susceptible de créer des gradients de charge inverses à la topographie des dépressions et de contribuer ainsi à la recharge de la nappe phréatique profonde des latérites, à la bordure des aires podzolisées (Nascimento *et al.,* 2008). La mobilisation des éléments chimiques a lieu essentiellement à l'amont, dans le nappe phréatique des latérites (pour Fe), mais aussi dans les fronts de podzolisation lors de la recharge de la nappe perchée (à la fois pour Fe et Al) (Fig. 9). Cette nappe, chargée en matière organique dissoute et colloïdale, est donc susceptible de contribuer à la formation des complexes organiques, puis à leur accumulation dans les organisations périphériques, encaissantes lors du rabattement de cette

nappe. La forte baisse des teneurs en silice dissoute et en métaux (Fe et Al) dans la nappe perchée des horizons sableux des podzols (Fig. 9) témoigne enfin d'un temps de résidence court des eaux noires qui drainent les aires podzoliques (Bravard & Righi, 1989; Lucas *et al.*, 1996; Patel-Sorrentino *et al.*, 2007).

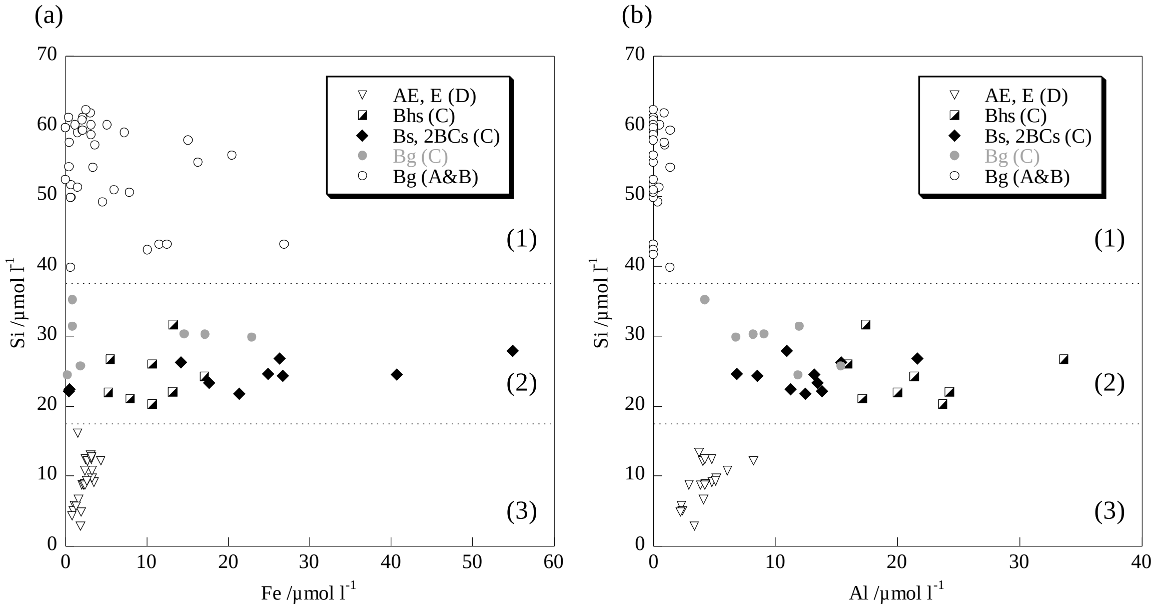


Figure 9*. Composition géochimique des eaux (Si, Al, Fe) dans les trois compartiments majeurs de la séquence du Jau : (1) à l'amont dans la nappe phréatique des latérites, (2) dans les fronts latéraux de podzolisation et (3) dans la nappe perchée des podzols de l'aval.*

Figure 10*. Front latéral de podzolisation en forme de double langue dans la séquence du Curicuriari (site 4): Latérites jaunes appauvris (à gauche) et podzols évolués (à droite).*

Les structures pédologiques mise en place dans les dépressions de ces plateaux reflètent dès lors la dynamique évolutive de ces systèmes. Les travaux entrepris par Nascimento et al. (2004) au Jaú et ceux que nous avons entrepris à São Gabriel da Cachoeira montrent que le développement vertical des podzols est arrêté dès qu'une discontinuité texturale ou structurale est rencontrée (une dalle rocheuse ou une altérite). Ces podzols ne peuvent donc plus se développer que latéralement, ce qui aboutit par soutirage à un agrandissement de la taille des dépressions. Latéralement, la transition entre latérite et podzols présente une forme en "double langue" qui a systématiquement été observée dans le haut bassin amazonien (Fig. 10). Cette structure peut être reliée à la dynamique des nappes perchées de ces podzols (Nascimento *et al.,* 2008). La langue inférieure est attribuée aux périodes de rabattement des nappes et plus particulièrement au soutirage généré par les écoulements latéraux de la nappe phréatique amont des latérites dans les systèmes podzoliques. La langue supérieure est associée aux fluctuations de la nappe perchée au voisinage de la surface topographique et à la bordure des aires podzoliques lors d'épisodes particulièrement pluvieux en saisons humides.

2.7. Processus d'altération et d'érosion, relations avec la morphogenèse

Deux grands types de processus peuvent être invoqués pour expliquer l'évolution des modelés sur les surfaces continentales: (i) des processus érosifs associés aux écoulements superficiels et aux transports de matières en surface (ruissellement en nappe ou concentré avec décapage ou incision des versants et dépôts dans les zones planes aval), et (ii) des processus érosifs associés à l'altération, aux écoulements internes et au transport d'éléments en solution (lixiviation) ou au transfert de particules en suspension dans les horizons poreux du sol (lessivage ou éluviation). Les premiers processus (érosion essentiellement physique) ont généralement été privilégiés dans de nombreuses études géomorphologiques au détriment des seconds (érosion principalement chimique) pour expliquer la mise en place des paysages. En particulier des épisodes d'érosion physique intense en climats secs seraient propices à la mise en place de surfaces d'aplanissement ou de pénéplaines (King, 1953). Ces surfaces pourraient être ultérieurement incisées en période plus humides et par abaissement des niveaux de base locaux, aboutissant ainsi à des inversions de relief. En particulier et comme cela semble être le cas pour le bassin amazonien, des plateaux pourraient ainsi résulter de l'incision d'immenses surfaces d'érosion et de sédimentation, marquant ainsi d'anciennes positions basses du bassin.

D'autres travaux ont néanmoins montré que l'érosion chimique des couvertures d'altération par soutirage interne (véritable fonte géochimique) et exportation au réseau hydrographique de matières en solution et ou en suspension pouvaient former des dépressions en surface (dolines en milieu karstique), des décrochements sur les versants et également de vastes zones déprimées ou plaines dans les paysages (Trescases, 1975; Millot, 1983; Lucas *et al*., 1988; Dubroeucq & Volkoff, 1998). Dans les régions arides d'Afrique de l'Ouest, des processus d'éluviation (pertes) et d'illuviation (gains), associés à des systèmes de nappe, se relayent latéralement sur de vastes zones aplanies (Bocquier, 1971; Boulet, 1974). Comme nous le verrons par la suite dans ce mémoire, il sera parfois difficile de déterminer l'origine de certaines facettes des paysages du bassin amazonien (e.g. dépressions et vastes chenaux anastomosés des bas plateaux). Ces facettes pourront soit marquer d'anciennes structures sédimentaires (chenaux fluvio-lacustres) soit résulter d'une véritable fonte géochimique des latérites avec comme stade ultime l'individualisation de podzols dans les zones déprimées des paysages, soit encore résulter d'une combinaison de ces deux types de processus (a "t*wo stage process*", e.g. Wayland, 1934; Linton, 1955; Budel, 1957; Planchon et al.,1987).

CAPITULO 3. O EMPOBRECIMENTO DOS SOLOS LATERÍTICOS: UMA ETAPA PRÉVIA À PODZOLIZAÇÃO

Résumé

Le chapitre traite de l'appauvrissement des latérites comme étape préalable à la podzolisation. Cette étude a été réalisée dans la région de São Gabriel da Cachoeira à la bordure des aires fortement podzolisées du bassin versant du Curicuriari. Cinq profils latéritiques ont été sélectionnés depuis la bordure d'un plateau disséqué vers la partie centrale d'une dépression à podzols hydromorphes. Sur un transect de 1,6 km de long, les cinq profils (P1 à P5) illustrent les pertes graduelles en minéraux argileux qui s'observent essentiellement dans la partie supérieure des profils d'altération. Le profil P5 est situé 5m en amont de la dépression à podzols. Des caractérisations pétrographiques, minéralogiques (DRX, IRTF et DRS) et géochimiques, elles-mêmes couplées à des calculs des fonctions de transfert (éléments majeurs et en trace), ont permis de révéler les principales étapes dans la perte sélective de matières et la différenciation verticale et latérale des profils latéritiques.

Les profils d'altération, développés sur des granites à corps mafiques de la formation Uaupés, appartiennent à la surface d'aplanissement *Ucayali*. La latéritisation a généré une exportation totale des bases et partielle de la silice à la base de ces profils d'altération, et à une accumulation résiduelle du fer et de l'aluminium dans les principaux minéraux secondaires de

ces sols (kaolinite, gibbsite, hématite et goethite). La gibbsite, généralement présente en faibles quantités au sein de ces profils, est toutefois très abondante dans le profil sommital le plus rouge (P1), probablement due aux excellentes conditions de drainage régnant dans cette partie du paysage. Une altération plus ménagée des minéraux métamorphiques ou corps mafiques (illite, épidote, biotite, titanite, apatite, allanite, magnetite) dans les saprolites permet de différencier le manteau d'altération de l'épaisse couverture de sols (2.3 m) qui le surmonte.

Les différentiations latérales très progressives et l'absence de structures lithologiques d'origine sédimentaire sont en faveur d'une perte de matière par érosion interne des couvertures d'altération (lixiviation et lessivage). Ces différenciations latérales, qui affectent séparément le compartiment sol et le manteau d'altération, se rejoignent à l'aval (P5). Dans les sols, un net jaunissement, associé à des pertes ménagées de matières, est tout d'abord observé de P1 à P2. Cette première étape dans la différenciation latérale de ces sols est attribuée à une dissolution sélective des hématites dans le pool des oxydes de fer. Elle traduit une plus grande hydratation des matériaux et de ce fait un pédoclimat plus humide. Une perte très progressive de minéraux fins argileux, associée au développement d'une porosité d'assemblage inter-quartz, est ensuite constatée entre P2 et P5. L'absence de revêtements argileux et des pertes de matières à rapport Al/Fe sensiblement constant d'un profil à l'autre suggèrent une altération conjointe des kaolinites et oxydes de fer (essentiellement de goethite) lors de la fonte géochimique. Un léger accroissement du rapport Al/Fe de la base vers le sommet de ces sols suggère néanmoins une plus grande dissolution de goethites. Dans le manteau d'altération, des pertes brutales en fer sans variations texturales majeures et ordonnées le long de la séquence (nette accroissement du rapport Al/Fe) sont reliées au blanchiment d'altérites rouges sous l'action d'une nappe phréatique. Ce blanchiment et ces pertes en fer sont localisés à l'amont (P2 et P3) et généralisés à l'aval (P4 et P5). Enfin, la partie supérieure blanchie du réservoir de nappe s'appauvrit brutalement à l'aval de ce transect (P5). Les pertes ultimes d'éléments fines dans ce réservoir affectent également les éléments en trace (Zr), témoignant de ce faite de transport particulaire (zircon) en milieu saturé.

En conclusion, cette étude montre que les pertes de matières s'expriment différemment suivant qu'on se situe au voisinage de la surface dans les sols en milieu non-saturé, mais à hydratation saisonnière croissante vers l'aval, ou plus en profondeur en milieu saturé dans le manteau d'altération. Ainsi, des processus lents de dissolution sélective et de lixiviation prédominent dans les sols. A l'inverse dans le manteau d'altération, les pertes de fer puis de

minéraux argileux sont brutales et nettement dissociées latéralement dans le réservoir de la nappe phréatique. Lorsque le milieu devient suffisamment poreux, les pertes ultimes d'éléments fins lors d'écoulements latéraux de nappe pourraient en grande partie se faire sous forme particulaire. Les pertes de matières en surface et en profondeur aboutissent à l'individualisation en bordure des dépressions d'un compartiment sableux dont la transition latérale présente une forme caractéristique en "double langue". Comme nous le verrons dans le second article, cette nouvelle structure sera exploitée ultérieurement par la podzolisation. L'étude souligne également que les re-mobilisations de matières attribuées à une ultime évolution podzolisante resteront minimes par rapport à celles résultantes d'un appauvrissement préalable des latérites.

3.1. Introduction

The weathering of rocks in tropical regions leads to the intense leaching of base cations and silica. In high elevated and freely drained environments of the landscapes, this kind of weathering, also known as lateritisation (Kronberg & Melfi, 1987; Fanning & Fanning, 1989), leads to the residual accumulation of the less mobile Al and Fe in secondary minerals, predominantly kaolinite, Al- and Fe-oxides (mainly gibbsite, hematite and goethite), and the formation of thick clayey regoliths comprising both soils and saprolites (Ségalen, 1966; Nahon, 1991; Tardy, 1993; Fritsch et al., 2002).

Weathering of granitic rock basements may also lead to the residual accumulation of metallic trace elements (MTE) such as Zr, Ti and Th, which are frequently used as invariants in the assessment of losses or gains of more mobile chemical elements (Brimhall *et al.*, 1991; Braun et al., 1993). The commonly weak mobility of Zr in regoliths derived from granites is mainly due to its incorporation in zircon, a highly resistant primary mineral to chemical weathering with dominant silt and fine sand particle sizes (Braun et al., 1993; 2005; Balan *et al.*, 2001; Maurin, 2005; Taboada et al., 2006). The mobility of Ti and Th is also low in lateritic soils as they are incorporated in stable secondary minerals of smaller particle sizes (mostly anatase and thorianite) (Fritsch et al., 2005). However, the mobility of both MTE may be enhanced at depth in saprolites, depending on the nature of the parent host minerals. In particular, the weathering of titanite, rutile and ilmenite into anatase (Middelburg et al., 1988; Cornu et al., 1999) may contribute to significant losses of Ti.

The upward accumulation of clay minerals in loose laterites has been related to major crystallographic changes in kaolinites and Fe-oxides. In particular, the gradual transition from saprolite to soil is mostly due to decreasing size and increasing disorder of kaolinites (Balan et al., 2005). The upward yellowing of red laterites has been related to increasing proportion of goethite and Al substitution rates in the pool of Fe-oxides (i.e. in both hematite and goethite) (Fritsch et al., 2005). Such crystallographic trends illustrate changing weathering conditions in soil horizons that have been attributed to soil aging and longer wetting periods in the upper part of the soils. They also reveal cyclic dissolution and crystallization reactions that concern both kinds of minerals (i.e. kaolinites and Fe-oxides). These mechanisms increase the specific area and reactivity of the soil minerals and favor the aggregation of the soils. However, the upward yellowing of soils has also been related to clay depletion and soil structure breakdown (Fritsch et al., 1989; 2005).

In the Rio Negro watershed of the upper Amazon Basin, lateritic soils are widely and closely associated with waterlogged Podzols. Red clayey lateritic soils (Ferralsols) are commonly found at the margin of strongly dissected low elevation plateaus that belong to the pan American *Ucayali* peneplain (Campbell et al., 2006). By contrast, podzols are commonly found in poorly drained depressions of the central parts of the plateaus. Podzol formation results from the downward and downslope migration of organic acids (Pedro, 1987) in highly porous sandy materials during the lowering of perched groundwaters (Bravard and Righi, 1990; Nascimento et al., 2004). The accumulation of the organic acids at the periphery of the podzolic areas enables to sustain the perched groundwater. It also promotes the weathering of clay minerals and the formation of organo-metallic complexes (Lundström et al., 2000, Nascimento et al., 2004). Accordingly, the dominant Al and Fe previously incorporated in mineral phases of the lateritic environments become predominantly bound to organic matter in waterlogged podzols (Bardy et al., 2007; Fritsch et al., 2009). The high porosity of the sandy horizons of podzols explains the short residence time of water (Nascimento et al., 2008) and fast lateral fluxes in perched groundwater (Lucas et al., 1996) that enhanced the lixiviation and acidification of the soils. In these highly reduced, acidic and organic-rich environments, the heavy minerals such as Ti-oxides and zircon may be partly dissolved, and the metal cations released in solutions be exported in black surface waters (Colin et al., 1993; Oliva et al., 1999; Braun et al., 2005). The interstices managed by the quartz sands of these podzols may also promote the physical transport in perched groundwater of clay and silt size

particles, comprising therefore kaolinite, thorianite, Ti-oxides and to some extent zircon (Nascimento et al., 2004).

Red clayey laterites (Ferralsols) and waterlogged podzols belong to two end-members of soil catena on the low elevation plateaus of the Rio Negro watershed. A transition zone between these two end-members comprises yellow clay-depleted laterites (Acrisols) that can extend on several hundred meters on the plateaus. Soil catena studies have shown that podzolic areas can increase in size and form at the expenses of their surrounding clay-depleted laterites (Turenne, 1977; Chauvel et al., 1978; Lucas et al., 1987; Bravard and Righi, 1990; Nascimento et al., 2004). This kind of soil dynamics then suggests that yellowish clay-depleted laterites could in the same manner be formed laterally from better-drained laterites exhibiting heavier texture and redder colours. Pre-existing weathering processes associated with drastic colorimeric and textural changes seem therefore necessary to form waterlogged podzols on the plateaus. Such processes that enhance the chemical and physical erosion of laterites still remain poorly understood. Moreover, the hydraulic regime contributing to greater erosion and the compartments of the regoliths where they are acting need to be better defined. On this regards, Bravard and Righi (1990) and Nascimernto et al. (2004) point out that tropical podzols commonly form in poorly drained areas. This suggests that reducing conditions that promote yellowing and bleaching in laterites (Chauvel et al., 1977; Peterschmitt et al., 1996) could be one of the major soil change processes promoting the formation of podzols, the second one being associated to clay depletion. Fe could therefore be mobilized before Al in the transition zone between red clayey laterites and waterlogged podzols. At least, the removal and the transfer of matters that play a major role in the vertical and lateral differentiation of regoliths (Simonson, 1959), may be assigned to two major mechanisms (Fanning & Fanning, 1989): (i) solution transport (lixiviation or chemical erosion) and (ii) particulate or suspension transport (eluviation or mechanical erosion). Solution transport and redistribution of major and trace elements by chemical erosion are mostly controlled by hydrological regimes and weathering conditions (e.g. Eh, pH) (Van der Weijden and Van der Weijden, 1995; Grybos et al., 2007). Particulate transport depends on pore size, dispersion/flocculation properties and the existence of hydraulic gradients (Soil Survey Staff, 1975). This suggests that chemical erosion and solution transport might prevail in the transition zone, whereas particulate transport could be also involved close to the podzolic areas due to greater development in soil matrix of macro-voids between adjacent quartz grains.

Structural, geochemical and mineralogical (XRD, FTIR et DRS) investigations were performed in five profiles (P1 to P5), located along a 1.6km long transect from the margin of a dissected plateau to the border of a huge depression containing waterlogged Podzols. The profiles illustrate vertical and lateral differentiations associated with the formation of reddish clayey laterites (Ferralsols) at the margin of the plateau and their lateral transformation into yellowish clay depleted laterites (Acrisols) towards the depression. Lateral differentiations in the field are mostly assigned to colorimeric and textural changes in both soils and saprolites The aims of this work are to reveal (i) the sequence of major weathering processes that generates losses of clay minerals and therefore promote the podzolisation of lateritic landscapes, (ii) the general hydric regimes that enhanced the chemical and physical erosion of the regoliths and (iii) the places in the landscapes where these weathering processes and hydraulic regimes are acting.

3.2. Environmental setting

The transect with its five profiles is located near São Gabriel da Cachoeira (0^o 15’ 50”S; 67^o 03’ 10”W) in the upper Negro River watershed (see star in Fig. 1). It belongs to the *Ucayali* peneplain, formed during an intense erosion phase of the mid Miocene (Campbell et al., 2006) that corresponds nowadays to the low elevation and dissected plateaus of the upper Amazon basin (about 90m above mean sea level, or 15m above mean river level at São Gabriel da Cachoeira). This transect is also located at the margin of a huge podzolised and inundated peneplain that covers 95% of the Curicuriari subcatchment in the West.

The vegetation of the region is in agreement with the soil distribution. The evergreen Amazonian forest covers the lateritic soils of the plateaus (*Terra Firme*), whereas a lower and more open forest with thin tree trunks (*Caatinga*) is growing on the hydromorphic Podzols of the depressions and peneplains (Silva et al., 1977). The mean annual temperature in that region is 25^oC and the rainfall is about 3000 mm per year with two maxima, on January (289 mm) and April (339 mm), and two minima, on February (282 mm) and August (124 mm) (Costa et al., 1977).

Soils in the region of São Gabriel da Cachoeira are formed on (titanite)-(amphibole)-biotite-granites and gneisses, with similar composition, of the western part of the Guyana Shield. They yielded 1518 +/- 25 Ma age by the ID TIMS U/Pb (zircon) method (Santos et al., 2000)

and younger thermotectonic event, related to Grenville orogeny, has been affect these granites at 1200 +/- 100 Ma (K'Mudku episode).

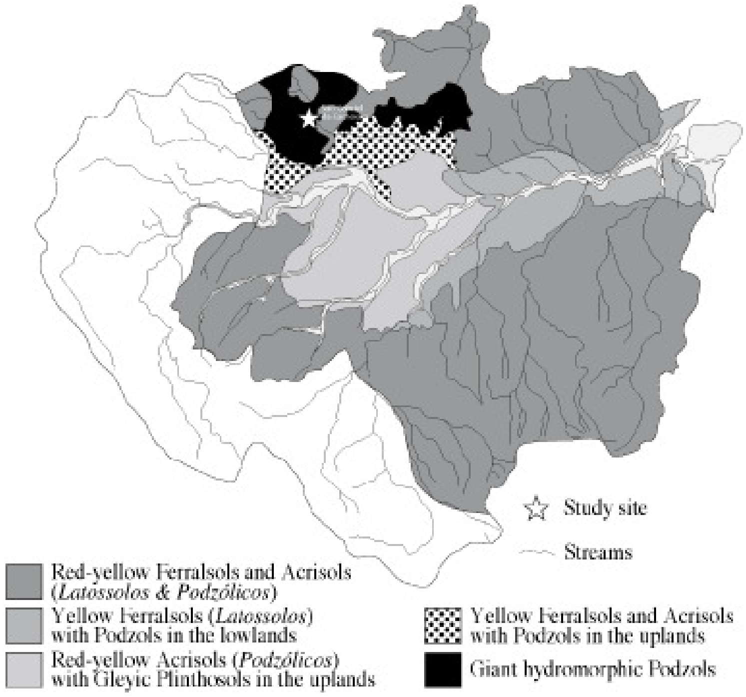


***Figure 1**. Broad scale soil map of the Brazilian Amazon basin (reduced and simplified from RadamBrazil maps at 1:2.500.000) showing the site location (star) at the margin of a highly podzolised region of the Rio Negro watershed.*

Granitoid rocks of the region comprise mafic-bearing granitic bodies locally sheared and mineralized and are crosscut by pegmatite or quartz veins (Fernandes et al., 1977, CPRM, 2006). Two major structural lineaments were recognized in that region: a dominant NE-SW to ENE-WSW lineament and a secondary NW-SE one. In the low course of Curicuriari River, the rock basement belongs to two granitic suites: (i) the syenogranites to alkali-feldspar granites of the Curicuriari Suite and (ii) the monzogranites to quartz-monzonites of the Uaupés Suite (Almeida, 2005, CPRM, 2006). Profiles of the transect have formed on the quartz-monzonite and monzogranite of the Uaupés Suite that contain less quartz (15%) and alkali-feldspar (30%) than that of the Curicuriari Suite (42 and 50%, respectively) and much more plagioclase (44% versus 5%) and mafic minerals (11% versus 3%).

Table 1 : Analytical data from electron microprobe analyses (wt% oxides) of major minerals identified in the granite

Minéral	SiO_2	Al_2O_3	FeO	K_2O	Na_2O	CaO	MgO	MnO	TiO_2	P_2O_5	La_2O_3	Ce_2O_3	ZrO_2	LOI	Total
Microcline	64.62	18.63	0.14	15.99	0.49	-	-	-	-	-	-	-	-		100.4
(σ, n=10)	(0.45)	(0.14)	(0.06)	(0.26)	(0.13)	-	-	-	-	-	-	-	-		
Anorthite	60.83	25.34	0.10	0.10	7.76	6.46	-	-	-	-	-	-	-		100,6
(σ, n=10)	(0.89)	(0.52)	(0.11)	(0.03)	(0.28)	(0.60)	-	-	-	-	-	-	-		
Albite	66.29	21.21	0.27	0.17	9.93	1.82	-	-	-	-	-	-	-		99,7
(σ, n=15)	(2.23)	(1.44)	(0.29)	(0.19)	(0.85)	(0.60)			-	-	-	-	-		
Biotite	39.13	16.52	20.04	9.16	-	-	8.61	0.59	1.61	-	-	-	-		95.7
(σ, n=15)	(2.00)	(0.37)	(1.13)	(0.31)	-	-	(0.81)	(0.08)	(0.20)	-	-	-	-		
Amphibole	41.97	9.98	21.07	1.32	1.17	11.28	7.88	0.93	0.80	-	-	-	-		96.5
(σ, n=15)	(0.41)	(0.05)	(0.26)	(0.02)	(0.03)	(0.16)	(0.28)	(0.05)	(0.09)	-	-	-	-		
Titanite	30.34	2.15	1.73	-	-	26.88	-	0.18	34.80	-	-	-	-		96.1
(σ, n=15)	(0.39)	(0.21)	(0.48)	-	-	(1.19)	-	(0.05)	(0.65)	-	-	-	-		
Apatite	0.47	-	0.10	-	-	54.19	-	0.08	-	40.88	0.18	0.39	-		96.3
(σ, n=15)	(0.20)	-	(0.10)		-	(0.50)	-	(0.03)	-	(1.20)	(0.10)	(0.18)	-		
Allanite	31.13	13.79	14.51	0.07	0.31	11.42	0.25	0.54	1.02	0.10	4.54	8.16	-		86.0
(σ, n=15)	(1.07)	(0.81)	(1.99)	(0.03)	(0.13)	(1.19)	(0.07)	(0.12)	(0.39)	(0.06)	(0.73)	(0.65)	-		
Garnet	38.05	23.32	11.95	0.09	-	22.33	0.11	0.48	0.10	-	0.03	0.08	-		96.7
(σ, n=15)	0.65)	(0.28)	(0.29)	(0.12)	-	(0.43)	(0.14)	(0.02)	(0.01)	-	(0.01)	(0.04)	-		

In the bedrock of the profiles, the alkali-feldspar corresponds to perthitic microcline with Tartan type twinning, which locally encloses quartz and plagioclases inclusions. The plagioclase show two generations and common polysynthetic twinning. Indeed, phenocrystals of plagioclase (2nd generation), highly saussuritized, exhibit sericite, epidote and smaller plagioclase inclusions (1st generation). The centrimetric mafic clots, which give to the rock its characteristic speckled aspect, mostly consist of biotite and amphibole (8%) and accessory minerals, such as apatite, allanite, zircon and opaque minerals (mostly magnetite and also locally pyrite) commonly surrounded by titanite. Allanite crystals are locally surrounding epidote and often aggregated with titanites. When apatite and allanite crystals appear as inclusions within biotite crystals, they often display a thin fringe of radiation-induced defects in the phyllosilicate (pleocroic haloes). The crystal chemistry of most of the major and accessory minerals on thin sections is given in table 1. It has permitted to identify the main mineral carriers for trace elements in rocks, saprolites and soils (e.g. mostly titanite and rutile for Ti, apatite for P and Ca, allanite for light rare earth element (La, Ce) and zircon for Zr).

3.3. Materials and methods

Soil survey, soil description and sampling

We used 2005 Ikonos satellite images to map the main geomorphologic and pedological units at the transition between the huge podzolized and waterlogged peneplain of the Curicuriari watershed and their lateritic counterpart at the border of the Guianense shield, in the western part of the watershed (Fig. 2a). Field surveys under forest were carried out in selected areas to

control map unit demarcations and to obtain precise topographic data using Topcon Hiper GPSs with a pair of Paulin Altimeters. Satellite images together with topographic GPS and altimeter data allowed building up a block-diagram for the investigation region using 3D design softwares (black insert in Fig. 2a and Fig. 2b). The site selected for this study belongs to the *Ucayali* Peneplain (Campbell et al., 2006) at the margin of the low elevated lateritic plateaus, just before reaching the huge podzolic and inundated peneplain of the region. It corresponds to a 1.6 km long transect on the edge of an incised plateau. The transect starts on the right bank of the Curicuriari river with red clayey laterites and ends up 5m before reaching the margin of a large podzolized depression (white dashed line in Fig. 2a,b). Along the transect, topographic survey was made at 7 m intervals and 27 soil augerings allowed the selection of 5 pits (from P1 to P5 in Fig. 2c) for soil sampling and investigations. Soil pits are located on hill-top positions at a water divide in the dissected plateau to minimize the contribution of colluvial deposits. Soil description was done according to ISRIC-FAO (1994). 121 samples from the 5 pits and 4 samples from rock outcrops were collected for chemical, physical and mineralogical investigation. 32 undisturbed samples of rocks, saprolites and soil horizons were also collected in cardboard boxes. They were impregnated with resin, cut and grounded for the elaboration of thin sections. The latter were observed under plain-polarized light (PPL) and cross-polarized light (CPL) using a microscope.

Chemical and physical analyses

Air-dried soil samples were sieved through a 2-mm screen. Particle-size distribution was determined by sieving (sand fractions) and pipetting (clay and silt fractions) after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. pH was measured both in water and in 1 M KCL (soil:solution; 1:2.5). Organic C and N contents were determined using a Carmograph LECO CHN analyser. Total chemical composition was performed on pulverized samples (150 mesh) at Actlabs Ltd (Canada); major elements by inductively coupled plasma atomic emission spectrometry, and trace elements by inductively coupled plasma atomic mass spectrometry.

Electron Punctual Microprobe Analyses (EPMA) were carried out on thin sections to determine the chemical composition of parent material minerals using a CAMECA SX50 equipped with four Wavelength Dispersive Spectrometers (WDS) and operating at 15 kV and 30 nA at the Centre d’Analyse des Minéraux de PARIS (CAMPARIS, Université Pierre et Marie Curie, Paris, France).

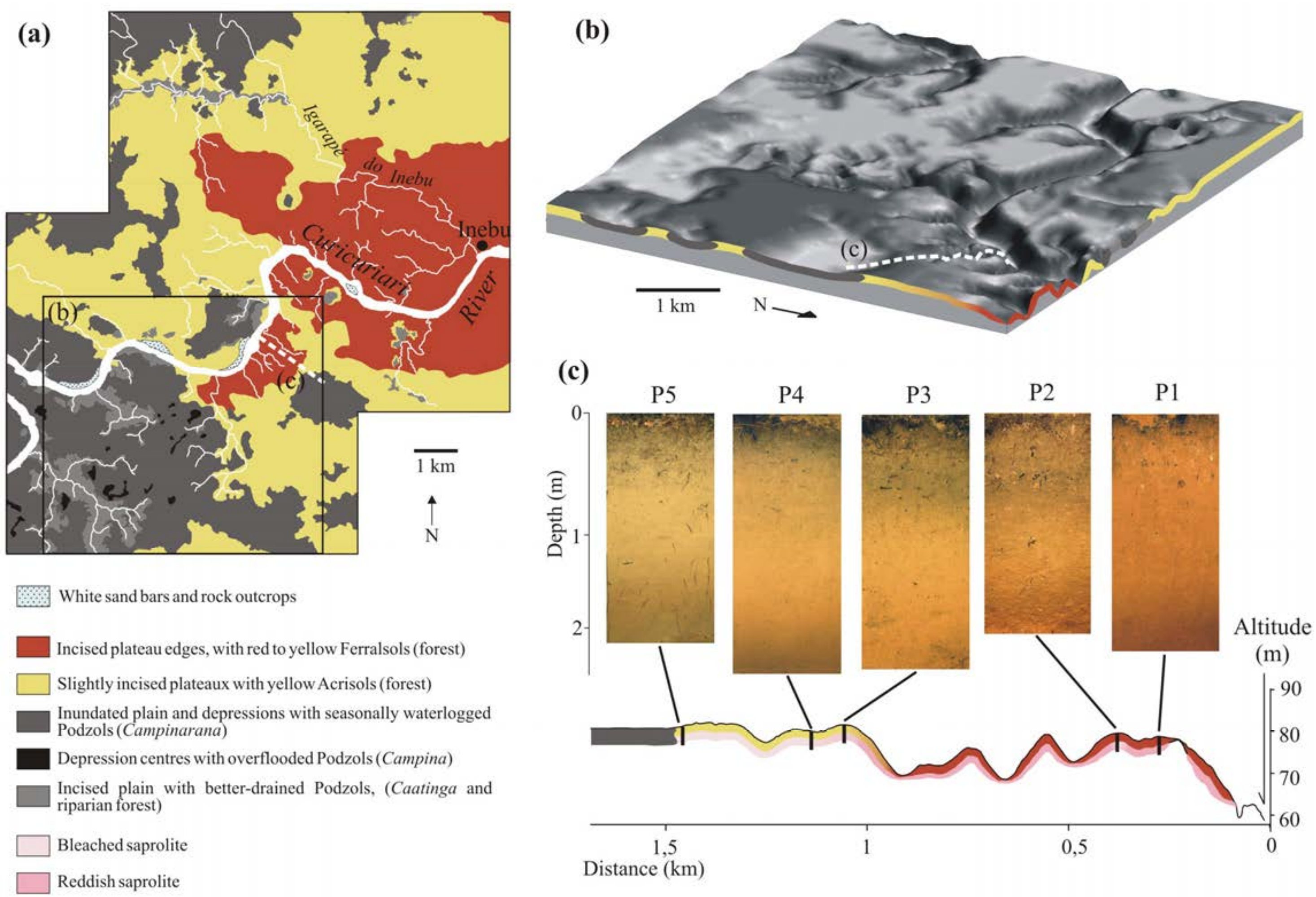


***Figure 2**: (a) Regional map of major soil landform units with their vegetation in the lower course of the Curicuriari watershed at the transition between podzols and laterites, which also shows the localisation of the transect (white dashed line), (b) 3D representation of the same area (see black rectangle insert in (a) for location of the selected zone), (c) soil transect with the position of the five selected profiles (from P1 to P5) and photographs of their upper parts (soils).*

Total chemical analyses and the mass-balance approach (Brimhall et al., 1991, Chadwick et al., 1990) were used to assess the relative losses or gains of chemical elements in the 5 profiles as compared to their underlying bedrock. This approach requires the selection of a chemical element, considered as immobile during weathering processes. In our investigation site, the element used as an invariant (suffix *i*) to assess the mobility of other elements (suffix *j*) in saprolites and soils is Zr. Indeed, Zr is present in zircon in the granitic rocks and their overlying weathered products, i.e. in an accessory mineral known for its high resistance to chemical weathering. The iso-element approach of Brimhall et al. (1991) requires the selection of a protore (suffix *p*), considered as chemically homogeneous and representative of the parent material for the overlying weathered (suffix *w*) saprolite and soil layers (average of the four rock samples). The relative loss or gain of a chemical element (*j*) in the investigated profiles were then determined from the mass balance factor ($_{j,w}$) according to the following equation (Chadwick et al., 1990):

$$_{j,w} = \frac{C_{j,w}/C_{i,w}}{C_{j,p}/C_{i,p}} - 1$$

In this equation, the mass balance factor is expressed independently of the volumetric strain (ε), related either to soil swelling or expansion (positive ε values) or soil shrinkage or collapse (negative ε values) during weathering processes. This mass balance factor corresponds to concentration ratios between a chemical element (*j*) and the chemical invariant (*i*) in a considered weathered material (*w*), as compared to its corresponding parent material (*p*), minus 1. The ratio of both elements in the protore (*p*) is a reference and thus assimilated to a constant. A mass balance factor smaller than 1 will then refers to a loss of chemical element (*j*), which is completed at $_{j,w}$ = O, whereas a mass balance factor greater than 1 will reveal a gain of the same element.

X-Ray diffraction and spectroscopic analyses

The mineralogical composition of clay and bulk samples was assessed by powder X Ray Diffraction (XRD) with a PHILLIPS PW 1730 using Co K radiation and operating at 40 kV and 30 mA at the Institut de Minéralogie et Physique des Milieux Condensés (IMPMC, Paris, France). XRD traces were collected for 2 angles ranging from 5 to 120° with a 0.02° steps and a counting time of 400s per step. Grounded powder samples (± 30 m) were prepared according to the technique of the "back pack-mounted slide" (Bish and Reynolds, 1989).

Identification of the mineral phases was carried out by comparing the experimental XRD traces with those from the mineral references of the ICDD data set.

FTIR spectroscopy was performed in the transmission mode using a Nicolet Magna 560 IR Spectrometer. One mg of oven-dried sample was mixed with 300 mg KBr and pressed at 10 $t.cm^{-2}$ to form a KBr disc. KBr discs were heated at 105°C overnight to remove absorbed water. Spectra were run in the 250 to 4000 cm^{-1} range with a 2 cm^{-1} resolution and normalized with sample exact weight.

Diffuse reflectance spectroscopy (DRS) was performed on bulk samples using a Cary 5G (US-VIS-NIR) spectrophotometer with a 100 mm-diameter integrating sphere coated with Halon (Labsphere, Inc., USA). Samples were gently ground (breakdown of the aggregates), overnight oven dried at 60° and filled into a 27 mm diameter and 2 mm thick hole of an Al holder without packing to minimize preferential orientation and specular reflection. An optically treated silica slide was used to cover the sample holder. Reflectance R was measured relative to a Halon standard. The spectra were run in the 200 to 2500 nm range with a 1 nm increment. The wavelength-dependent reflectance function was transformed into Kubelka-Munk remission functions by $f(R) = (1 - R)^2 / 2R$, which is proportional to the absorber concentration. The curves were smoothed using a cubic spline fitting procedure then the second derivatives were calculated (Malengreau et al., 1996). The nature and relative proportion of Fe-oxides (mostly goethite and hematite) were determined from the position and intensity of the optical transitions on the second-derivative curves calculated from f(R) (Kosmas et al., 1984).

Soil colour was quantified from the reflectance curves in the visible range (from 360 to 830 nm). The CIE tristimulus values (X, Y, Z) were computed from the spectral reflectance and energy of the light source for each wavelength using the colour matching functions of the CIE standard illuminant C (Wyszecki & Stiles, 1982). Tristimulus values were converted into colour units (x, y and Y%) of the CIE System (1931) and in those of the Helmholtz coordinates (L_d and P_e). They were ultimately plotted in the colour diagram of the visible range. In this diagram, the dominant wavelength (L_d) is the slope between the white light source and a given dot, and is related to the tint of the sample. The excitation purity (P_e) is equivalent to the chroma of the Munsell colour chart. It is scaled between 0 % for a colourless sample and 100 % for a pure colour monitored at the output of a monochromator (Bedidi et al., 1992).

3.4. Results

3.4.1. Vertical and lateral soil differentiation along the transect

Two sets of horizons are distinguished in the 5 soil profiles: (i) an approximately 2.3m thick soil cover (solum), strongly weathered and relatively homogeneous showing gradual changes of colour, texture and structure towards the depression and (ii) an underlying saprolite, slightly heterogeneous, less weathered and massive, which display abrupt changes of colour and then of texture towards the depression.

In the freely drained environment of the margin of the dissected plateau (P1), the regolith is clayey and intensively coloured by Fe-oxides. The thick massive saprolite (BC and C horizons) inherited from the weathering of granites of the Uaupés Suite (reached at 5m deep in P1) is clay loam to sandy clay loam and dominantly red. It exhibits slightly darker colours at the bottom of the saprolite due to the weathering of centrimetric mafic bodies of the granites. The transition with the overlying soil cover is progressive and mainly associated with (i) heavier sandy clay textures (decrease of the silt size fraction, predominantly made of clay minerals, and increase of the fine sand fraction with dominant quartz), (ii) more yellowish colours (yellowish red soils) likely due to greater amounts of goethite, and (iii) the development soil aggregates in B-horizons (mostly medium to fine blocky aggregates, with micropeds of biological origin). Towards the soil surface, the soil impregnated by the organic matter turns yellowish brown and becomes clay-depleted. Such changes thus mark at about 0.4m deep the second major transition between topsoil A-horizons and subsoil B-horizons. From the edge of the plateau (P1) to the margin of the podzolic area (5m upslope of latter in P5), the following morphological changes are reported (Fig. 2c).

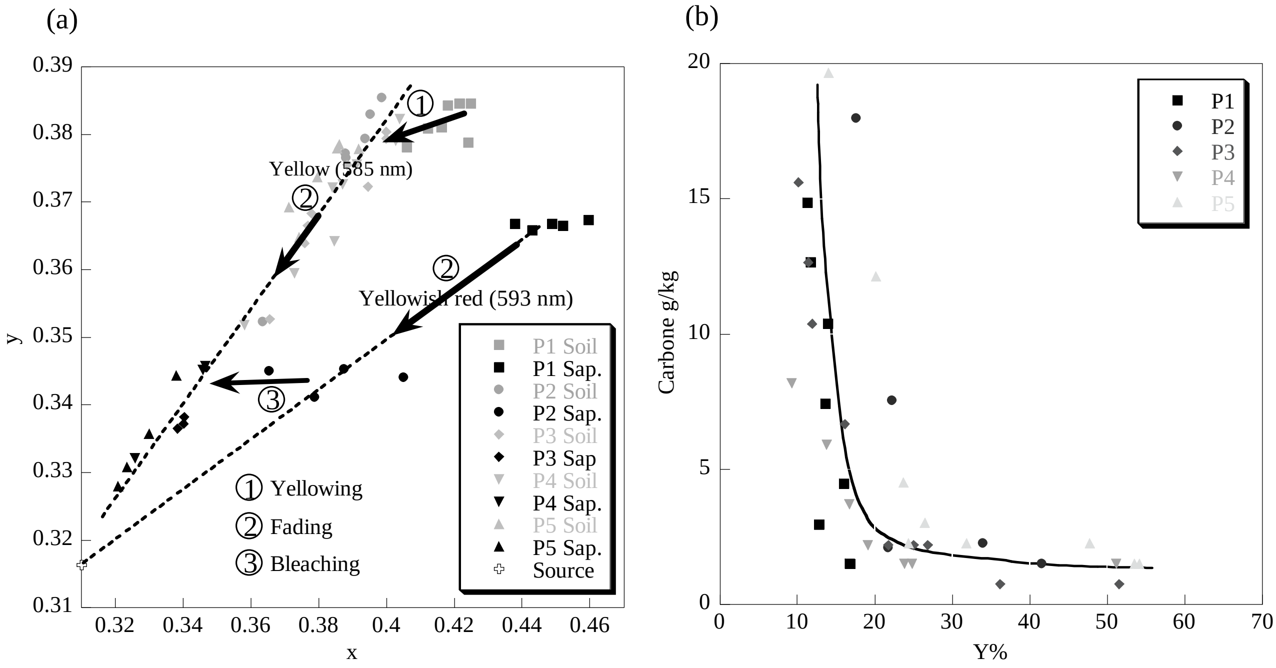


***Figure 3**. (a) x and y values of the CIE System (1931) for soil (grey symbols) and saprolitic (black symbols) samples of the five profiles (P1 to P5) plotted in the visible colorimeric diagram, slope and distance from the CIE standard illuminant C (source: white cross) are used to calculate the dominant wavelength (L_d) and the excitation purity (P_e), respectively for each sample (Helmholtz coordinates), (b) Y% value of the CIE System (1931) versus total carbon content.*

In the upper soil cover, lateral changes are progressive but also slightly dissociated in space for colour and texture. From P1 to P2 and within the 2m thick B-horizons, soil colour grades from reddish-yellow to yellow whereas the soil texture remains almost unchanged (sandy clay). Such a soil yellowing is revealed on a colour diagram by a slight decrease of the dominant wavelength (L_d) that reaches an average value of 585nm in P2 (arrow 1 in Fig. 3a). Change of texture occurs later on and range from sandy clay in P1 and P2, to sandy clay loam in P3, sandy loam in P4 and loamy sand in P5 (Fig. 4a). This regular decrease of clay particles from P2 to P5 occurs without significant change of tint in B-horizons, but is closely associated with fader soil colours. On the colour diagram, this second colorimeric trend is related to equivalent dominant wavelength (average L_d of 585 nm) but to smaller values for excitation purity (P_e) (arrow 2 in Fig. 3a).

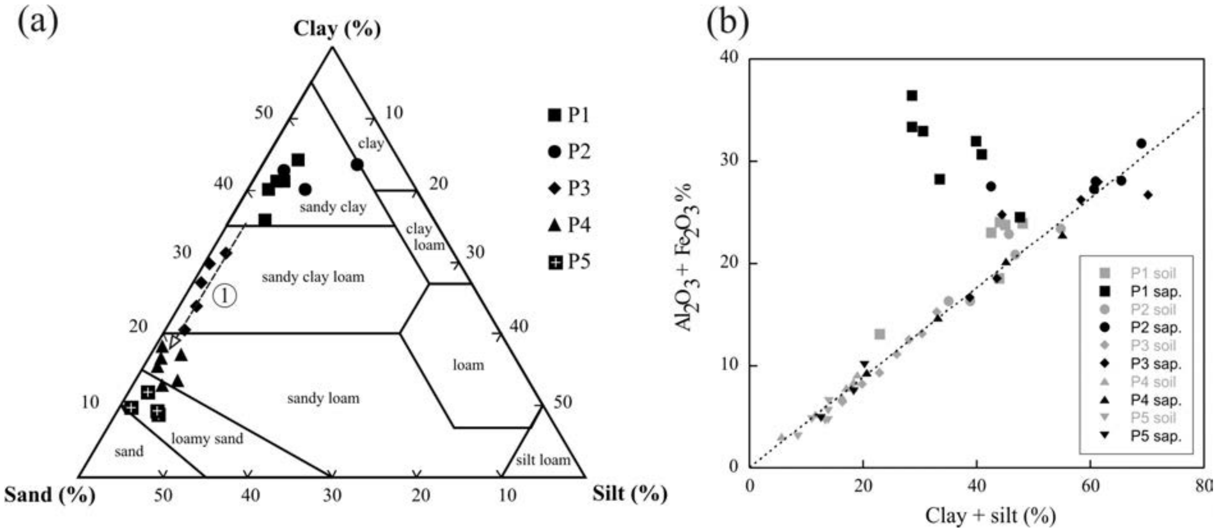


Figure 4*. (a) Ternary representation of the percentage of clay, silt and sand in soil samples of the B-horizons from the five profiles (P1 to P5) with corresponding soil texture classification, showing the gradual loss of fine clay minerals towards the depression (arrow 1), (b) positive correlation between the amount of clay + silt (< 50µm) weight % determined from particle-size extractions and the amount of clay minerals assessed from the* Al_2O_3 + Fe_2O_3 *% in bulk samples (negative correlation for P1).*

Losses of fine particles is also linked laterally in the soil cover to soil structure breakdown and to changes in mineral assemblage on thin sections between coarse primary minerals (mostly quartz) and finer secondary clay minerals (mainly kaolinite and goethite), as already discussed in Fritsch et al. (1989) for a soil catena of western Africa at the transition between forest and savannah. Indeed, soil structure tends to exhibit a greater range of aggregate size in P3 and P4 than in P1 and P2 and to become massive in P5. Concomitantly on thin sections (not shown), the assemblage between primary and secondary minerals (Brewer, 1964) is (i) dense with numerous, well-defined, thin cracks (porphyrosquelic) in P1 and P2 (Clay% > 35), (ii) less dense with larger and ramified macro-voids delineating soil matrix aggregates of various sizes (agglomerplasmic) in P3 and P4 (15 < Clay% < 35), and (iii) more open and porous with almost adjacent quartz grains and clay bridges between some of them (intertextic) in P5 (5 < Clay% < 15). The more macro-porous and compact assemblage of quartz sands (granular), linked to an almost total loss of clay particles (Clay% < 5), was not reached as it mostly characterizes the eluviated E horizons of podzols (out of the selected zone for this study). Accordingly, the selective but continuous loss of matter leads in a first stage to soil structure breakdown that most likely should reduce soil permeability and in a second step to a gradual increase in macro-voids between quartz grains, that become closer and closer, thus increasing in return water fluxes in soils (Fritsch et al., 1989; Bruand et al., 1990).

In the underlying clay loam to sandy clay loam saprolite, lateral changes of colour and texture are more abrupt and neatly dissociated along the transect. Redder colours as compared to the overlying soils are at first noted in the freely drained saprolite of the plateau edge, as illustrated on figure 3a by higher wavelengths (L_d), with an average value of 593nm in both P1 and P2. However, the saprolites also exhibit fainter reddish colours in P2 than in P1 (decrease of the excitation purity P_e, arrow 2 in Fig. 3a). They also display bleached mottles or layers at different depths that become more and more abundant from P2 to P4 (see also arrow 3 in Fig. 3a). Veins of kaolin were also found at depth in bleached saprolites of P4. In P5 and close to the downslope podzolic area of the depression, the saprolite is completely bleached and its upper part is also strongly depleted in fine particles. The groundwater table reached the clay-depleted area of the saprolite during the dry season (e.g. at 2.4m the 15th of November 2006).

3.4.2. Geochemistry of major and trace elements

Major elements (Si, Al, Fe, Na, K, Ca and Mg) and Zr

All five profiles are strongly depleted in base cations (Na, Ca, K and Mg) as the mass balance factor ($_{j,w}$) calculated in the whole regolith, using Zr as an invariant, is almost nil for each of these highly mobile chemical element (not shown), with the exception of the bottom part of the saprolite only reached in P1. This suggests the almost total weathering of the feldspars (albite, anorthite and microcline) and ferromagnesiens (biotite and amphibole) inherited from the bedrock (see also the average chemical composition of these primary minerals and that of the granite in Tab. 1). Petrographic observations confirm the disappearance of these primary minerals in the regolith. Moreover, the extremely low CEC (< 10 cmolc/dm^3) and base cation saturation of the exchangeable sites (<4%), predominantly occupied by Al^{3+} and H^+, thus pertains to low activity clay soils specific to laterites and confirm the strong leaching conditions, which have prevailed in both soils and saprolites.

The amounts of total Al and Fe also vary vertically and laterally according to major morphological patterns. Firstly, the total amounts of clay plus silt in both soils and saprolites is positively correlated to the Al_2O_3 + Fe_2O_3 content (Fig. 4b) and negatively correlated to the SiO_2 content, excepted in P1 due to the occurrence in the sand fractions of small nodules of gibbsite. This indicates that most of the clay minerals (i.e. kaolinite and Fe-oxides) is in particle-size fractions smaller than 50µm. As we previously reported greater amounts of silt in

saprolites than in soils, we then conclude to the occurrence kaolinite populations of larger particle size at depth than close to the surface. At the margin of the plateau in P1, the total amounts of Al_2O_3 (Fig. 5a) but also of Fe_2O_3 (Fig. 5b) tend to decrease vertically upwards from saprolites to soils. The reverse trend is reported for Zr (Fig. 5c), the less mobile chemical element of these regoliths. Accordingly decreasing size of clay minerals from saprolites to soils seems also to be link to loss of these secondary minerals, and consequently to a residual accumulation of the more resistant primary minerals to chemical weathering, i.e. predominantly quartz but also accessory minerals, such as zircon.

From the plateau edge to the margin of the depression, the amounts of clay minerals assessed predominantly by the Al_2O_3 content remain almost unchanged in the soils from P1 to P2, and then decrease gradually from P2 to P5 (arrow 1 in Fig. 5a). These amounts are much higher in saprolites than in soils from P1 to P4 and then decrease abruptly in P5 (arrow 2 in Fig. 5a). As already reported from textural data, two clay-depleted zones are reported downslope close to the podzolic area (arrows 1 and 2 for P5 in Fig. 5a). In the deeper clay depleted one of P5 (arrow 2 in Fig. 5a), loss of clay minerals is also linked to an important loss of Zr (arrow 2 in Fig. 5c, note that the Zr values are there lower than that in the bedrock, materialized by a vertical dashed line on the figure). This likely indicates physical transfer and loss of zircon, of mostly silt particle size, due to the development of macro-voids in clay-depleted saprolite and abundant lateral fluxes in groundwater. As a matter of fact, Zr can no longer be used as a chemical invariant in such a place. The amounts of Fe-oxides, assessed by the Fe_2O_3 content, decrease laterally in soils, from P1 to P5 (arrow 1 in Fig. 5b). In the underlying saprolite, it decreases significantly from P1 to P2 that exhibits faint reddish yellow colours and reaches smallest values further downslope in bleached saprolites (from P3 to P5) (arrow 2 in Fig. 5b). Mass balance factor calculation ($_{j,w}$) confirms the vertical losses of Al and Fe from saprolites to soils on the plateau edge (Fig. 5d and e). Losses increase laterally towards the depression (from P1 to P5). Mass balance factors also show that 60% of the initial stock of Si from the bedrock is lost in saprolites following the dissolution of primary minerals (mostly feldspars and ferromagnesians) and the neoformation of clay minerals (Fig. 5f). In the overlying soils, Si losses slightly increase (arrow in Fig. 5f), likely due to greater dissolution rates of secondary minerals.

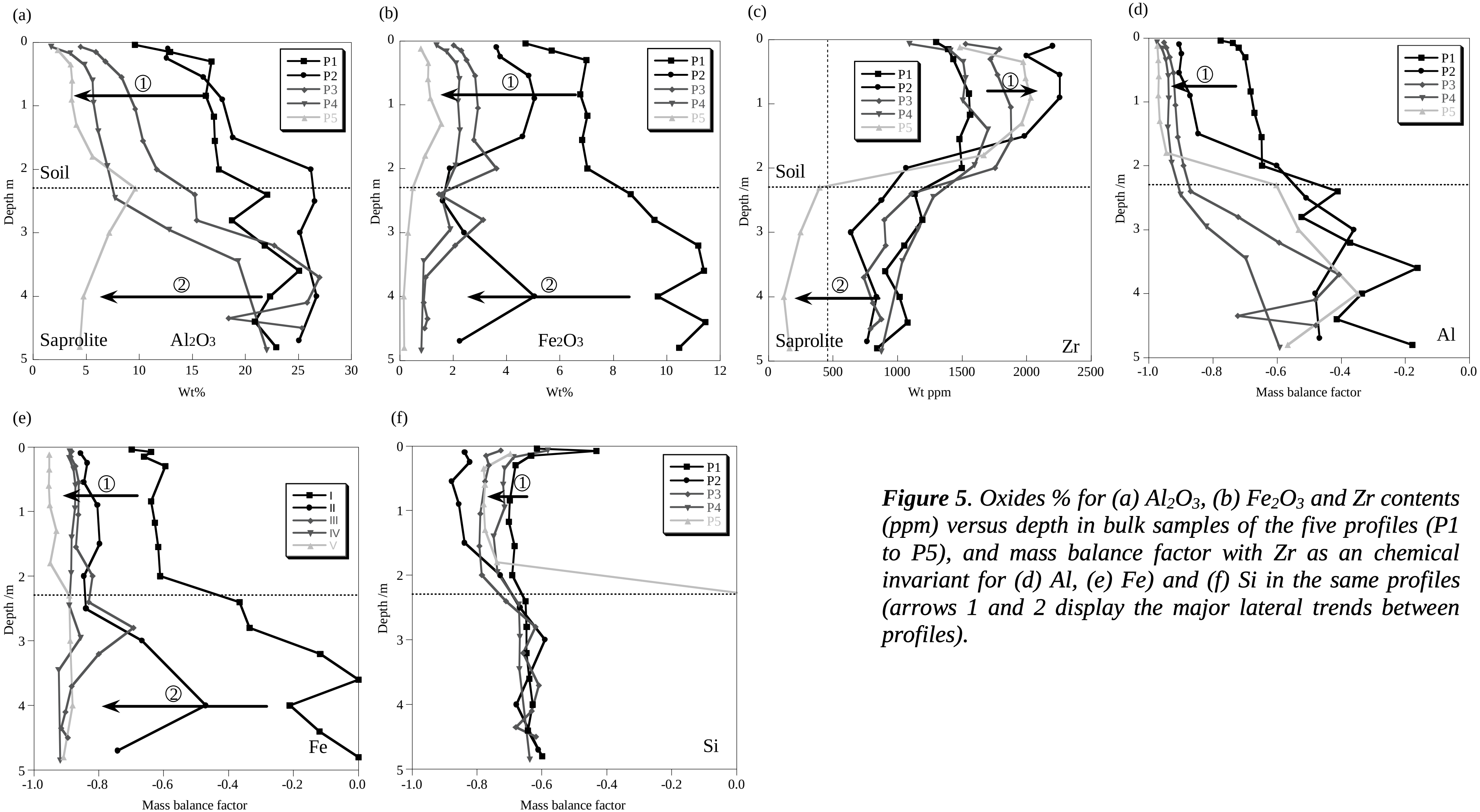


***Figure 5**. Oxides % for (a) Al$_2$O$_3$, (b) Fe$_2$O$_3$ and Zr contents (ppm) versus depth in bulk samples of the five profiles (P1 to P5), and mass balance factor with Zr as an chemical invariant for (d) Al, (e) Fe) and (f) Si in the same profiles (arrows 1 and 2 display the major lateral trends between profiles).*

The relative loss of Fe as compared to Al appears quite different in soils and saprolites, as illustrated by the Al_2O_3/Fe_2O_3 ratio as a function of the Zr content for all samples (Fig. 6). On the plateau edge in P1, the Al_2O_3/Fe_2O_3 ratio is equivalent in both saprolites and soils, indicating therefore an upward residual accumulation of both Al and Fe. Towards the depression from P2 to P5, this ratio also remains almost unchanged in soils. Al and Fe are thus exported simultaneously either by chemical erosion or physical transport. However the ratio increases slightly from the bottom to the top of each profile suggesting a greater dissolution of Fe-oxides than kaolinites. This trend is strongly amplified in bleached areas of the underlying saprolites thus indicating a massive dissolution of Fe-oxides.

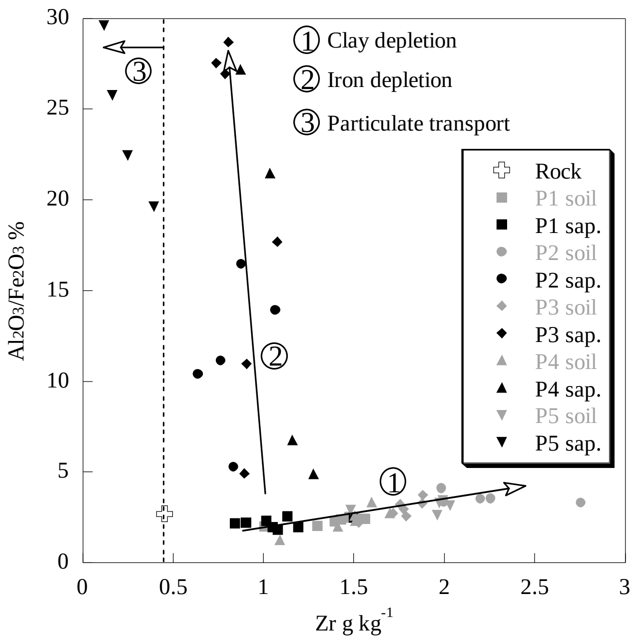


Figure 6. *Al_2O_3/Fe_2O_3 ratios of bulk samples in the five profiles (P1 to P5), showing the pathways for clay depletion, selective iron depletion and particle transport (1, 2 and 3 respectively in the figure) in soils (grey symbols) and saprolites (black symbols).*

Accessory elements (Ti, P, La, Ce, Yb, Th, U and Pb)

Accessory elements enable to distinguished saprolites from soils, as well as freely drained environment (P1 and P2), from more hydrated or waterlogged ones (from P3 to P5). The more abundant accessory element, Ti (up to 2.5% of TiO_2), is about half lost in saprolite according to mass-balance calculations (Fig. 7a). Petrographic observations (not shown) and electron punctual microprobe analyses (EPMA) (Tab. 1) relate Ti losses to the weathering of titanite crystals that surround opaque minerals (mostly poorly weathered magnetite) from rich-mafic

clots in the mafic-bearing granites. Such losses increase upwards and become stabilized in soils following the complete weathering of titanite. The remaining Ti in soils belongs to primary rutile and secondary anatase from XRD (not shown), and represents about 40% of the initial stock of Ti in P1 and 20% in the other profiles (Fig. 7a).

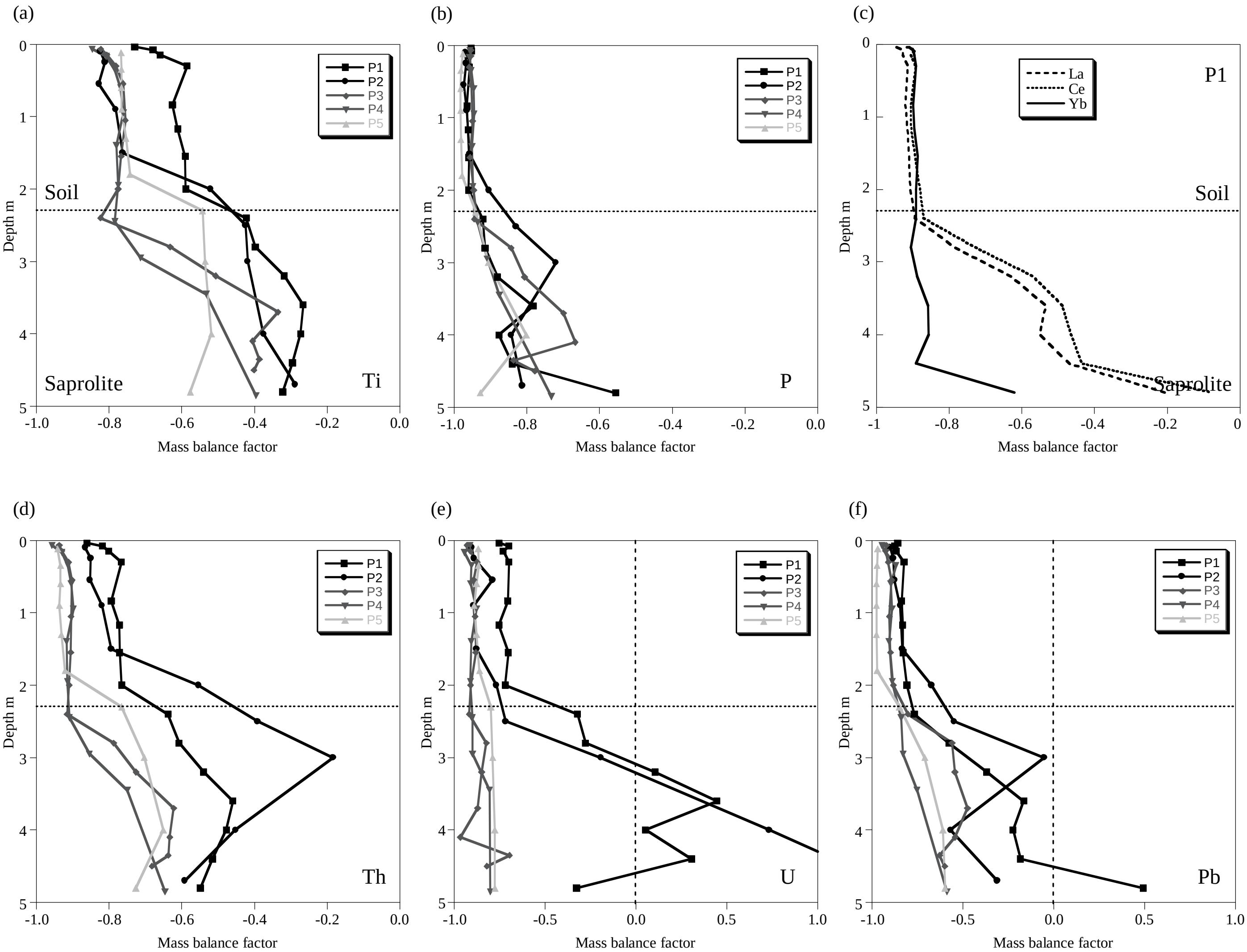


Figure 7. *Mass balance factors versus depth for (a) Ti, (b) P in the five profiles (P1 to P5), for LEE (La and Ce) and HEE (Yb) in P1, and for (d) Th, (e) U, and (f) Pb in the five profiles (horizontal dashed line demarcates the saprolite from the overlying soil and the vertical dashed line relates to no loss or gain of chemical elements).*

Although present in much less quantities in the bedrock (Tab. 1), the phosphorous (P) and light earth elements (LEE) exhibit similar trends upward in saprolites and soils. Losses of P (Fig. 7b) and LEE (see La and Ce in Fig. 7c) are mainly attributed to the weathering of apatite and allanite crystals, respectively according to EPMA (Tab. 1). Phosphorous is almost completely lost in soils following the complete disappearance of apatite crystals. By contrast,

about 10% of the initial stock of LEE in preserved in soils. Heavy earth elements (HEE) behave differently than LEE in saprolites. They are more rapidly lost likely due to their incorporation in more easily weatherable minerals (see Yb in Fig. 7c).

Three other trace elements (Th, U and Pb) also display similar trends that however differ significantly from the plateau edge to the margin of the depression (i.e. from P1 to P5). Actinides in these lateritic regoliths are most likely incorporated in zircon (Balan et al., 2005) but also in apatite and allanite (occurrence of fission tracks in the surrounding primary minerals of the granite). The upward losses of Th (Fig. 7d), U (Fig. 7e) but also of Pb (Fig. 7f) is likely due to the opening of the decay chains of Th and U during the weathering of apatite and allanite. However, U and Pb behave differently between freely drained (P1 and P2) and poorly drained environments (P3 to P5). In P1 and P2, losses of both elements in soils are linked to gains of the same elements at depth (positive values are locally obtained for mass balance factors in saprolites). By contrast, this kind of vertical transfer does not occur from P3 to P5. Indeed, greater losses of both elements are reported in bleached saprolites and consequently smaller losses upward in soils. This confirms the downward accumulation of actinides in freely drained, red lateritic profiles and the contribution of Fe-oxides in the storage of these elements at depth (P1 and P2). The quite specific chemical behavior assigned to these accessory chemical elements during the vertical development of the lateritic regoliths must be linked to the occurrence of mafic bodies in the granitic rock basement of the transect.

3.4.3. Mineralogy of clay minerals

DRX (not shown) and spectroscopic data in the infra red (FTIR) and visible (DRS) ranges reveal a quite monotonous mineral composition for clay minerals (mostly kaolinite, gibbsite, hematite and goethite as secondary minerals and residual magnetite as primary mineral) but a high variability in the proportions of these minerals from bottom to top of the regolith and from the plateau edge to the margin of the depression in bulk samples of both soils and saprolites (Figs. 8 and 9). The changes in the proportion of the Al-bearing minerals (kaolinite and gibbsite) are assessed from FTIR (Fig. 8), whereas those of the Fe-oxides (hematite, goethite and magnetite) are deduced from second-derivative spectra - SDS (Fig. 9).

Al-bearing minerals (kaolinite and gibbsite)

The redder lateritic profile from the edge of the dissected plateau (P1) is easily differentiated from the other profiles (P2 to P5) by the much larger quantities of gibbsite in the pool of Al-bearing minerals. In this profile (Fig. 8a), the largest contents of gibbsite are reported in the saprolite, more specifically in the lower section of this layer and at different depths. In particular, Al hydroxides are almost exclusive at 3.6 and 4.8m deep. In the overlying soils, the relative proportion of kaolinite increases significantly and becomes nearly as abundant as gibbsite.

The reverse trend is observed towards the depression with dominant kaolinite in more yellowish soils and in the underlying faint red to bleached saprolites (i.e. from P2 to P5). Gibbsite is mainly observed in the soils, more specifically in their lower sections and is barely detectable in the underlying bleached and waterlogged saprolites (depths > 2.5m in Figs. 8b, c and d). According to such trends, the longer periods of episodic (soils) or more permanent (saprolites) water saturation in regoliths seem to restrict the formation of gibbsite. The vertical trends in profiles also suggest the downward accumulated of gibbsite following the dissolution of kaolinite in overlying regolith compartments. This vertical transfer of Al and precipitation of Al hydroxides is likely limited (hardly detected by mass balance factors) but slightly enhanced by textural discontinuities, in particular just above the rock/saprolite transition in freely drained environments (P1), and closer from the soil surface at the soil/saprolite transition in poorly drained environments (from P2 to P5). The upward depletion of clay minerals in soils and towards the depression is linked to simultaneous collapse of the OH vibration bands for both kaolinite and gibbsite (Figs. 8b, c and d).

In the dominant kaolinitic and poorly drained area of the transect (e.g. from P3 to P5 in Figs 8b, c and d), the high resolution of the two internal bands (3668 and 3652 cm^{-1}) for the out-of-phase motion modes of inner-surface OH groups reveal low defect kaolinites (Balan et al., 2001). Defect in kaolinites are better observed in normalised spectra, as larger crystallographic disorder are mainly linked to significant changes in the two internal bands, with a decrease of the magnitude of the band at 3668 cm^{-1} and a broader and intense band centred at 3650 cm-1 (Balan et al., 2005). Normalised spectra (not shown) reveal weak crystallographic changes both vertically and laterally along the transect. The well-ordered kaolinites always occur in saprolites, more specifically at different depths in P3 and P4 (kaolins, see for instance 3.9m deep for P4 in Fig. 8c). Disorder in kaolinites can increase slightly in the overlying soils (for example in P3 and P4), but always remains limited. This

strongly differs from other lateritic profiles of the Manaus region, where lateritic soils mostly consist of high defect kaolinites (Balan et al., 2005).

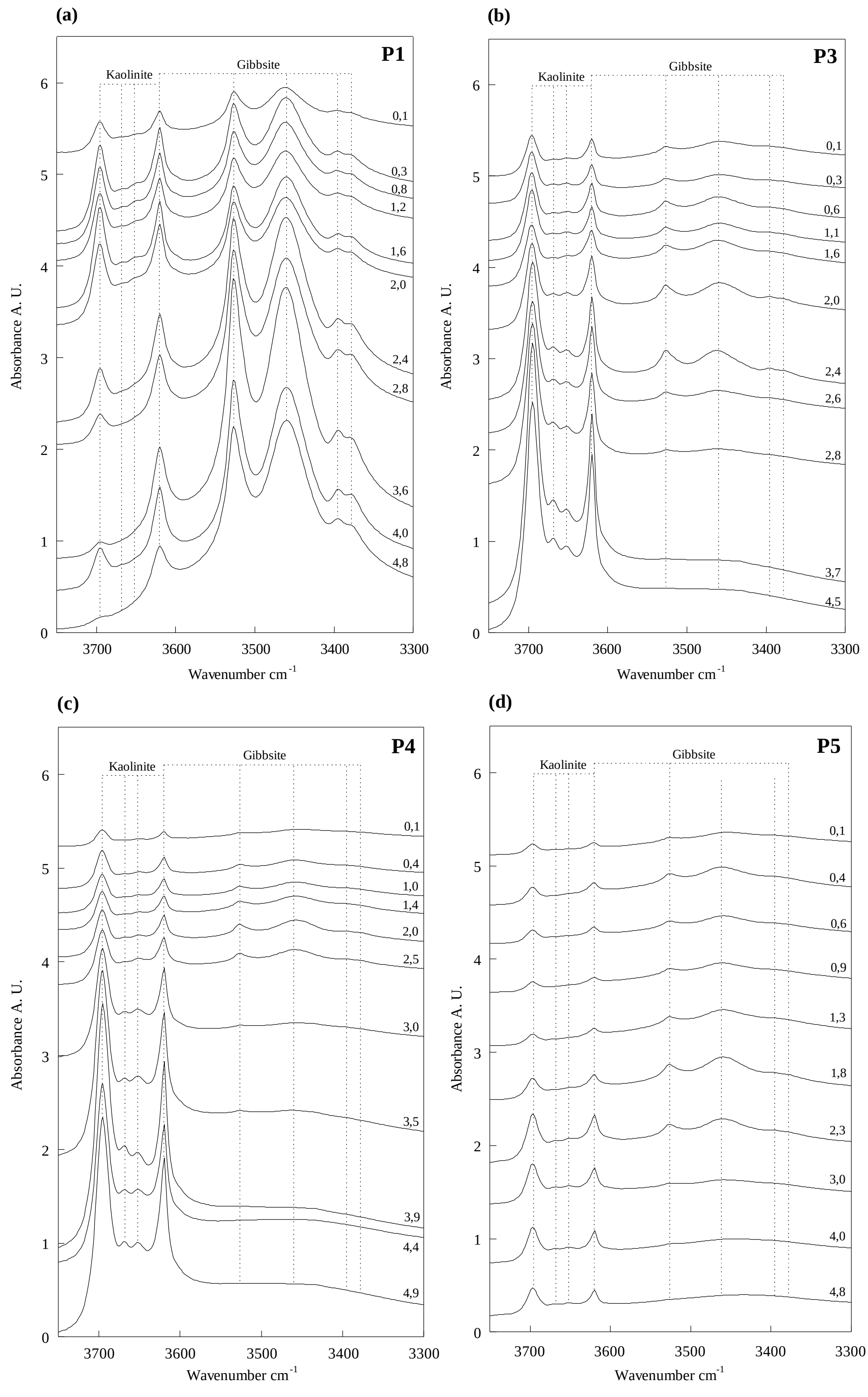


***Figure 8**. FTIR spectra in the OH stretching region showing the four characteristic bands of kaolinite (3695, 3668, 3652 and 3620 cm^{-1}) and the five bands for gibbsite at lower*

wavenumbers (3620, 3527, 3460, 3395 and 3378 cm^{-1}), as well as changes in the intensity of the bands (or proportion of these Al-bearing minerals) in bulk samples of profiles (a) P1, (b) P3, (c) P4, and (d) P5 (P2 is not presented as it displays similar FTIR spectra than P3).

Fe-oxides (hematite, goethite and residual magnetite)

Major colorimeric changes observed both vertically and laterally at the border of the dissected plateau (from P1 to P2), are related to contrasted changes in the contents of hematite (Hm) and goethite (Gt) (Fig. 9). The proportion of hematite is much larger in saprolites than in the overlying soils, but also decreases significantly in saprolites from P1 to P2 (Figs. 9a and b). On this regards, the assignment of the three major bands for Hm and Gt are related to minima on the second derivative of the remission functions. In the saprolites, the low contents of Hm and Gt assessed by DRS, as compared to the amount of total Fe determined by chemical analyses, indicate large proportions of magnetite, which are easily recognized on thin sections. Upward in profiles P1 and P2, the amount of hematite decreases slightly and that of goethite increase strongly (Figs. 9d and e). Simultaneously the content of magnetite decreases drastically, more specifically in P1 (Fig. 9d). Accordingly, the intense weathering of magnetite in soils contributes largely to the formation of goethite. However, hematite to some extend seems also to contribute to the formation of goethite through dissolution/cristallisation cycles, as already proposed by Fritsch et al. (2005) in other lateritic profiles.

From the margin to the center of the plateau, yellowing in soils is at frist related to significant losses of Hm (from P1 to P2, Figs. 9a and b) and fading to losses of the remaining Gt (from P2 to P5, Figs. 9b and c, see also Figs 9e, f, g and h). Bleaching in saprolites is mostly assigned to the disappearance of both hematite and goethite (Fig. 9c, see also Figs 9f, g and h).

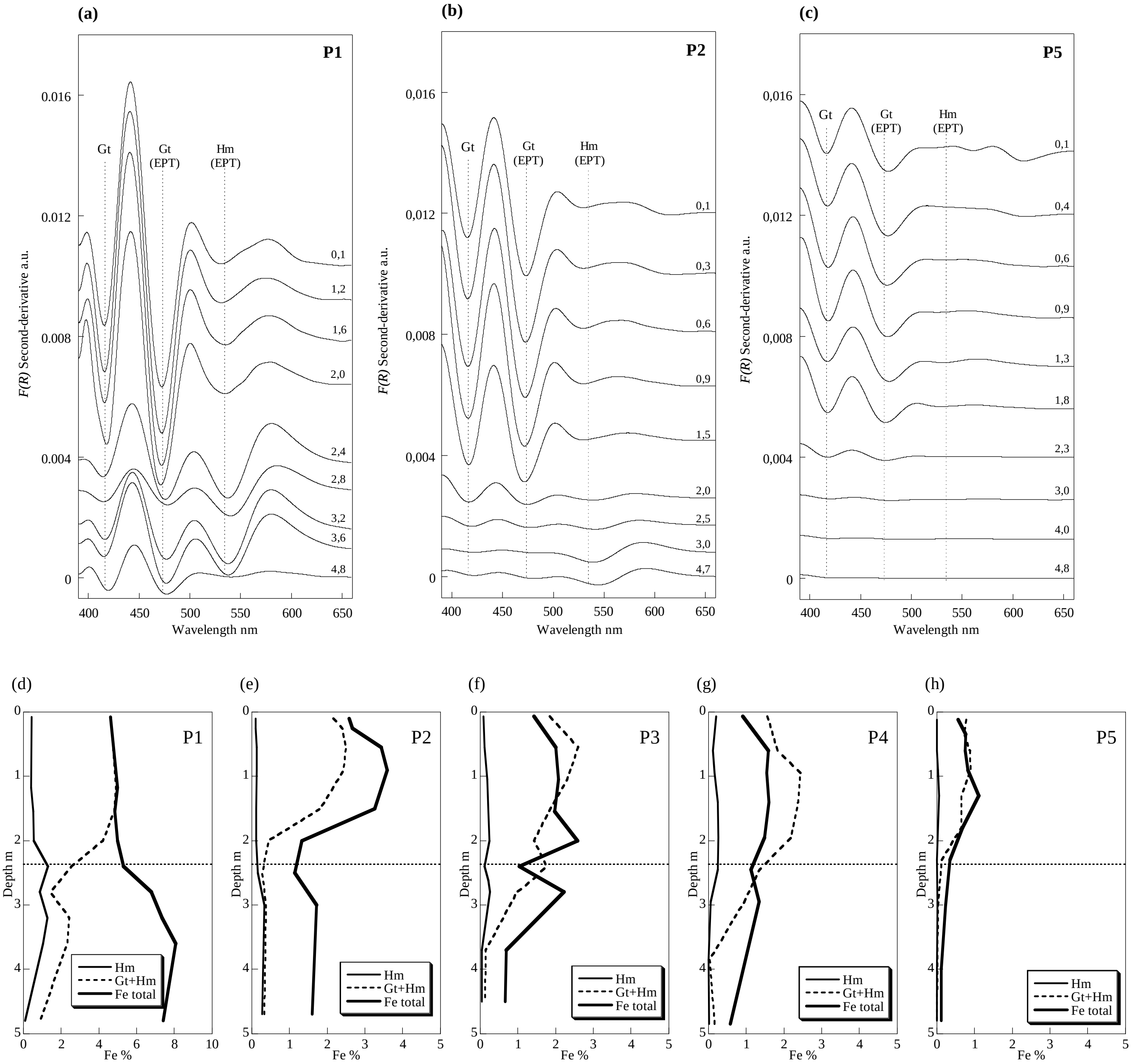


Figure 9*. Second-derivative spectra of the remission function f(R) (DRS) showing the absorption bands (minima) for goethite (Gt) and hematite (Hm) in selected bulk samples from (a) P1, (b) P2 and (c) P5 and assessment of the relative proportion of hematite (Hm,), goethite and magnetite (determined indirectly) from DRS and total chemical analyses in (d) P1, (e) P2, (f) P3, (g) P4, and (h) P5 (horizontal dashed line demarcates the saprolite from the overlying soil).*

3.5. Discussion and conclusions

The study enables to establish major geochemical and mineralogical changes in the vertical differentiation of lateritic profiles from (titanite)-(amphibole)-biotite granites of the margin of the Guyana Shield. It also enables to establish selective geochemical and physical erosion trends in their lateral transformation following the incision of *Ucayali* peneplain surface by the modern Amazon drainage system. River incision formed the low elevation plateaus of the upper Amazon Basin. In this kind of humid tropical landscape, the freely drained conditions favourable to the vertical development of red clayey laterites are preserved on the edges of the plateaus. They mainly result from the incision of the plateau edges by numerous tributaries of river systems. By contrast, poorly drained conditions have settled in the central parts of the plateaus and have likely increased in space and time. They have enhanced the lateral and internal erosion of laterites, generated depressions and prepared their ultimate transformation into highly degraded and waterlogged podzols. In the study site, the lack of sedimentary structures in regoliths from the edge to the centre of the plateaus then assigns the geochemical and physical erosion of laterites to yellowing in soils, bleaching in saprolites, as well as to an ultimate depletion of clay minerals in both kinds of compartments.

On the edges of the plateaus, lateritisation has led to complete depletion of base cations and partial loss of silica at the bottom of deeply weathered profiles and therefore to residual accumulation of Al and Fe in secondary minerals (kaolinite, gibbsite, goethite and hematite) following the complete dissolution of major primary minerals of the granites of the Uaupés Suite (mostly feldspars, biotites and amphiboles). The occurrence in these granites of pegmatites and mineralised zones have also generated differential chemical weathering processes and led to specific geochemical signatures in regoliths. Accessory minerals of the mafic-bearing granites, more resistant to chemical weathering, are indeed partly preserved in the overlying regoliths. They mostly consist of titanite, apatite, allanite, and magnetite, which are particularly rich in Fe, Ti, Ca, P, LEE and actinides.

As commonly reported in the tropics, lateritisation is a two-step process that first leads to the vertical development of thick saprolites and ultimately to the accumulation of more intensively weathered, bioturbated and aggregated products in soils (Gombeer and D'Hoore, 1971; Nahon, 1991; Tardy, 1993; Fritsch et al., 2002; Balan et al. 2005). The second weathering step frequently marks greater losses of chemical elements as well as relevant changes in the proportion and nature of primary and secondary minerals. In other deeply weathered lateritic profiles of the Amazon basin, these changes were mostly assigned to

decreasing size and increasing crystal disorder in populations of kaolinites, suggesting alternate dissolution - recrystallisation steps leading to residual accumulation of small and poorly ordered soil kaolinites (Balan et al., 2005). Changes in the nature and Al substitution rates of Fe-oxides were also reported upwards in these soils (Fritsch et al., 2005). In our study site, the upward transition between saprolites and soils also marks a decrease in the particle size of kaolinites, but is not linked to relevant changes in the crystal order of kaolinites. Indeed, low defect kaolinites in saprolites remains weakly altered upward in soils. By contrast, the transition also results in an intense weathering of the accessory mineral remnants inherited from the mafic bodies. In particular, it marks the complete disappearance of titanite, apatite and allanite, as well as the ultimate dissolution of magnetite that feeds the pool of secondary Fe-oxides (i.e. hematite and goethite) in soils.

The freely drained conditions prevailing at the margin of the plateaus also favour the crystallisation of hematite over goethite, as well as that of gibbsite over kaolinite, more specifically at depth in the highly porous saprolite. The larger amount of gibbsite at depth could also result from the downward accumulation of Al following the dissolution of kaolinite in the overlying soil compartment with however a global loss of this element to the rivers as pointed by mass balance factor calculations. This downward transfer of matter in oxic environments also affects actinides, which accumulate significantly at depth in iron-rich saprolites. The larger amounts of kaolinite and goethite in the overlying soil likely result from denser and less permeable materials, which are finely divided and more frequently and durably hydrated by rainfalls. This trend is enhanced laterally, illustrating therefore longer periods of hydration in soils or waterlogging in saprolites from the margin to the centre of plateaus. However, small quantities of gibbsite may still be produced and accumulated downward at the transition between soils and saprolite.

We also recognised two distinct compartments (soils and saprolites) subject to significant losses of matter from the plateau edge to the margin of depression. The first one corresponds to unsaturated soils that average 2.3m of thickness in our investigated site. In this upper compartment, losses of matter are progressive in space and probably slow in time. They are most likely linked to selective dissolution of clay minerals and soil leaching, which could result from increasing periods of soil wetting towards the depression of the plateau, particularly during the rainy season. In this soil compartment, losses of matter are at first limited. They are mostly assigned to selective dissolution of Fe-oxides, particularly hematite, and therefore related in the field to soil yellowing (e.g. Peterschmitt et al., 1996). This

chemical erosion is closely followed by the weathering of the remaining clay minerals (i.e. goethite and kaolinite) and thus to clay depletion and soil fading (Fritsch et al., 1989; Chauvel et al., 1977, Chauvel & Pedro, 1978). By contrast, losses of matter are more abrupt at two distinct places in the underlying saprolitic compartment. They are first related to the complete removal of secondary Fe-oxides (i.e. hematite and goethite) and therefore to bleaching under the action of the groundwater. They enable to differentiate in saprolites the saturated zone from the unsaturated one at higher elevations. Further downslope and at the margin of the depression, groundwater dynamics may also lead to depletion of fine clay particles in the upper part of the bleached saprolite, likely due to greater lateral water fluxes.

Losses of matter change the type of assemblage (from compact to granular) between coarse primary minerals (mostly quartz) and finer secondary clay minerals. These textural changes induce the development of macro-voids between quartz grains (Fritsch et al., 1989), which favour the transfer of fine particles (mostly clay but also silt) during gravity flows (Bruand et al., 1990). This leads us to suggest that chemical erosion (lixiviation) with preferential dissolution of F-oxides could at first prevailed in sandy clay to sandy clay loam soil horizons and favour particle dispersion and soil structure breakdown. Later on, the development of interconnected macro-voids in sandy loam to loamy sand horizons would also favours the transfer of suspended fine particles (first clay then silt) during lateral water flows and the formation of eluviated compartments and close to major groundwater reservoirs (Bocquier, 1971; Boulet, 1974; Fritsch et al.,1990a, 1990b; Bravard and Righi, 1990; Lucas et al., 1996).

Losses of matter in the unsaturated topsoils and at greater depth in the waterlogged saprolites lead to the formation of a highly porous eluvial compartment that clearly displays a double tongue-like shape transition towards upslope positions. The abundant and interconnected macro-voids produced in this compartment enable the downward migration of humic substances in soils, their accumulation at depth and at the margin of the depression in clay-depleted laterites. This accumulation of organic matter in less permeable materials tends to waterproof the periphery of the eluvial compartment thus favouring the implementation of a perched groundwater in newly formed podzols, which are widely spread in the region. The study thus reveals that yellowing, bleaching and losses of clay minerals in soils and saprolites are preliminary steps to podzolisation. It also points out that the characteristic and spectacular double tongue-like shape transition, which demarcates the upslope clay-depleted laterites from the downslope podzols, has been acquired before the transfer of organic substances, by chemical and physical erosion and according to major hydraulic fluxes in regoliths.

Acknowledgements

The research was funded by CAPES-COFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l'Univers du CNRS), through the "Ecosphère continentale" programme: "Podzolisation des latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)".

CAPITULO 4. PODZOLIZAÇÃO DOS SOLOS LATERÍTICOS E INCISÃO DOS PODZÓIS HIDROMÓRFICOS NO ALTO RIO NEGRO

Résumé

Le chapitre présente les résultats d'une étude minéralogique et structurale d'une séquence de sols développés sur les granites de la formation Uaupés de la région de São Gabriel da Cachoeira, à la bordure des aires fortement podzolisées du bassin versant du Curicuriari (site 4). Ce bassin versant, podzolisé sur prêt de 95% de sa superficie, présente des eaux noires et des sables blancs dans les lits de ses principaux tributaires, attribués à l'érosion physique des podzols. Appartenant aux vastes pénéplaines podzolisées et inondées d'une surface d'érosion, la séquence débute sur une colline résiduelle à latérite et se termine dans un bas de versant convexe résultant d'une incision d'un tributaire du Curicuriari. Le long de cette séquence de 80m de long, six tranchées de sols et d'altérites ont été ouvertes, décrites et échantillonnées. L'étude intègre des caractérisations pétrographiques, minéralogiques (DRX, IRTF et DRS), géochimiques et des calculs des fonctions de transfert (éléments majeurs et en trace). Dans un premier temps, l'étude vise à établir les analogies minéralogiques et structurales par rapport à ce qui a déjà été révélé dans les environnements podzoliques peu incisés de la région du Jaú (site 3). Les principales différences entre sites (3) et (4) sont abordées dans un second temps. Elles nous conduisent à traiter des effets des incisions du réseau hydrographique sur la morphologie et géochimie des podzols et donc des interactions entre podzolisation et incisions en relation avec la dynamique des nappes dans les paysages.

De grandes analogies sont révélées entre les deux sites d'étude ce qui laisse présager d'une grande similitude de processus et de fonctionnement dans la mise en place de ces podzols. La plus importante est la reconnaissance des mêmes ensembles structuraux, avec les sols jaunes appauvris surmontant les ensembles hydromorphes, essentiellement saprolitiques, des laterites de l'amont et les aires podzoliques de l'aval. L'autre analogie de grande importance, qui a toujours été reconnue lors d'étude de séquence de sols en Amazonie, est la transition latérale en forme de "double langue" entre laterites et podzols. La langue supérieure témoigne d'un développement de podzols faiblement différenciés sur les latérites (horizons éluviés surmontant un horizon spodique Bhs). Plus à l'aval, la base de podzols mieux différenciés repose en profondeur sur les saprolites hydromorphes des latérites. Elle se prolonge à l'amont dans la partie supérieure hydromorphe des latérites formant ainsi la seconde langue inférieure de la transition (cette dernière peut correspondre en 3D à des chenaux remontant le versant sur plus de 15m). Cette connexion témoigne de ce fait d'interactions entre deux systèmes de nappe : (i) une nappe phréatique à eaux claires pour les latérites amonts et (ii) une nappe perchée à eaux noires dans les horizons sableux des podzols. Ces distributions relatives montrent également le contrôle des discontinuités structurales (dans le cas de l'étude entre sol et saprolite) dans le développement vertical des podzols et sa contribution dans la différentiation des horizons spodiques. En effet, la discontinuité sol-saprolite limite le développement vertical des podzols et favorise à l'inverse son expansion latérale dans les paysages. Par ailleurs, l'horizon Bh s'individualise à la base ou périphérie des réservoirs sableux des podzols et l'horizon BCs dans la partie supérieure des saprolites hydromorphes sous jacentes. Les accumulations absolues de matières organiques dans les horizons spodiques des podzols réduisent la porosité de ces matériaux et assurent de ce fait la mise en charge de la nappe perchée. Des reliques de matériaux latéritiques imprégnées par la matière organique dans les aires podzoliques aval montrent également que le précèdent équilibre entre structures et fonctionnement de nappe est précaire et que ces systèmes podzoliques peuvent se développer assez brutalement vers l'amont.

De grandes analogies minérales et géochimiques sont également établies entre les deux sites. Les latérites jaunes appauvries de l'amont sont dominées par le quartz mais aussi par des phases minérales résiduelles, essentiellement de la kaolinite mais aussi de la gibbsite et goethite. L'étude montre aussi, et d'une façon plus claire que dans celle du Jaú, que l'enrichissement en gibbsite dans le niveau saprolitique sous-jacent (essentiellement dans sa partie supérieure) est relié à une baisse des teneurs en kaolinite et que cette gibbsitisation bien

marquée à l'amont de la séquence tend à s'estomper vers l'aval. Ces évolutions minéralogiques ne vont pas sans rappeler notre précédente étude sur la pré-podzolisation et confirment de ce fait qu'elles soient bien antérieures à la podzolisation. Le calcul des fonctions de transfert révèle pour les éléments majeurs et en trace une altération latéritique dominante couplée à une perte considérable de matières (essentiellement en Al, Si et Fe) qui est attribuée en grande majorité à un appauvrissement de ces sols en minéraux argileux. Ces calculs montrent également que cet appauvrissement a affecté la partie supérieure et la plus altérée du niveau saprolitique. Ce dernier a de ce fait été scindé en une saprolite fine très altérée et appauvrie, surmontant une saprolite plus grossière, moins altérée (grains de microcline, anorthite, amphibolite) et non appauvrie. Si les pertes attribuées à la podzolisation restent minimes (moins de 12% de l'Al total et 5% du Fe total de la roche), elles n'en demeurent pas moins significatives. L'étude montre aussi l'importance non négligeable du transport particulaire dans ces pertes de matières en environnement podzolique ou pré-podzolique. Dans les horizons sableux blanchis, les plus poreux des podzols, nous révélons ainsi une perte significative en éléments traces (surtout Ti et Th, mais aussi Zr à l'aval de la séquence), présents dans des phases minérales réputés stables et difficilement altérables (rutile, anatase, thorianite, zircon…). Ces éléments se retrouvent accumulés dans les horizons spodiques sous-jacents (Ti plutôt dans Bh et Th plus en profondeur dans BCs). Ces accumulations absolues pourraient résulter de la formation et du transfert vertical de complexes organo-métalliques (comme pour Al et Fe). Toutefois, elles ont pu être reliées pour l'un d'entre eux (Ti) à un accroissement très important des phases minérales porteuses de l'élément considéré (anatase), confirmant de ce faite le transfert de particules de la taille des argiles (<2 µm) dans les podzols. Ce transfert d'éléments fins est confirmé plus à l'amont par la présence de revêtements argileux (cutanes) dans les horizons blanchis et appauvris (Bg) du sommet du réservoir de la nappe phréatique des latérites. Enfin et comme dans la séquence du Jaú, l'accumulation de substances organiques dans les horizons spodiques des podzols peu différenciés (Bhs), ou plus en profondeur de ceux de podzols mieux différenciés (Bh et BCs), est couplée à une accumulation de métaux, qui s'observe aussi à plus grande profondeur pour Al (dans Bhs et BCs) que pour Fe (essentiellement dans Bh).

Les podzols incisés de cette site (4) présentent des différences notoires par rapport à ceux étudiés antérieurement au Jaú (Site 3) dans des dépressions. Ces différences s'observent à deux niveaux : (i) à l'amont au niveau des fronts latéraux de podzolisation, soulignés en surface par un léger affaissement topographique, et (ii) à l'aval des versants qui acquiert alors

une forme convexe du faite d'une érosion régressive par les rivières. A l'amont, les accumulations de matières organiques sont nettement moins abondantes dans les fronts de podzolisation, plus particulièrement dans les horizons spodiques des podzols peu différenciés (moindre épaisseur des horizons Bhs), mais aussi dans les horizons Bh (fins et discontinus) de la bordure des réservoirs sableux. D'autre part, la plus grande abondance de ségrégations ferrugineuses dans les saprolites hydromorphes jouxtant les aires podzoliques de l'amont témoigne de périodes d'oxydation plus prolongées. A l'aval, l'érosion du bas de versant semble propice à une nette réactivation du processus de podzolisation. Cette réactivation se traduit par la descente du front de podzolisation dans les saprolites fines puis grossières des latérites et la formation d'une seconde génération d'horizons spodiques très fortement imprégnés par les substances organiques. De l'amont vers l'aval des aires podzolisées, l'accroissement en profondeur des imprégnations organiques dans les horizons illuviés ou spodiques est étroitement couplé à un épaississement des horizons éluviés de surface où prédominent les résidus organiques. Ce gradient latéral affectant à la fois les horizons éluviés et illuviés des podzols peut dans un premier temps être attribué à une augmentation des apports organiques, avec le développement d'une forêt plus ouverte à l'amont en milieu mieux drainé et d'une forêt dense ripariènne dans la zone d'affleurement de la nappe à l'aval. Il est aussi le reflet de conditions de drainage contrastées. Le rabattement des nappes à l'amont des aires podzoliques améliore les conditions de drainage, réactivant de ce fait la minéralisation des substances organiques des horizons spodiques des podzols et libérant de ce fait les métaux préalablement associés à ces composés organiques. A l'inverse, le maintien de conditions anoxiques en bas de versant favorise l'accumulation de substances organiques sans doute plus récentes. La faible acidification de ces nouveaux environnements podzoliques riches en minéraux altérables favorise la production de grandes quantités de complexes organo-métalliques (principalement Al).

4.1. Introduction

We present in this study results of geochemical, mineralogical and structural investigations performed along a 80m long soil catena, which illustrated the lateral transition between clay-depleted laterites and podzols, and the consequences of the downslope incisions of waterlogged podzols by river incisions. Soils of the catena are formed on granites of the Uaupés Suite and are localised 30km West of the town of de São Gabriel da Cachoeira, at the

border of the widely podzoliszed region of the Curicuriari subcatchment (Radam Brasil, 1974). This subcatchment is located in the high rainfall region of the upper Negro River watershed and covered by waterlogged podzols on 95% of its surfaces. It is then dominantly drained by black waters and presents in major riverbeds white sands from the physical erosion of podzols. Belonging the huge podzolised and waterlogged peneplains of the *Ucayali* surface (Campbell et al., 2006), the soil catena extends from yellowish clay-depleted laterites on a residual hill-top of the peneplain to waterlogged podzols eroded by a tributary of the Curicuriari river. Results of this study are compared to those obtained previously on less podzolized landscapes and drier climates of the Jaú region, 600km South East of São Gabriel da Cachoeira in the middle Negro River Watershed (Nascimento et al., 2004). In the Jaú region, small areas of poorly drained waterlogged podzols are found in the central parts of low elevation plateaus. The main objectives of this study is to establish the structural and mineralogical analogies between both types of soil catena and to reveal the major differences, which mostly result from the incision and drainage of waterlogged podzols of the upper Amazon Basin.

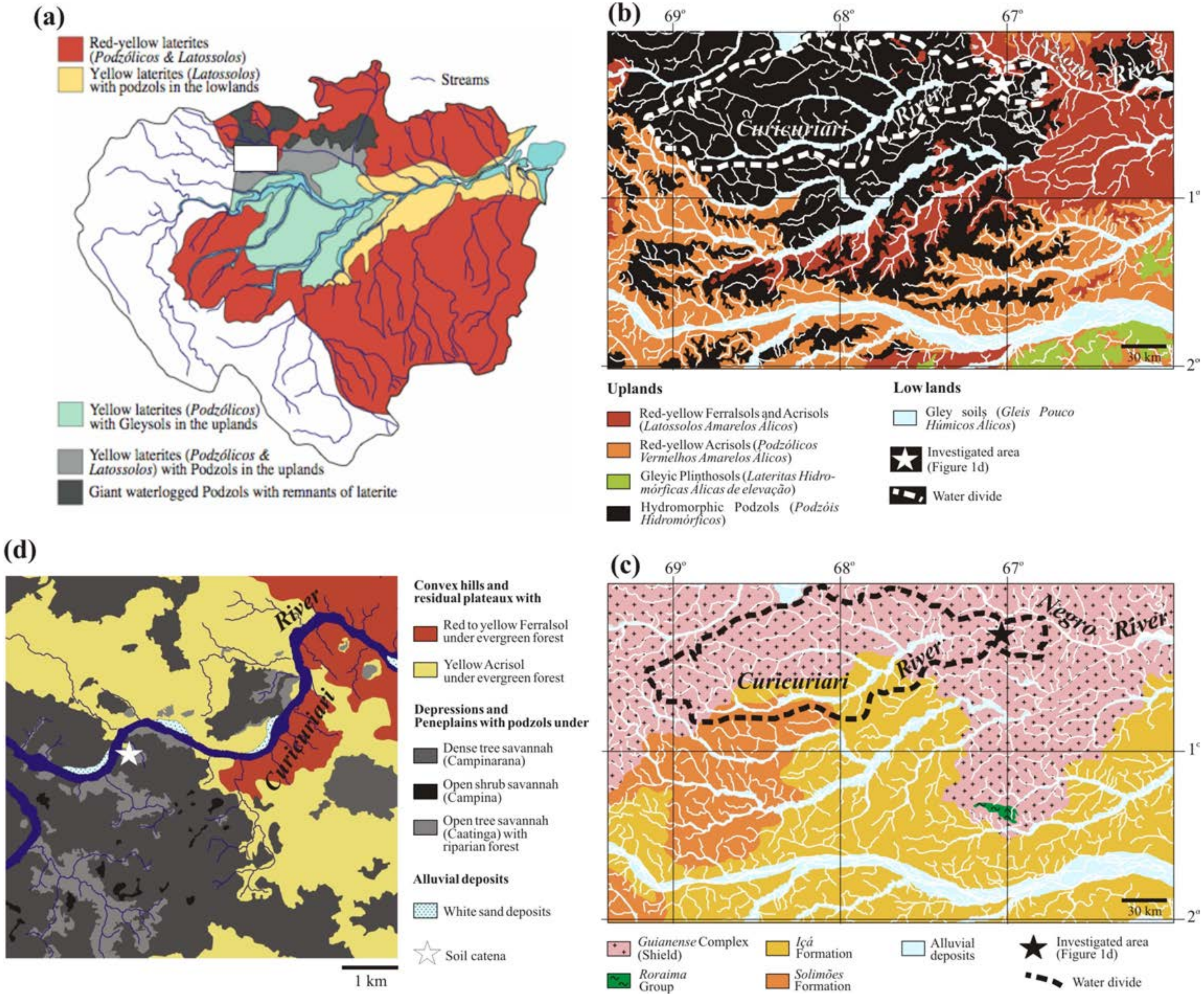


***Figure 1**. (a) Broad scale soil map of the Brazilian Amazon Basin (reduced and simplified from Radam Brasil maps at 1:2 500 000) showing the extent of podzols in the upper Basin (white rectangle insert refers to Figure 1b,c). (b) Regional soil and (c) geological maps (extracts from the Radam Brasil maps at 1 :1 000 000) showing the distribution of Gleyic Plinthosols and Hydromorphic Podzols in relation to better drained lateritic soils (Ferralsols and Acrisols) of the low elevation peneplain formed on both rock and sedimentary formations (stars insert refers to Figure 1d). Note that the Curicuriari watershed (water divide in dashed line) is almost completely podzolised. (d) Local geomorphological and vegetation map at the lateral weathering front between laterites and podzols (white star insert refers to the soil catena).*

4.2. Materials and methods

Soil description and sampling

Soil profiles were photographed on clean cuts trenches and pits and described according to the ISRIC-FAO (1994) vocabulary along a 80m long soil catena. Photographs (Figure 2a) and soil description allowed the construction of a bi-dimensional representation of the soil organization along the catena using graphic softwares (Figure 2b) (Rinder et al., 1994). The soil catena illustrates the transition between well-drained Acrisols and waterlogged Podzols of the low elevation peneplain of the upper Rio Negro watershed (Figure 1d). A small brook of the Curicuriari River incises the downslope podzols of the catena. This brook is 5m below the hill-top level with Acrisols. The soil catena presents a convex sloping side and extends from a forest on the hill-top to a *Caatinga* in the midslope position and an inundated riparian forest near the brook.

Soil profiles were described in detail and sampled at 8 key sites along the catena (I to VIII in Figure 2b). A total of 89 bulk samples were collected vertically in soil and saprolite of the investigated profiles for chemical, physical and mineralogical investigation. We also sample in cardboard boxes 32 undisturbed fragments of soil horizons, saprolites and rocks from pits or nearby riverbed outcrops. Air-dried undisturbed samples were oven dried at $35^{o}C$ during 1 week, impregnated with resin, cut and ground for thin section elaboration according to Fitzpatrick (1970). Thin sections were observed with a Zeiss Axioskop 40-Hall 100 microscope, under plain-polarized light (PPL) and cross-polarized light (CPL).

Chemical and physical analyses

Air-dried soil samples were sieved through a 2-mm screen prior to chemical and physical analyses. Particle-size distribution was determined by sieving (sand fractions) and pipetting (clay and silt fractions), after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. pH was measured both in water and M KCL (soil:solution; 1:2.5). Organic C and N were determined on air-dried samples using a Carmograph LECO CHN analyser. Total chemical analyses were performed at Actlabs Ltd (Canada) on crushed and pulverised samples passing a 150-mesh (106 µm) sieve. Chemical composition of the samples was determined by inductively coupled plasma atomic emission spectrometry for major elements and inductively coupled plasma atomic mass spectrometry for trace elements. Mass balance factors (j,w) were calculated vertically at the 8 sampling sites (Figure 2b) according

to the iso-element approach of Brimhall et al. (1991) to assess the relative losses or gains of major and trace elements. Calculations were done as follow (Chadwick et al., 1990):

$$_{j,w} = \frac{C_{j,w}/C_{i,w}}{C_{j,p}/C_{i,p}} - 1$$

where Cj,w and Ci,w is the concentrations of the element (j) and the invariant (i) in the weathered material (w), respectively; and Cj,p and Ci,p is the concentrations of the same elements (j and i) in the protore or parent rock (p) .

X-Ray diffraction and spectroscopic analyses

Mineralogical composition of the samples was assessed on fine earths (<2mm) and clay size fractions (<2µm) by powder X Ray Diffraction (XRD) with a PHILLIPS PW 1730 using Cu K radiation and operating at 40 kV and 30 mA. XRD patterns were collected for 2 angles ranging from 3 to 90° with a 0.03° steps and a counting time of 15s per. Fine earth samples were manually ground to powders (± 30 m) in an agate mortar and prepared according to the technique of the "back pack-mounted slide" (Bish and Reynolds, 1989). Identification of the mineral phases was carried out by comparing the experimental XRD patterns with those from the mineral references of the ICDD data set.

Fourier-transform Infra-Red spectroscopy (FTIR) was performed in the transmission mode using a Nicolet Magna 560 IR Spectrometer. One mg of oven-dried and dispersed clay was mixed with 300 mg KBr and pressed twice at 10 ts.cm^{-2} to form a KBr disc. The KBr discs were heated at 105°C overnight to remove absorbed water. The spectra were run in the 400 to 4000 cm^{-1} range with a 2cm^{-1} resolution.

Diffuse reflectance spectra were obtained from gently ground bulk samples, oven dried at 60°C overnight. Samples were put into a 27 mm diameter hole in an Al disk (3 mm thick) then gently pressed against a quartz glass. Spectra were taken from 200 to 2500 nm at 0.1 nm increments using a Cary 5G US/VIS/NIR spectrophotometer with a 150 nm integrating sphere (Labsphere, Inc., USA). Reflectance measurements were made relative to a teflon standard covered with a quartz glass. The wavelength-dependent reflectance functions were transformed into remission functions, which were smoothed using a cubic spline fitting procedure then the second derivatives were calculated (Malengreau et al., 1996). The same smoothing and derivative parameters were applied for all the spectra.

Colours were determined from the reflectance curves in the visible range (from 360 to 830nm) as follows: the CIE tristimulus values (X, Y, Z) were computed from the spectral reflectance and energy of the light source for each wavelength using the colour matching functions of the CIE standard illuminant C (Wyszecki & Stiles, 1982). Tristimulus values were converted into colour units (x, y and Y%) of the CIE System (1931) and in those of the Helmholtz coordinates (L_d and P_e). They were ultimately plotted in the colour diagram of the visible range. In this diagram, the dominant wavelength (L_d) is the slope between the white light source and a given dot, and is related to the tint of the sample. The excitation purity (P_e) is equivalent to the chroma of the Munsell colour chart. It is scaled between 0 % for a colourless sample and 100 % for a pure colour monitored at the output of a monochromator (Bedidi et al., 1992).

4.3. Results and discussion

Vertical and lateral soil differentiation along the catena

According to structure and consistency, two superimposed and unconsolidated sets of horizons can be distinguished over the fresh granitic basement (R) of the catena (Figure 2): (1) a dense and compact saprolitic layer (C, CB and BC horizons), and (2) a loose soil mantle (A, AE, B and E horizons) less than 2.5m thick. The saprolite lacks soil structure, and presents a continuous groundmass. At the base of the saprolite, the porphyric texture and heterogeneous colours of the granite are preserved (C and CB horizons). Coarse sands (200 – 2000µm) are abundant (Figure 3a) and primary minerals are partly weathered (Figure 3b). More strongly weathered materials with finer sands are observed in the upper section of the saprolite, mostly in midslope positions (BC horizons), but also in the overlying soil mantle (A, AE, B and E horizons) (Figure 3a,b). However in the downslope position, the lower part of the soil mantle (E/C horizon) exhibits coarse sands and partly weathered primary minerals, as in the underlying coarse saprolite (C and CB horizons) (Figure 3a,b).

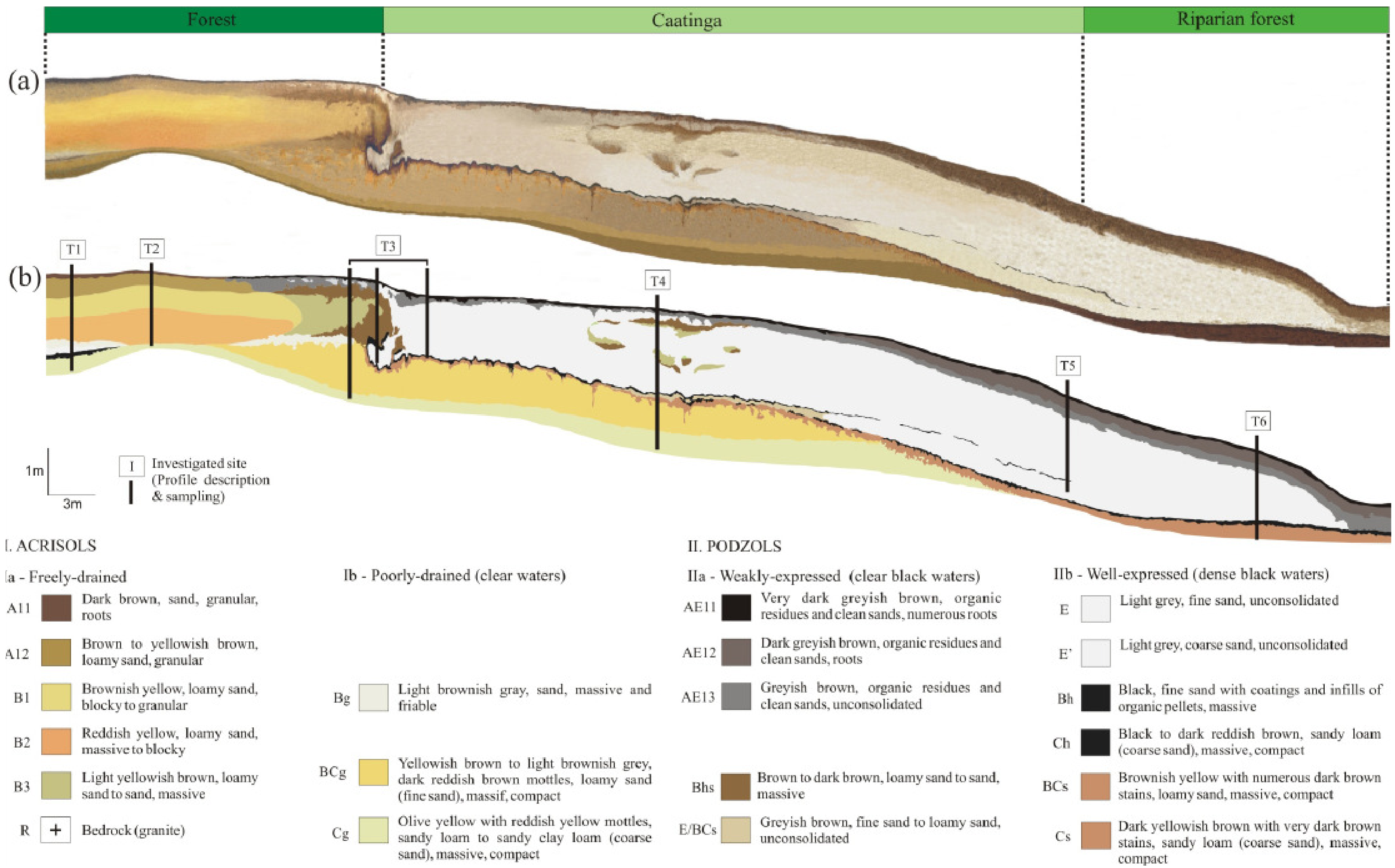


Figure 2*. Soil catena and type of vegetation from a hill-top to a major incision of a tributary of the Curicuriari River: (a) photo composition of pits and trenches used with detailed field descriptions to delineate (b) the major horizons at the weathering front between Acrisols and Podzols. Horizons are grouped in three major compartments of contrasted hydro-geochemical properties (I, II and III).*

The saprolite and soil mantle can further be dissociated in three main compartments according to texture and colour (I, II and III in Figure 2). The three compartments correspond to: (1) the freely drained topsoil A and B horizons of Acrisols on the hill-top, (2) the hydromorphic subsoil Bg, BCg and Cg horizons of Acrisols in upslope and midslope positions and (3) the eluviated topsoil (AE & E) and illuviated subsoil (Bhs, Bh, BCh & BCs) horizons of podzols in midslope and downslope positions. Similar types of compartments were already recognised in the podzolised soil landscapes of the upper Amazon Basin (Dubroeucq et al., 1999; Nascimento et al., 2004). They were assigned to contrasted hydrological regimes and geochemical environments, with clear waters in permanent deep groundwater for the upslope and hydromorphic subsoil, and black waters in perched groundwater for the downslope podzolic area (Nascimento et al., 2008). Moreover, the drastic hydro-geochemical change reported in the topsoil between the upslope Acrisols (freely drained) and the downslope podzols (acidic and periodically waterlogged) has significant impacts on the vegetation. It explains that the structure of the vegetation match those of the soils (Figure 1d, 2a).

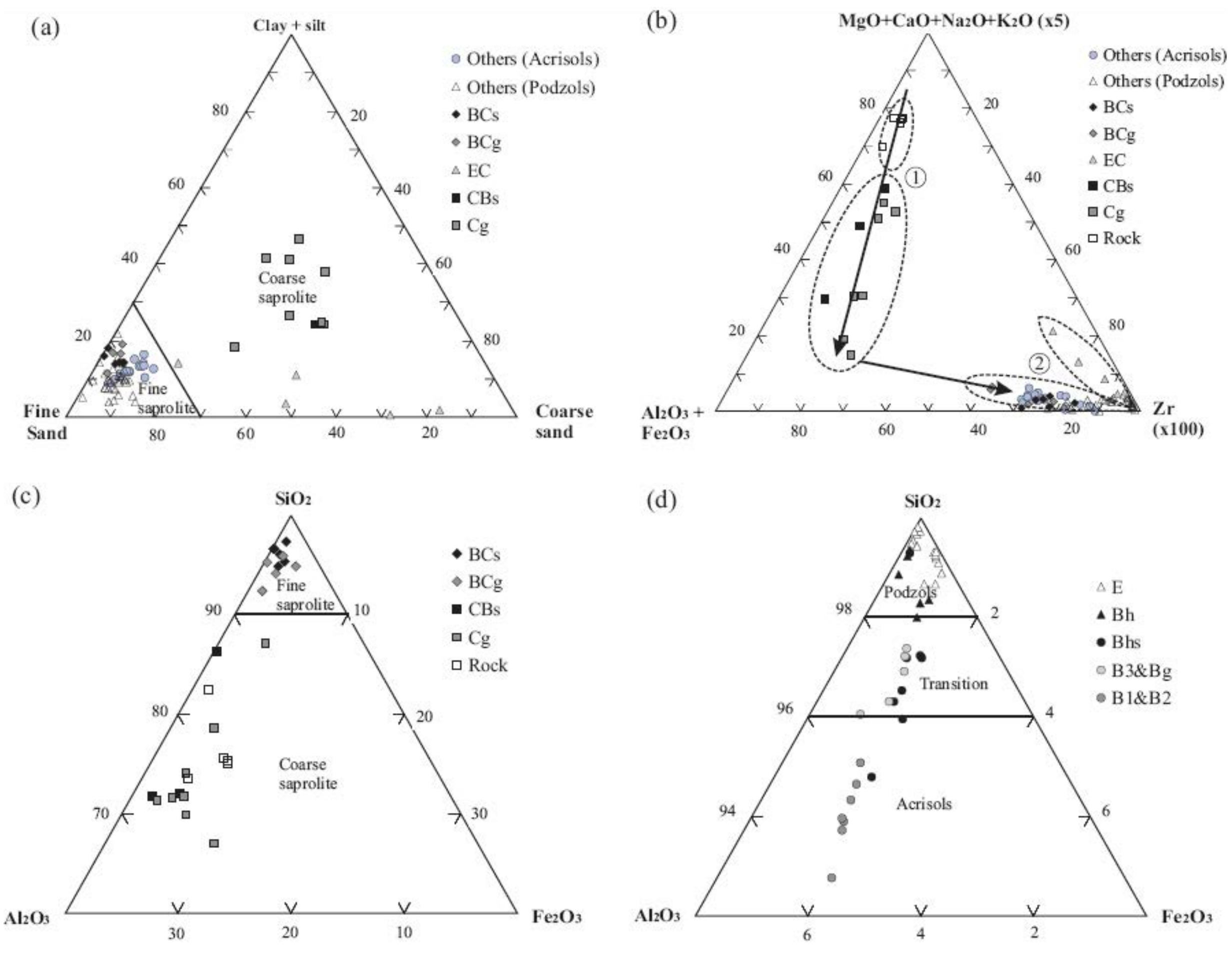


Figure 3*. (a) Textural and (b) chemical plots of major horizons in ternary diagrams showing (a) large proportion of coarse sands and (b) less weathered materials at the base and downslope part of the soil catena (C, BC and E/C). Proportion of* SiO_2*,* Al_2O_3 *and* Fe_2O_3 *in*

ternary diagrams of (c) saprolite and (d) soil horizons of the soil catena, illustrating (c) the drastic loss of Al- and Fe-bearing minerals from the coarse to the fine saprolite and (d) the minor but ultimate loss of such minerals from the upslope Acrisols to the downslope podzols.

The 1st compartment on the hill-top of the catena is covered by forest. The relative homogeneity of its A and B horizons, and their light textures and blocky to granular structures are indicators of a freely drained environment with dominant vertical water flows. The mineral B-horizons are loamy-sand and present the largest clay contents of the soil mantle (8 - 12%). They grade progressively upwards from reddish yellow (7.5YR6/8) in B2 to brownish yellow (10YR6/6) in B1. Under microscope, the iron coloured clay domains are scattered, around or between close packed quartz sands (Figure 4d). Towards the surface, the slight decrease in clay contents and net increase in organic matter leads to the differentiation of the yellowish brown to dark brown (10YR4/3 - 5/6) A12 and A11 horizons. Laterally, the mineral B1 and B2 horizons give progressively place to a light yellowish brown (2.Y6/4) B3 horizon, which marks the transition with the downslope podzols. This last horizon reveals a slight decrease of the clay content and a complete soil structure breakdown.

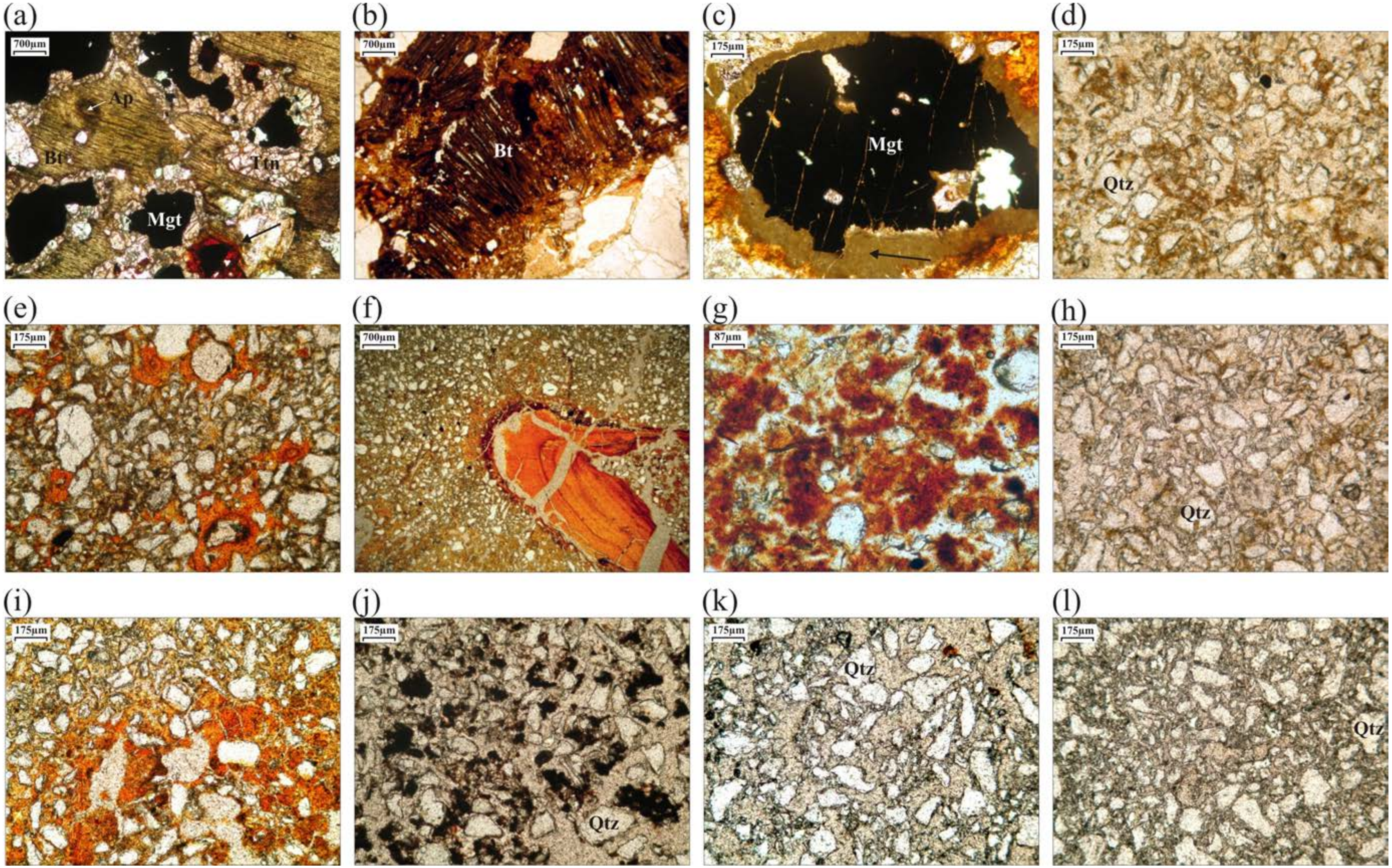


***Figure 4**. Petrographic fabrics of rocks and soil horizons under unpolarized light: (a) detailed view of a mafic body in the granite showing large crystals of biotite (Bt) with smaller inclusions of magnetite (Mgt) surrounded by grains of titanite (Ttn), note red weathered products at the*

margin of a magnetite (black arrow) and an apatite crystal (Ap) with surrounding fission tracks in biotite, (b) weathered biotite (Bt) residues strongly impregnated by Fe-oxides in coarse saprolite (BC2g), (c) yellowish brown weathered products (arrow) of titanite at the margin of a magnetite grain in coarse saprolite (BC2g), (d) dispersed iron coloured clays around or between close packed quartz sands (Qtz) in B-horizon of Acrisols, (e) reddish iron stains around quartz grains or on pore walls in fine saprolite (BC1g), (f) dark reddish iron stains on the wall of a macrovoid and cracked clay cutan infill variously coloured by Fe-oxides in fine saprolite (BC1g), (g) Dark brown organic compounds coating clay minerals in Bhs horizons of podzols, (h) low proportion of clay minerals between close packed assemblage of quartz (Qtz) in Bg horizon, (i) Dark brown, fine-grained and cracked organic coatings on clay minerals in the upper part of the fine saprolite, (j) Black organic decays aggregated in pellets that infill incompletely the interstices between quartz grains in Bh horizon, (k) sandy and porous AE horizons of podzols with dispersed fresh organic residues and black organic pellets, (i) close packed assemblage of quartz (Qtz) in E horizons of Podzols.

The 2nd compartment of the catena is observed at greater depth in upslope and midslope positions and related to Bg, BCg and Cg horizons (Figure 2), which clearly exhibit redoximorphic features. It thus corresponds to the aquifer of the deep groundwater. At the base of this compartment, the coarse saprolite (Cg) is sandy loam to sandy clay loam and is highly heterogeneous, with a dominant olive yellow colour (2.5Y6/6). The coarse saprolite may contain up to 35 wt% of clay, which are mostly inherited from the weathering of the predominant feldspars of the granite (albite, anorthite and microcline). The reddish yellow (5YR5/5) mottles of this saprolite are, on the opposite, mostly assigned to the weathering of mafic minerals (biotite, amphibolite and magnetite), which are grouped in scattered millimetric to centimetric bodies in the granite (Figure 4a). Biotites and amphibolites are strongly weathered in the coarse saprolite. Iron segregations are either observed as coatings on primary mineral remnants (Figure 4b) or as stains on secondary clay minerals. By contrast, the more resistant magnetite to chemical weathering are locally preserved as small grains in the saprolite and overlying soil mantle (Figure 4c,d). Small crystals of titanite are commonly surrounding the gains of magnetite in granite (Figure 4a). They are rapidly dissolved and replaced by yellowish brown weathering rings in the coarse saprolite (Figure 4c). The overlying fine saprolite (BCg) is laterally discontinuous along the catena and particularly thick in midslope positions (Figure 2b). It is clay depleted and deeply weathered (Figure 3a,b). Mafic minerals and feldspars are much less abundant than in Cg, and the quartz grains have predominantly a fine sand particle size. This saprolite is loamy sand and presents similar clay contents than the above Acrisol B-horizons (8 - 12%). It exhibits a yellowish brown (10YR5/4) to light brownish grey (2.5Y6/2) groundmass with dark reddish brown (2.5YR3/4) iron segregations. The latter surround remnants of mafic minerals (mostly magnetite) or more commonly impregnate clay minerals as diffuse stains on pore walls or within the groundmass (Figure 4e). Crescent clay cutans, variously impregnated by Fe-oxides, are also observed in macrovoids of the saprolite (Figure 4f). Both iron stains and clay cutans are more abundant in the upper part of the fine saprolite than in its lower part, particularly close to the podzolic area. At this location, a thin and discontinuous Bg horizon can dissociate the fine saprolite from the overlying B-horizons of Acrisols (Figure 2b). This horizon is light brownish grey (2.5Y6/2), almost devoid of iron stains, and is lacking soil structure and consistency. It has less clay contents (4 - 8%) and also displays under the microscope less clay minerals (Figure 4h) than its overlying B (Figure 4d) or underlying BC (Figure 4e) horizons.

The 3rd compartment of the catena corresponds to the podzolic area that expands from midslope to downslope positions on a convex sloping side (Figure 2). It comprises eluviated horizons over illuviated ones (also named spodic horizons) and corresponds to the aquifer of a perched groundwater drained by the river network. An open forest (*Caatinga*), with smaller trees than those growing on the upslope Acrisols, covers the podzols in midslope positions. It gradually gives place to a riparian forest close to major river incisions, and thus reveals wetter lands in downslope positions. Podzol development differs on both types of topographic location and vegetation cover. In midslope positions, the vertical development of podzols is impeded, at about 1.5m deep, by the fine saprolite. Podzols thus mostly expand laterally at the expense of the upslope A, B and Bg horizons of Acrisols. Both types of soils display laterally a characteristic double tongue-like shape transition (Figure 2), which has been systematically observed at the margin of the podzolised areas of the upper Amazon Basin (Dubroeucq & Volkof, 1998; Dubroeucq et al., 1999; Nascimento et al., 2004). This kind of transition has recently been assigned to the dynamics of the groundwater (Nascimento et al., 2008).

At high water levels, the perched groundwater seeps at the surface at the margin of the podzolic area. Weakly developed podzols can then form at the expense of the A and B3 horizons of the upslope Acrisols and gives place to the AE and Bhs horizons, respectively, with the local individualisation in between of bleached E materials (upper section of pits III and IV). In the AE horizons, the clay content is less than 4%. The mineral phases consist of clean sands and the organic ones of fresh plant remains (leaves and roots) as well as coarse dark brown to black organic decays. These organic substances and the fine roots of the open forest decrease downwards from the very dark greyish brown (10YR3/2) AE11 horizon at the surface to the greyish brown (10YR6/2) AE13 horizon in the subsurface. They nearly disappear in the underlying and downslope light grey (10YR7/1) E horizon. The latter is bleached and unconsolidated. It is almost free of clay minerals and consists of close packed quartz grains of a dominant fine sand particle size in midslope positions (Figure 4i). Fine grained organic matter accumulates at the margin of podzolic area into the B3 and forms the brown (10YR5/3) to dark brown (10YR3/3) Bhs horizon. It impregnates the clay minerals between the quartz grains and demarcate at micro-scale diffuse, dark brown organic stains on pore walls and within the groundmass (Figure 4g).

At low water levels, the deep groundwater of the upslope Acrisols can seeps into the lower part of the podzolic area and thus feeds the perched groundwater. Greater trough flow and loss of matter in perched groundwater explain the lateral expansion of the E horizon into the

hydromorphic subsoil horizons of the upslope Acrisols (Nascimento et al., 2008). The lower tongue then forms at the base and margin of the podzolic area (lower section of pit IV). Moreover, podzolic horizons can expand upslope on longer distances (up to 15m) at the favour of twisting channels, more specifically within the clay-depleted and light brownish grey Bg horizon of Acrisols (one of these channels is cut perpendicularly in the lower section of pit II). This reveals that eluviation and illuviation of clay in the upper part of the groundwater aquifer might be pre-existing mechanisms to podzolisation. Due to larger losses of clay particles, a small topographic slope break marks the connection of the upper and lower tongues (between pits IV and V). Downslope, remnants of B3 and Bhs within the bleached E horizon of well-expressed podzols (upper section of Pit VI) suggest that the upslope expansion of the latter is not a continuous process. This lateral expansion has likely acted abruptly in successive steps, most likely during periods of exceptional high rainfalls. At least, spodic Bh and BCs horizons are also formed at the base and margin of the podzolic area. They result from the vertical transfer of organic substances in the perched groundwater of podzols and their physical fractionation and accumulation in texture contrasted subsoil horizons during the recede of that groundwater (Duchaufour, 1972; Fritsch et al., 2009). Organic colloids or particles, accumulated at the margin and base of the eluviated E horizon, form the black (10YR2/1) Bh horizon. The latter is thin and discontinuous at the margin of the podzolic area. Under the microscope, it exhibits black organic pellets that fill incompletely the interstices managed by the quartz grains (Figure 4j). Finest organic substances accumulate at greater depths, mainly in the upper part of the saprolite. They form dark brown and cracked organic stains or coatings (Figure 4i) in brownish yellow (10YR6/6) to dark brown (7.5YR3.5/3) BCs horizon, as in Bhs (Figure 4g).

Towards downslope positions, the convexity of the slope increase, the podzols deepen and the granite outcrop in the brook. Physical denudation of the downslope podzols, which has fed in white sand deposits the Curicuriari river, has thus also favoured its downward expansion into the saprolites (Figure 2). This soil dynamics starts at the nicking point of the convex sloping side and is initiated by the formation, under the thin Bh horizon, of a greyish brown (10YR5/2) sandy E/BC horizon (lower section of pit VI). This horizon gradually turns light grey downslope (E horizon) and a second generation of spodic horizons are formed at greater depths. In low-lying positions and under the riparian forest, podzols expand ultimately into the coarse saprolite forming the light grey (10YR7/1) E/C horizon above the black (5YR3/1) and dark yellowish brown (10YR4/4) spodic horizons (CBh and CBs, respectively).

Observation of the whole catena (Figure 2) also shows that organic compounds weakly accumulate at the margin of the podzolic area and, on the opposite, deeply impregnate the eroded soil landforms in lowlying positions. In particular, the thicknesses of the eluviated organic topsoil (AE) and spodic subsoil horizons (Bh and BCs, and ultimately CBh and CBs) of podzols increase gradually towards the brook likely due to longer periods of waterlogging and change of vegetation (from *Caatinga* to riparian forest).

Geochemistry of trace elements (Zr, Ti and Th)

Deep weathering of rocks in tropical regions commonly leads to complete removal of alkali and alkali hearth elements (Na, K, Mg and Ca), partial depletion of Si and therefore to residual accumulation in soils of less mobile elements such as major metal cations (mostly Al and Fe) and trace elements. Trace elements such as Zr, Ti and Th generally accumulate from bottom to top of autochtonous tropical soils (e.g. Ferrasols) and the positive correlations established between each other testimonies of their weak mobility during weathering processes (Fritsch et al., 2002). This is commonly attributed to their incorporation in accessory minerals, which are very resistant to chemical weathering (e.g. zircon for Zr). They are thus commonly used as invariants for mass balance modelling and assessment of losses and gains of more soluble elements in weathered profiles (e.g. Braun et al., 1993). However, chemical analyses of water systems have established that organic acids could initiate the chemical weathering of these accessory minerals in waterlogged environments and contribute to the transfer of trace elements to river systems (Viers et al., 1997). Chemical investigations along soil catena has also emphasised that losses and gains of such elements could also be related to biological uptakes, runoff and selective translocation of their parent minerals according to particle size (Fritsch et al., 2007).

Zirconium behaves differently than Ti and Th in the study site. As expected for most tropical soils, the Zr content increases from rock to saprolite and ultimately to the overlying soil horizons (Figure 3b). The reverse trend is reported for both Ti and Th (Figure 5a). This is consistent with the incorporation of Zr in zircon, an accessory mineral highly resistant to chemical weathering (Balan et al., 2001; Taboada et al., 2006). Zircon in granites and regoliths of the study site has also an average particle size of about 150µm that prevents its translocation in most soil horizons. It was then used as a chemical invariant to calculate mass balance factors and assess relative losses or gains of other chemical elements. Results obtained for trace elements indicate that 80% of the initial stock of Ti and 90% of the Th are

lost in the fine saprolite and overlying soil horizons of the upslope Acrisols (Figure 5b). This is attributed for Ti to the weathering of titanite crystals in coarse saprolite (Figure 4c) and the formation in soils of small grains (< 2µm) of anatase, according to petrographic and XRD investigations. Similar mechanisms have likely happened for thorium with the dissolution at depth of Th-bearing minerals (e.g. apatite and allanite) and the formation in soils of thorianite crystals. However, the tiny size and the small concentration of the latter have prevented its identification.

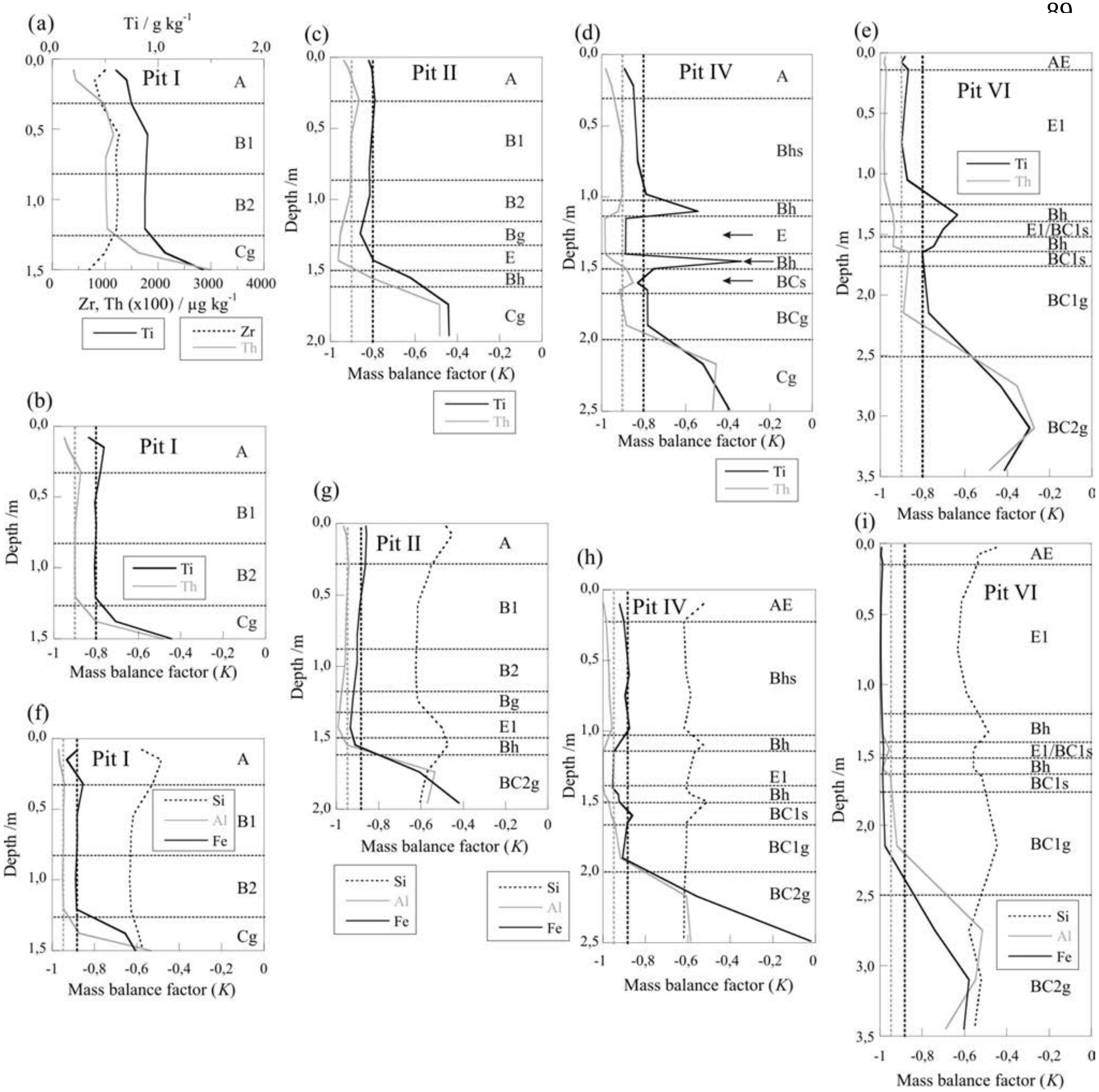


Figure 5*. (a) Vertical distribution of Zr, Ti and Th in the upslope Acrisol (Pit I) and mass balance factors calculated vertically for (b, c, d and e) Ti and Th, and (f, g, h and i) Si, Al and Fe in four profiles of the soil catena (I, II, IV and VI, respectively).*

As the eluviated and illuviated horizons of podzols mainly form laterally at the expense of the upslope Acrisol soil horizons, the remaining fractions of Ti (20%) and Th (10%) stored in the latter will be used as new threshold values for assessing losses and gains of both elements in the downslope podzols (see vertical dashed lines in Figure 5). Figure 5c,d,e shows that the development of podzols into Acrisols leads to drastic losses of Ti and Th in their eluviated horizons and, on the opposite, gains of the same elements in their illuviated or spodic B-horizons. Losses of Ti and Th are initiated at depth in the Bg and E horizons of the twisted channels that enter into the upslope Acrisol, on top of the saprolite (bottom section of pit II in Figure 5c). In the transition zone (pit IV in Figure 5d), losses of both elements are also initiated near the surface in the AE and Bhs horizons of weakly expressed podzols (upper tongue). These losses become more relevant at the same topographic location, but at greater depth, in the bleached E horizon of better differentiated podzols (lower tongue). They are optimal and remains almost unchanged in the eluviated AE and E horizons of the well-developed podzols in midslope and downslope positions (pit VI, in Figure 5e). Thorium has almost been completely removed from these horizons whereas half of the initial stock of Ti stored in Acrisols has been lost. Both elements are on the opposite accumulated in the illuviated or spodic horizons of well-expressed podzols (Figure 5d,e). These gains are more important for Ti than Th and the former accumulate at shallower depth in Bh horizons than the latter in the underlying BCs horizons. This dissociation with depth of both types of trace elements in two superimposed spodic horizons suggests that they could be bound to distinct organic carriers, and translocated vertically according to their particle size. Dissolved organic carbon and their chelated Th would then accumulate at greater depth in BCs than higher molecular weight organic fractions and associated Ti. However, Ti and Th could also be incorporated in crystals of anatase and thorianite, whose particle sizes (< 2µm) allow their vertical transfer in the macro-voids of AE and E horizons of podzols. As thorianite crystals are much smaller than that of anatase, they can accumulate at greater depth in less porous horizons. XRD investigations on clay size fractions (< 2µm) confirm the physical translocation of anatase, as the main diffraction peak for the latter appear much more important in Bh horizons than in their overlying E or underlying BCs horizons (not shown). Physical transfer of organic and mineral phases is thus an important mechanism in podzol development and consistent with the concept of eluviation and illuviation commonly attributed to the formation of these soils. Obviously, this does not exclude the contribution organic acids in the weathering of clay and accessory minerals and the formation and transfer of organo-metallic complexes. The greater loss of Th than Ti in eluviated horizons of Podzols

and their smaller accumulation in their underlying spodic horizons also indicate that this element is massively exported in the black waters and rivers of podzolic environments.

Geochemistry of major elements (Na, K, Ca, Mg, Si, Al and Fe)

The contents of alkali and alkali earth elements (Na, K, Mg and Ca) stored in the bedrock decreases rapidly upwards in the weathered mantle, first in the coarse saprolite and ultimately in both the fine saprolite and overlying soil horizons (Figure 3b). The extremely low contents measured in the latter attest of the strong weathering conditions, which led to the almost complete weathering of feldspars, biotites and amphiboles from granites and the formation of Al- and Fe-bearing secondary minerals (predominantly kaolinite and gibbsite, and at lesser extent Fe-oxides). The contents of Al_2O_3 and Fe_2O_3 do not change significantly between granites and coarse saprolites but drop abruptly between latter and both fine saprolites and soil horizons (Figure 5c,d). These geochemical trends reveal that fine saprolites are clay-depleted whereas the underlying coarser ones are not. As already discussed, a third category of materials can be distinguished. They correspond to the base of the eluviated horizons of the downslope Podzols (E/C in Figures 2b and 3b), which is clay depleted but still contains alkali and alkali earth elements. This last trend confirms that podzols have ultimately expanded downwards in less weathered materials close to major river incisions.

According to mass balance factor calculations, about 60% of the Si, 90% of the Fe and 95% of the Al stored in granites have been lost by chemical weathering in the A and B horizons of the upslope Acrisols (Figure 5g). Losses seem to be less in A horizons than in B-horizons (particularly for Si), which is likely not the case as clay depleted topsoils appear also depleted in Zr (Figure 5a). As for trace elements, the remaining fractions of Al (5%) and Fe (10%) stored in the upslope B-horizons of Acrisols (see the vertical dashed lines in Figure 5) were used as new threshold values for assessing losses and gains of both metal cations in podzols (Figure 5h,i). Only losses are reported for Al and Fe, and both elements seem to be exported simultaneously (Figure 3d). Such losses, initiated in B3 and Bg horizons of Acrisols, become almost total in eluviated horizons of podzols (AE and E). For spodic horizons of podzols, their chemical compositions approach those of the surrounding horizons in which they have formed: BCg and Cg for BCs and Cs (Figure 3c), B3 and Bg for Bhs and E for Bh (Figure 3c,d).

Al-bearing secondary minerals (kaolinite and gibbsite)

DRX (not shown) and spectroscopic data in the infra red (FTIR) range reveal a monotonous mineral composition for secondary Al-bearing minerals (kaolinite and gibbsite) but a high variability in their relative proportions and total contents in bulk samples from bottom to top and upslope to downslope positions of the catena (Fig. 6). In the A and B-horizons of the upslope yellowish clay-depleted laterites (Acrisols), the contents of gibbsite are larger than that of kaolinite (Figure 6a). It slightly increases downwards in these horizons, and more abruptly in the upper part of the underlying coarse and clayey saprolite (Cg). This vertical trend in laterites likely results from the weathering of the Al-bearing minerals in the upper section of the soil profiles and the downward accumulation of Al, which precipitate as gibbsite and in larger proportion at the textural transition. It then indicates that both clay depletion and soil gibbsitisation are prior to soil podzolisation.

At the margin of the podzolic area, similar variations are observed (Figure 6b), with however lower amounts of gibbsite and kaolinite in the upper A and B horizons (AE, Bhs, B3 and Bg), but also in the underlying fine saprolite (BCg). Strong textural contrasts then exist between the fine (BCg) and coarse (Cg) saprolites, the latter still exhibiting larger amounts of Al-bearing secondary minerals and greater proportions of gibbsite in its upper section. Towards the downslope podzols, this trend is maintained. The textural contrast between the clay-depleted and upper section of the soil and the lower clay-rich saprolite in enhanced, mainly due to greater losses of Al-bearing minerals in the former (Figure 6c,d). In the midslope position (Figure 6c), the spodic horizons (Bh and BCs) do not form at this textural transition but just above at the structural transition between soil horizon and saprolite. It then confirms that clay depletion is prior to soil podzolisation but also reveals the structural control of the upper saprolitic limit in the downward expansion of podzols at the margin of the podzolic area. It also explains that podzolisation can locally pass through this transition, more specifically towards low-lying positions following deep river incisions in the landscapes. At least, gibbsite seems to be inexistent in the eluviated compartment of the downslope podzols whereas traces of kaolinite are still observed (Figure 6c,d). This new trend suggests greater dissolution rates for gibbsite than kaolinite in podzolic environments (Nascimento et al., 2004). However in the remnants of the Bhs horizons, which are preserved in the midslope position and contains greater amount of clay minerals, gibbsite is also weakly present (Figure 6c). We thus rather suggest that podzols have expanded in poorly drained laterites, restricting therefore the formation of gibbsite in their upper section.

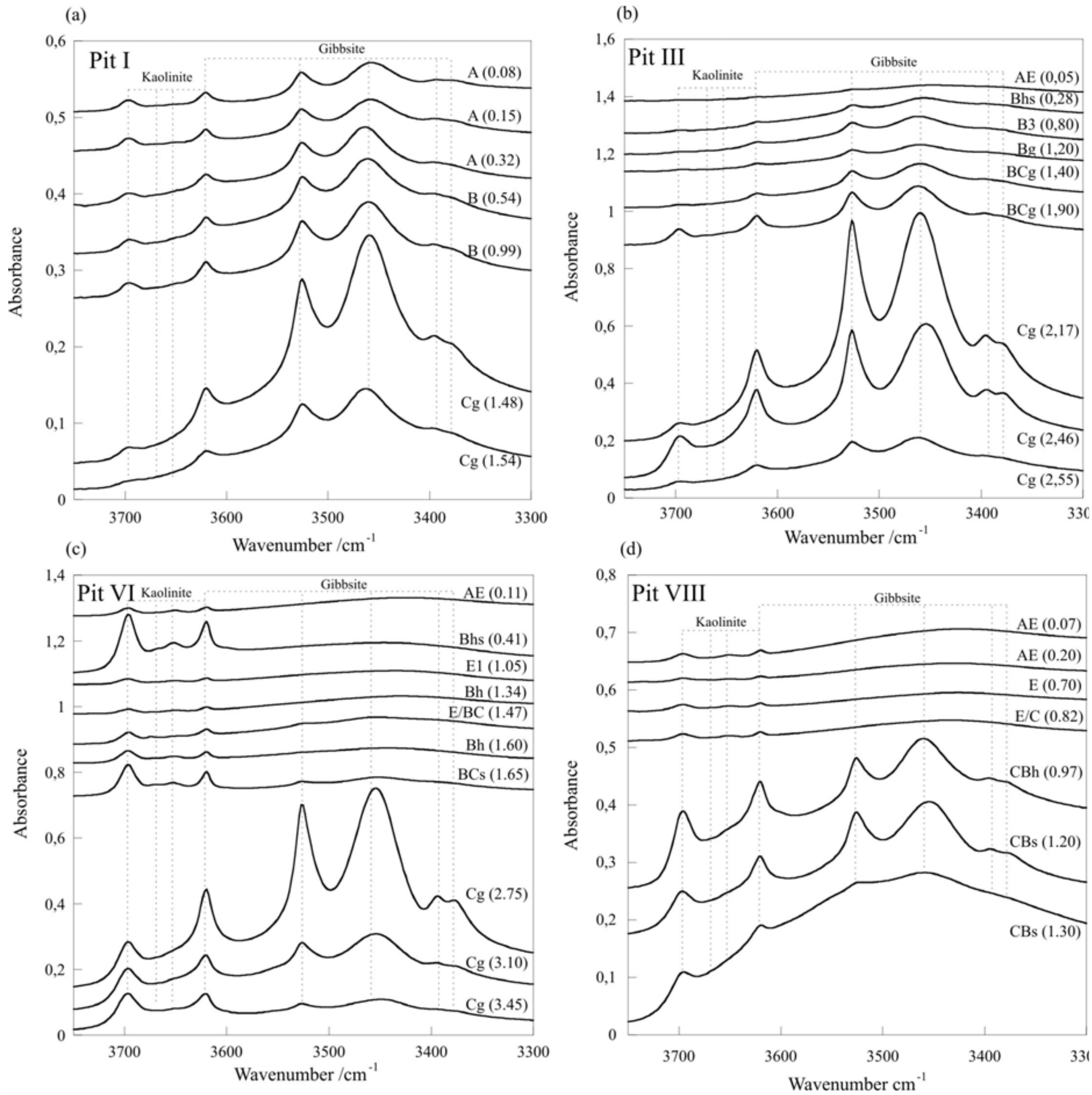


***Figure 6**. Infra Red spectra in the OH stretching band region of kaolinite and gibbsite of bulk samples from (a) the upslope Acrisol (Pit I), (b) the transition zone (Pit III) and (c,d) the downslope podzols (Pits VI and VIII, respectively) (sampling depth in meter of each sample is given in brackets).*

Fe-oxides and organically bound Fe

Diffuse reflectance spectroscopy reveals the nature and proportion of secondary Fe-oxides as well as the relative abundance of organically bound Fe (Figure 7). Soil profiles of the catena mainly contain goethite as Fe-oxides, whose proportion decreases significantly from the iron coloured topsoil A and B horizons of the upslope Acrisols to their underlying hydromorphic and downslope podzolic areas. Such global trend is illustrated with samples exhibiting on a

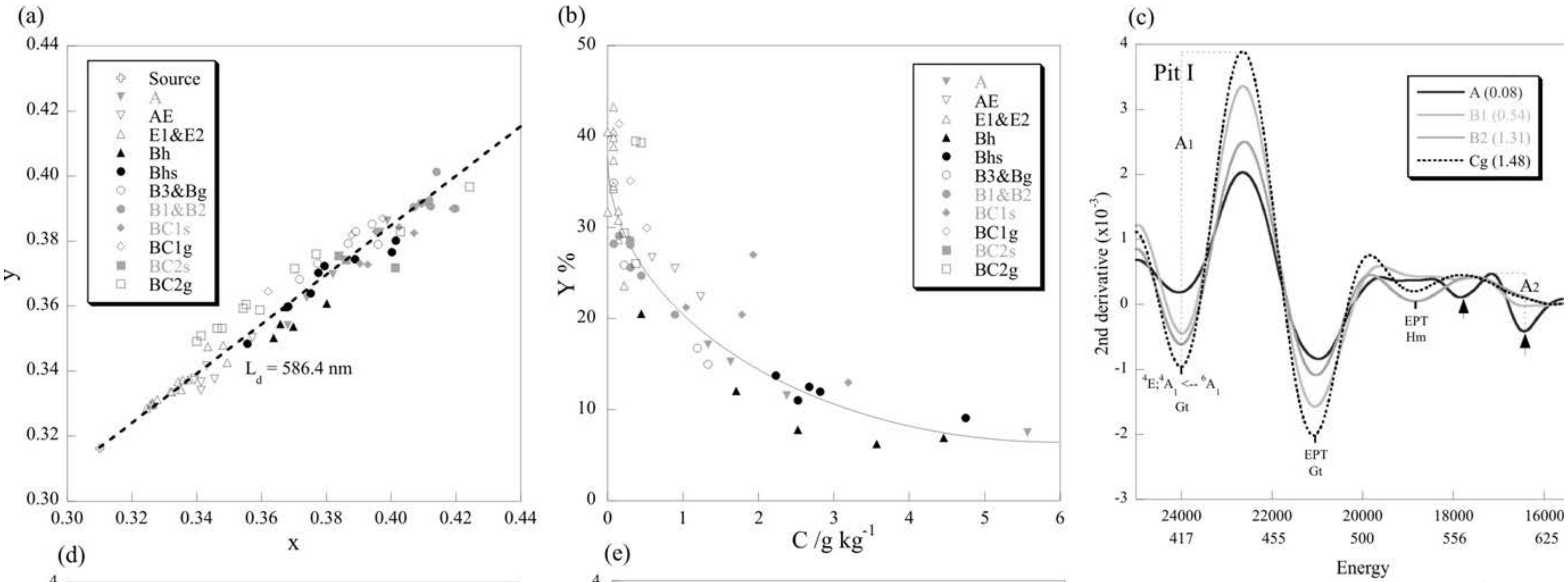
colorimeric diagram similar L_d (dominant wavelength) but contrasting P_e (excitation purity) (Figure 7a). The average L_d of 586nm is characteristic of goethite. The iron-rich samples (largest P_e values) correspond to the topsoil A and B horizons of Acrisols and the iron depleted ones (lowest P_e values) to the greyish samples of their underlying hydromorphic area (Bg, BC1g, BC2g) and all the topsoil bleached horizons of the downslope podzols (AE, E, E/C). Spodic horizons of podzols (Bhs, Bh, BC1s, BC2s) present intermediate values.

Second derivative of the remission function from reflectance curve in the visible range also exhibits two major bands (minima) for goethite (Gt) but also a minor band for hematite (Hm) at lower wavenumbers for the topsoil A and B horizons of the upslope Acrisols (Figure 7c). The relative proportion of hematite in the pool of Fe-oxides (i.e. both hematite and goethite) is optimal at the base of the B horizon and almost nil in its upper part, which is consistent with a gradual change of colour from reddish yellow (7.5YR6/8) in B2 to brownish yellow (10YR6/6) in the overlying B1. A significant decrease of the two minima for goethite (Gt) in the topsoil A horizon of Acrisols can also be linked to the appearance of two additional bands, at 16350 cm^{-1} (610 nm) and 17500 cm^{-1} (565 nm) (arrows in Figure 7c), which were assigned to organically bound Fe^{III} (Nascimento et al., 2004, Fritsch et al., 2009). At the transition between clay-depleted laterites and podzols, loss of goethite increases and the organically bound Fe is also reported in weakly expressed podzols, in topsoil AE horizons but also and mainly in their underlying Bhs horizons, as shown by the amplitudes of the two additional bands at 16350 and 17500 cm^{-1} (Figure 7d). This is further enhanced laterally in better-expressed podzols, where the organically bound Fe is also abundantly found in Bh horizons. By contrast, it is less abundant or absent in the underlying spodic BCs horizon. This is consistent with the formation of organically bound Fe following the dissolution of goethite in topsoil horizons of the margin of the podzolic area and the downward and downslope accumulation of organic colloids and Fe in Bh horizons of better-expressed Podzols (Fritsch et al., 2009).

Organic matter, organically bound Al and soil acidity

Carbon contents decrease regularly with increasing depth in the upslope clay-depleted laterites from up to 24 g kg^{-1} in A horizons to less than 3 g kg^{-1} in B horizons and the C:N ratio ranges from 10 to 27. In the podzolic area the carbon content increases (Figure 8a), more specifically in spodic horizons (up to 48 g kg^{-1}). The C:N ratio increase slightly near the surface in Bhs horizons of weakly expressed podzols, and more significantly at greater depths in Bh and BCs horizons (up to 67). The contents of Al extracted by the pyrophosphate

treatment (Al_p), which permit to assess the amounts of organically bound Al (Figure 8b), gave similar values than that obtained by Nascimento et al. (2004) on another catena associating on short distances clay-depleted laterites and waterlogged podzols. The Al_p contents in bulk samples of B-horizons average 1 g kg^{-1} in the upslope clay-depleted Acrisols. It remains almost unchanged or decreases significantly in organic-rich AE and Bh horizons of podzols and, on the opposite, increases in spodic Bhs and BCs horizons of podzols. This general trend is thus consistent with previous results of Bardy et al. (2007).



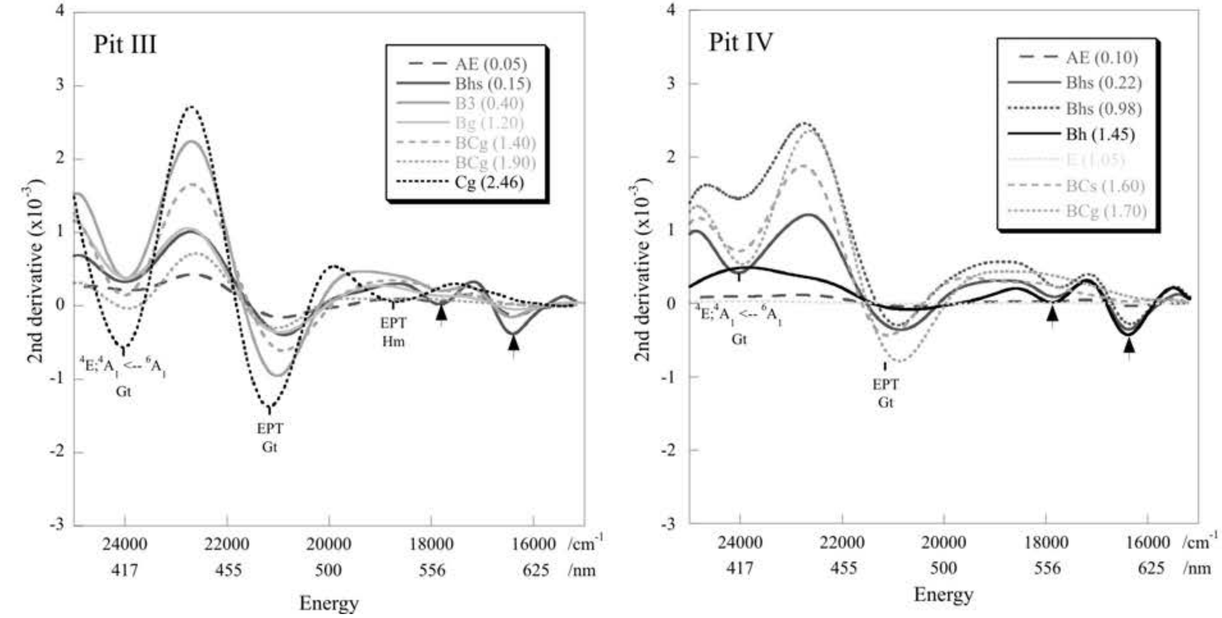


Figure 7*. (a) x and y values of tristimulus coordinates (CIE system, 1931) in a colorimeric diagram showing similar dominant wavelength (L_d) for all samples but distinct excitation purity (P_e) (tristimulus values were converted in Helmholtz coordinates: L_d and P_e), (b) Y% coordinate (CIE system, 1931) versus carbon content (C), Second-derivative spectra of the remission function f(R) in the visible range of Fe-oxides (Gt: Goethite, Hm: Hematite) in bulk samples of (c) the upslope Acrisol (Pit I) and (d,e) the midslope podzols (Pits III and IV, respectively) (sampling depth in meter of each sample is given in brackets).*

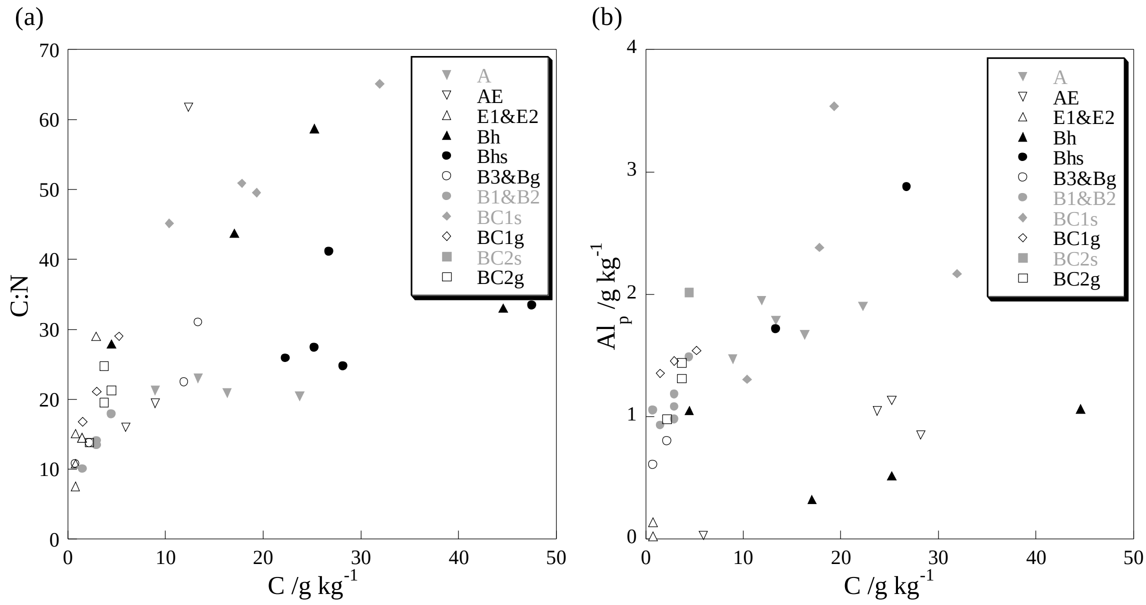


***Figure 8**. (a) carbon content (C) versus C/N ratio, (b) carbon content (C) versus amount of extractable Al by the pyrophosphate treatment (Al_d).*

The pH of soils and saprolites ranges between 5.5 and 4.0 along the catena (Figure 9). Highest pH values are reported in the topsoil A and B horizons of the upslope Acrisols. pH decreases slightly in the underlying hydromorphic horizons of these soils. It also decreases laterally in podzols. It reaches the lowest values (pH = 4) at the base of the bleached E horizons at the margin of the podzolic area in midslope positions. By contrast, pH increases downslope in eroded and less weathered waterlogged podzols.

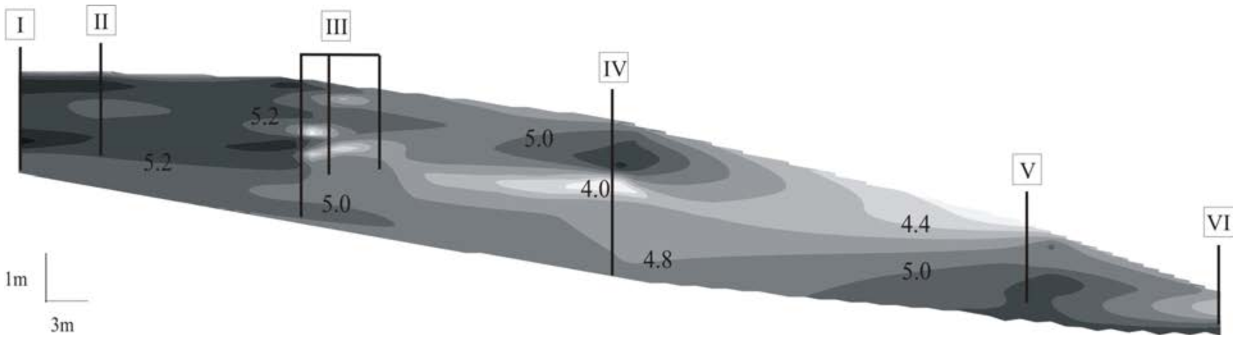


***Figure 9**. Range of pH along the soil catena.*

4.4. Discussion and conclusions

The soil catena investigated in this paper presents major structural and mineralogical analogies with that studied by Nascimento et al. (2004) in less podzolised soil landscapes of the Negro River watershed. The main analogy is the identification of the same type of structures along the catena with (i) the clay-depleted and freely drained upper part of laterites (Acrisols), (ii) their hydromorphic lower part, predominantly formed in saprolites, with their corresponding deep groundwater and (iii) the upper and downslope podzolic area, which sustains a perched groundwater. The second major analogy, which has systematically been observed along soil catena of the Amazon Basin, is the “double tongue-like” transition between the upslope laterites and the downslope podzols (Turenne, 1975; Bravard & Righi, 1989, 1990; Dubroeucq & Volkof, 1998; Lucas et al., 1987, 1996; Nascimento et al., 2004). The upper tongue results from the upslope and downward development of weakly expressed podzols on the clay-depleted laterites, thus forming thin eluviated AE and E horizons over weakly differentiated Bhs horizons. Further downslope and at greater depths, the bottom part of better-differentiated podzols is lying on the hydromorphic saprolite of laterites. It expands laterally into the upslope bleached and clay-depleted Bg horizons of the upper part of the groundwater aquifer, forming the second tongue or, in 3 dimensions, twisted channels on more than 15m long. These structures result from the interactions and dynamics of two groundwaters: (i) a permanent deep groundwater with clear waters fluctuating in the hydromorphic part of the laterites, and (ii) a more seasonal perched groundwater with black waters fluctuating in the eluviated horizons of podzols (Nascimento et al., 2008).

Soil organisations and groundwater dynamics also reveal the contribution of major structural discontinuities (in both study sites: the transition between soil and saprolite) in the vertical development of podzols and their consequences in the individualisation of well-differentiated spodic Bh and Bs (or BCs) horizons. The vertical development of podzols is impeded as soon as they reach this discontinuity, initiating therefore the lateral expansion of podzols in the landscape. In both study sites, the downward accumulation at the base of the eluviated E horizon of black organic colloids during the recede of the perched groundwater built up the Bh horizon in podzols. The accumulation just below of dissolved organic carbon in the less permeable hydromorphic saprolite of the laterites forms the BCs horizon. These accumulations of organic matter, at depth but also at the margin of the podzolic areas, reduce the porosity of their spodic horizons and favour the implementation of a perched groundwater in their overlying eluviated and bleached horizons. Remnants of lateritic horizons

impregnated by organic compounds are observed in the latter. They indicate that podzols may expend abruptly upslope at the expense of freely drained and clay-depleted laterites in response to major rainfall events and subsequent expansion of perched groundwater aquifers.

Soils and saprolites in both study sites also exhibit strong geochemical and mineralogical analogies. Better than that of the Jaú site, this study reveals that massive gibbsitisation of the upper clayey saprolite is likely linked do the downward accumulation of Al following the dissolution of Al-bearing minerals (mainly kaolinite and gibbsite) in the upper clay depleted horizons of laterites. This hypothesis suggests that gibbsitisation has occurred before the podzolisation of laterites. The greater proportion of kaolinite in the pool of the remaining Al-bearing minerals within the overlying soil horizons and towards the podzolic area also suggests higher dissolution rates for gibbsite than kaolinite in more acidic environments (Nascimento et al., 2004). However, such a trend could also result from the development of poorly drained conditions in laterites, before their ultimate podzolisation, which should restrict the formation of gibbsite.

In both study site, podzols are formed laterally at the expense of yellowish clay depleted laterites with mainly contains quartz grains but also residual clay minerals (kaolinite, gibbsite and goethite). Massive iron and clay depletion, confirmed by mass balance calculations, are preliminary weathering steps to soil podzolisation. Such preliminary weathering steps may even affect the upper part of the saprolite in hydromorphic environments. Losses of clay minerals develop interconnected macrovoids between quartz grains that promote the migration of fine particles. Chemical erosion of laterites then generates particulate transfer in clay-depleted horizons. Clay transfer mostly occurs in the deep groundwater of the upslope laterite and is consistent with the individualisation in their upper bleached and clay depleted Bg horizon or BCg saprolite of clay cutans in macrovoids. Transfer of clay and silt particles is strongly enhanced in the sandy and bleached horizons of podzols and is also associated with the downward accumulation of Th-, Ti-bearing minerals in spodic horizons. Simultaneously, the accumulation of organic substances in spodic horizons of weakly expressed Podzols (Bhs horizons of the margin of the podzolic areas), or at a greater depth in those of better differentiated podzols (Bh and BCs horizons) is associated with the accumulation of metals bound to organic ligands, which occur at greater depth for Al (Bhs and BCs) than for Fe (Bhs and Bh).

Podzols in the incised inundated peneplain of the study site also display relevant differences with the waterloged podzols studied elsewhere by Nascimento et al. (2004) in poorly drained

plateau depressions. Major morphological differences in podzols result from the incision of the podzolic areas by river systems. They are observed at two distinct places within the soil catena: (i) at the lateral weathering front between the upslope clay-depleted laterites and the midslope podzols, and (ii) in the downslope eroded podzols developing convex sloping sides with the river network. The accumulation of organic matter at the lateral weathering front is less abundant, in particular in the thinner spodic Bhs of weakly expressed podzols but also at greater depth in the thin and discontinuous Bh horizon of better differentiated podzols. Besides, the hydromorphic saprolite, directly in contact with the upslope podzolic area, locally displays numerous iron segregations. These major morphological changes likely result from shorter periods of anoxia due to river incisions and the recede of the perched groundwater from the upslope podzolic area. Indeed, shorter periods of anoxia at the lateral weathering front speed up the mineralization of organic mater, release the organically bound metals, and favour the precipitation of Fe-oxides. Downslope on the convex sloping side, the podzolic weathering front has expanded downwards into the fine and clay-depleted saprolite and ultimately in low-lying positions into the coarse saprolite. Consequently, this weathering front has initiated the formation of a second generation of eluviated and illuviated or spodic horizons in strongly and ultimately in less weathered saprolitic materials. The deeper impregnation of organic matter in spodic horizons from the upslope to the downslope position of the podzolic area is closely linked to a simultaneous increase of the thickness of the organic-rich and eluviated topsoil horizons of podzols. This lateral trend results from drastic structural changes in the vegetation cover and therefore in the organic inputs to soils, with a more open forest (*Caatinga*) in the upslope podzols and a dense riparian forest in the downslope podzols. It also assigned to contrasted hydrological regime, with higher turnovers of organic matter in better-drained podzols of the *Caatinga* and slower ones in the waterlogged podzols of the riparian forest. Moreover, the weak acidification of the downslope podzols mainly formed on weakly weathered saprolites prevents the release of metals bound to organic ligands.

Acknowledgments

The research was funded by CAPES-COFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l’Univers du CNRS), through the “Ecosphère continentale” programme: “Podzolisation des

latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)”.

CAPITULO 5. ALTERAÇÃO E EROSÃO DAS SUPERFÍCIES CENOZÓICAS E GÊNESE DOS PODZÓIS HIDROMÓRFICOS NA BACIA DO RIO NEGRO

Résumé

Ce chapitre est un essai de reconstitution de la dynamique d'expansion des podzols à nappes dans le bassin du Rio Negro à partir d'études ponctuelles réalisées sur des séquences de sols, de documents cartographiques obtenus à des échelles régionales et des connaissances actuelles sur l'histoire géodynamique et géologique du bassin amazonien. Les études minéralogiques et structurales réalisées le long de séquences de sols situées dans des points clés des paysages faiblement ou fortement podzolisés du bassin versant du Rio Negro (sites (3) et (4)) ont permis d'élaborer un modèle d'évolution de ces paysages qui intègre : (i) processus majeurs associés aux re-mobilisations et exportations de matières, et (ii) fonctionnements hydriques associés. La reconnaissance des principales surfaces géomorphologiques (surfaces d'aplanissement, dépôts sédimentaires, chenaux fluvio-lacustres…) de ce bassin nous a amené à extrapoler ce modèle à plus petites échelles, révélant alors les principaux facteurs associés à l'expansion des podzols à nappe dans les paysages latéritiques d'Amazonie.

Le modèle proposé oppose des processus d'altération propices à une fonte géochimique des formations continentales à des processus érosifs associés à l'incision de ces formations par le réseau hydrographique et à l'accumulation des produits de cette érosion dans les lits des rivières. Dans le bassin du Rio Negro, les surfaces continentales appartiennent essentiellement aux vastes pénéplaines du Tertiaire, qui ont été incisées au Quaternaire par les tributaires du

Rio Negro et ont de ce fait formé les plateaux surbaissés de ce bassin. Dans les parties hautes et bien drainées de ces plateaux, l'érosion chimique des formations continentales a conduit à la formation de latérites plus ou moins épaisses par accumulation résiduelle d'Al et Fe dans les minéraux argileux du sol. Dans les parties centrales et moins bien drainées de ces plateaux, l'érosion chimique accrue de ces latérites est associée à une plus grande mobilité d'Al et Fe. Les pertes de ces éléments sont reliées à un appauvrissement des latérites en milieu faiblement (au voisinage de la surface) ou fortement (en profondeur) anoxique puis, lorsque le milieu devient suffisamment perméable, à une podzolisation de ces latérites. Cette étape ultime dans l'érosion des latérites est liée à la dissolution des quelques minéraux argileux qui subsistent dans ces sols par des substances organiques qui migrent et s'accumulent dans les fronts latéraux de podzolisation sous forme de complexes organo-métalliques. Ce processus marque de ce fait un changement de spéciation majeur pour les métaux (du minéral vers l'organique). Il est étroitement lié à l'individualisation et fluctuation d'une nappe perchée dans le réservoir sableux des podzols et au développement de conditions réductrices et acides au sein de cette nappe. Les deux grands processus (appauvrissement puis podzolisation) transformant les latérites en un résidu sableux progressent de façon centrifuge, depuis le centre vers le rebord des plateaux. A cette fonte chimique des latérites s'oppose une érosion physique progressant dans une direction complètement opposée. Cette érosion régressive des bords des plateaux par les incisions des ruisseaux alimentent en sédiments les lits des rivières. Dans les plateaux faiblement podzolisés du bassin moyen du Rio Negro (site (3)), les dépressions à podzols sont faiblement incisées par les ruisseaux et l'érosion régressive des rebords des plateaux latéritiques fourni d'abondants sédiments argileux aux eaux brunes des rivières. Dans les vastes pénéplaines à podzols du haut bassin du Rio Negro (site (4)), les incisions du réseau hydrographique drainent les nappes de ces podzols et fournissent d'abondants sables blancs aux eaux noires des rivières.

Dans le bassin du Rio Negro, les surfaces continentales appartiennent (i) à la surface d'aplanissement pan-américaine *Ucayali* du Miocène Moyen, (ii) au dernier épisode sédimentaire du Tertiaire attribué à la Formation Içá, épisode qui s'est achevé fin Pliocène lors de la naissance du réseau hydrographique actuel du fleuve Amazone, et (iii) aux surfaces d'érosion et de sédimentation du Quaternaire. Les sédiments Quaternaires se sont essentiellement accumulés à deux endroits dans le lit majeur du Rio Negro formant les archipels de: (i) Mariuá (bassin moyen) et (ii) Anavilhanas (bas bassin). L'épaisseur des formations latéritiques du bassin du Rio Negro dépend étroitement de l'age de ces surfaces.

Ces formations sont généralement épaisses, parfois faillées, sur la surface d'aplanissement pan-américaine *Ucayali* et, à l'inverse beaucoup moins développées sur la Formation Içá (<1m). Cette dernière présente de nombreux chenaux et dépressions qui pourraient correspondre à d'anciens chenaux fluvio-lacustres.

La répartition des podzols dans le bassin du Rio Negro montre un contrôle lithologique et pluviométrique majeur dans l'expansion de ces formations dans les principales surfaces géomorphologiques du bassin. L'expansion des podzols est réduite dans les couvertures latéritiques peu épaisses de la Formation Içá. Elle est limitée aux chenaux ou dépressions de cette formation, ce qui laisse présager d'un contrôle de structures fluvio-lacustres dans la mise en place de ces podzols. L'expansion des podzols dans les paysages devient beaucoup plus importante au Nord et au Nord Ouest, dans les régions les plus pluvieuses du bassin. Dans ces régions, les vastes étendues à podzols se sont également développées sur des couvertures latéritiques plus anciennes et plus épaisses de la surface d'aplanissement *Ucayali*. Les plus grandes étendues de podzols au Nord Ouest sont drainées et incisées par les principaux tributaires du haut Rio Negro. Ils ont alimenté en sables blancs les lits des rivières et construit l'archipel de Mariuá dans le bassin moyen du Rio Negro, le plus grand piège à sédiments de podzols du bassin amazonien.

L'étude montre ainsi que les podzols à nappes du bassin versant du Rio Negro se sont essentiellement développés sur les surfaces d'aplanissement et sédimentaires les plus anciennes du Tertiaire ce qui laisse présager d'un grand âge pour ces sols. Leur plus grande expansion dans les paysages est contrôlée à la fois par les apports pluviométriques (propices aux engorgements par leur abondance) et la nature du support sur laquelle elles se forment (accrue sur latérites très altérées et anciennes de la surface d'aplanissement *Ucayali*). L'incision linéaire des surfaces Tertiaires, il y a environ 2.5 Ma lors de la mise en place du réseau hydrographique moderne du fleuve Amazone, a permis de drainer les aires les plus podzolisées à l'amont et au Nord du bassin du Rio Negro. Ce drainage associé à une érosion des bords de berges a permis de restreindre l'expansion de ces vastes étendues à podzols dans les paysages et d'alimenter en sables blancs les bords de berges et le principal piège à sédiments situé juste à l'aval de ces grandes étendues à podzols (archipels de Mariuá). Une seconde génération de podzols s'est ultérieurement développée sur les surfaces incisées des rebords de plateaux et les dépôts Quaternaires soulignant ainsi la grande continuité dans le temps du processus de podzolisation. En effet, ce processus continue de nos jours à alimenter en substances organiques et métaux les eaux noires des rivières du bassin versant du Rio

Negro, contribuant ainsi à entretenir un environnement extrême peu propice au développement de la vie.

5.1. Introduction

The Negro River catchment belongs to the northern part of the Amazon flat surface, bordered by residual hills, inselbergs and *Mesas* of the Guyana shield in the Northeast (Fig. 1). The dissection of this vast surface has generated a plateau-like relief (*Amazonian planalto)*, some tens meters above average river levels (90 to 60m a.s.l.), and the formation of narrow alluvial terraces in major river corridors (Franco et al., 1977; Costa et al., 1978). These low elevation plateaux (*terra firma*) commonly present dissected edges, with flat-top to convex hills, as well as dispersed and ramified depressions in their centre (Franco et al., 1977; Costa et al., 1978; Bezerra, 2003). While the most elevated relieves present some uniformity on their bauxite, iron pans, or reddish and clayey Ferralsols, the widespread low elevation plateaux with their incised edges and ramified depression network show high diversity of soils (Costa et al., 1978; Yamazaki et al., 1978; Dubroeucq et al., 1999). Such soil diversity is also manifest on the vegetation physiognomy that grade from an evergreen forest to a shrub savannah (SILVA et al., 1977; Magnago et al., 1978). Maps of the RadamBrasil Project (1972-78) reveal that diversity. Freely drained soils (Ferralsols and Acrisols) under forest are commonly present on plateau edges whereas waterlogged soils with various types of vegetations occupy the alluvial terraces and the depressions of the plateaux. Waterlogged soils on the plateaux are either clayey or sandy and correspond respectively to Gleyic Plinthosols and Hydromorphic Podzols. In waterlogged Podzols, the development of reducing and acidic conditions enhanced the production of organic acids, the weathering of clay minerals, the formation and downward accumulation organo-metallic complexes and their exportation to the river network (Lundström et al. 2000; Do Nascimento et al, 2004, 2008, Bardy et al., 2007, 2008, Fritsch et al., in review). The abundance of Podzols in the Negro River catchment explains the small quantity of suspended load, the extent of organic colloids and associated metals in most surface waters, and their dominant black colour (Allard at al. 2002, 2004; Benedetti et al. 2003).

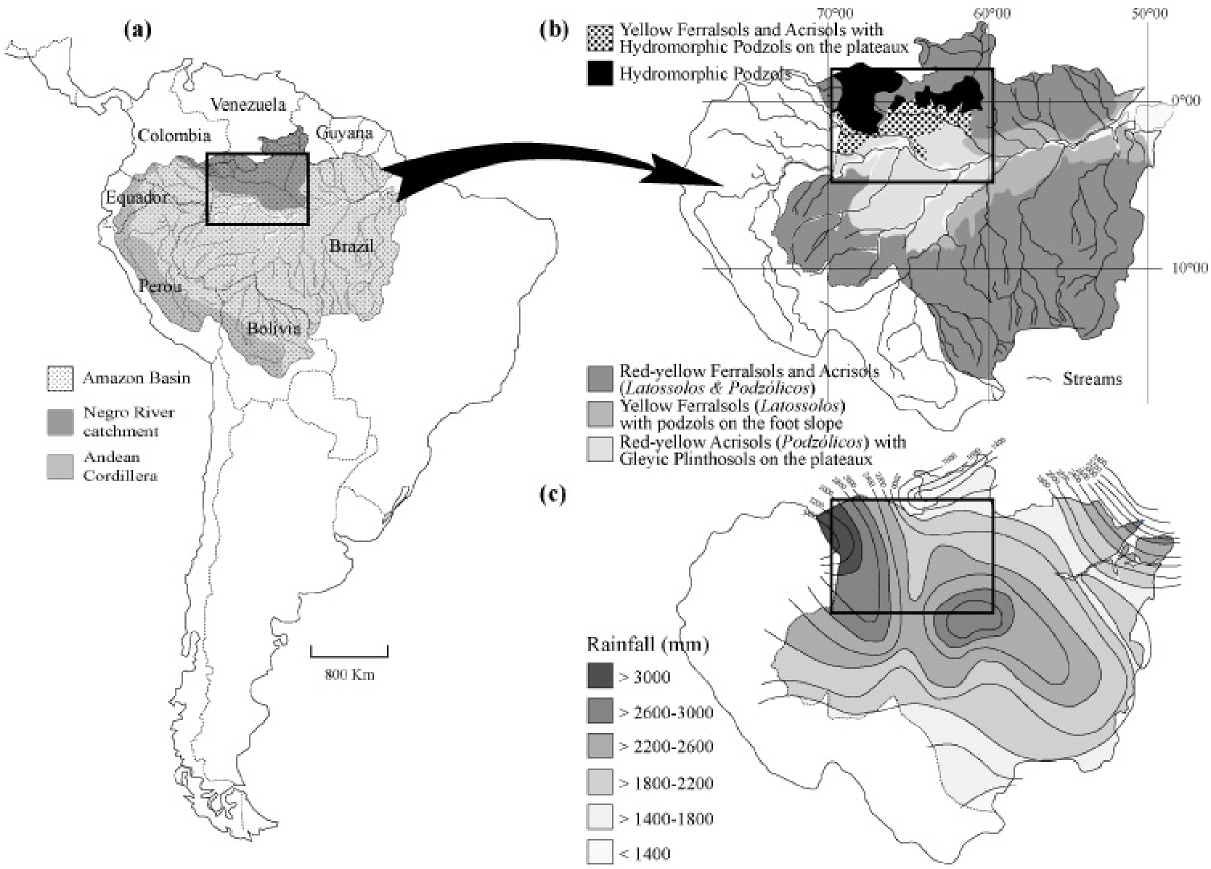


Figure 1*. (a) The Negro River catchment within the Amazon Basin in South America, (b) broad scale soil map (reduced and simplified from Radam Brazil maps at 1:1000.000) and (c) average annual rainfalls (from ANA) of the Brazilian Amazon Basin (black rectangle insert refers to site location in Fig. 2).*

The low elevation plateaux of the upper Amazon Basin is usually explained based on the principle of planation by erosion cycles, deriving from King's proposition (King, 1953). According to this author, the flat surfaces are elaborated by erosion and lateral slope retreat, mainly under dry climates, generating residual relieves, pediplains and ultimately sandy deposits (*playa* and *bajada*) at low elevations. Base-level lowering due to positive epeirogenesis or marine regression (King, 1953), or climatic oscillations towards the humid (Bigarella & Andrade, 1965; Franco et al., 1977; Costa et al., 1978) would be responsible for river incision phases which, alternating with planation phases, generated polycyclic landscapes. According to this model, the *Mesas,* inselbergs and major hills of the Negro River catchment would correspond to the residual relieves, the widespread flat surface to an active phase of soil denudation and the sandy deposits in depressions (*playa* and *bajada*) to sedimentation (Franco et al., 1977; Costa et al., 1978), generated during the late pediplanation

and sedimentation in the upper Amazon Basin. Deep river incisions and development of a ramified network of brooks (*igarapes*) in the lands would have eroded the edges of the low elevation plateaux and built up the alluvial terraces.

An alternative genetic explanation for the development of low elevation lands follows the principle of soil collapse governed by hypodermic chemical erosion. This approach proposes that geochemical processes, which act into the soil and saprolite mantles, drive landscape evolution towards planation (Bocquier, 1971; Boulet R., 1974; Millot, 1983, Dubroeucq et al., 1991). Indeed, soil change processes that transform laterally one soil type into another (Fanning and Fanning, 1989) are commonly related to losses of matter. Such losses generate soil collapse and therefore surface lowering. They first produce depressions and ultimately vast plains following the upslope expansion of weathering fronts. The importance of this kind of internal erosion depends on the type of weathering process involved in this soil dynamics, which is frequently linked to altered water regimes (e.g. changes from freely drained to waterlogged environments). On this regards, mobilization and export of iron in reducing environments is commonly related to dramatic colour changes in soils (Fritsch et al., 1986; Fritsch et al., 2004) but to limited losses of matter. This process would therefore have weak repercussion on landscape evolution. By contrast, the breakdown of Fe-clay and plasma-skeleton bonds, followed by the mobilization or destruction of clay minerals (Bocquier, 1971; Boulet, 1974; Chauvel et al., 1977) would lead to significant losses of matter, residual accumulation of sands, as thus to relevant change in the physiography of the landscape (Lucas et al., 1987; 1988, Dubroeucq et al.; 1991). Moreover, by producing slope gradients in closed or open depressions, this soil landscape dynamics and associated chemical erosion may generate at or near the surface various types of physical erosion (e.g. sheet, rill, gully and piping) (Planchon et al. 1987, Fritsch et al, 1994). According to this second approach, intense geochemical erosion of weakly or strongly weathered laterites that form clay-depleted soils (Acrisols) and ultimately sandy Podzols would correspond to the major driving process for the development of depressions and vast inundated plains within the low elevation plateaux of the Negro River catchment (Dubroeucq et al., 1991; 1999).

Two opposite interpretations are thus given in the literature to explain the formation of waterlogged Podzols in the Northern part of the upper Amazon basin. The first approach closely links the formation of Podzols to sandy deposits (e.g. Klinge 1965; Bezerra, 2003), suggesting therefore a major sedimentary control in the development of weathering processes. The second approach reveals that waterlogged Podzols may form in poorly drained

environment (between major tributaries of the Negro River) from *in situ* weathering of laterites leading the residual accumulation of quartz sands and major exportations of organo-metallic complexes to the river network (e.g. Lucas et al., 1987; 1988). Both sedimentary and weathering processes could also have acted simultaneously in the Negro River catchment. This highlights that the large development of degraded soil landforms in this catchment, with the ultimate formation of waterlogged and acidic Podzols, must be replaced in the frame of the late Tertiary sedimentation in the upper Amazon Basin and the birth of the Amazon River system during the Quaternary.

We have undergone pedo-geomorphic investigations at three different scales in the Negro River catchment (from global to very detailed field surveys and related laboratory investigations) to reveal major landforms and associated chemical and physical erosion processes that have contributed to the formation of highly degraded lands. In the discussion of this paper, a schematic model of soil landscape evolution is proposed to explain the formation of these lands in the frame on the sedimentary, tectonic and climatic history of that part of the Amazon Basin.

5.2. Environmental Setting

We present in this section the most recent interpretations on the Tertiary history of the Amazon lowlands and the ultimate birth of the Amazon River system. Tectonic events (Quechua I and II), related to the collision between the South American and Nazca tectonic plates and the birth of the Andean cordillera, have strongly altered the physiography of the upper Amazon basin during the Tertiary. From the early to the mid-Miocene Quechua I orogenic phase of Andean tectonism, the drainage system of the Amazon basin discharged sediments into a Pacific embayment. It formed the largest continental deposits of the world, known in Brazil as the Solimões formation (Sampaio and Northfleet, 1973). This sedimentary event was followed by intense phase of erosion associated with the formation of the Andean cordillera during major orogenic events of the Quechua II. This orogenic event cut the western drainage system and forced the rivers to turn east. A very extensive marsh and lake-region was born in the middle of the upper Amazon Basin (Campell et al. 2006). In the late Pliocene, base-level lowering has initiated the development of the modern Amazon River system, the incision of the lowlands and thus formed the low elevation plateaux of the upper Amazon Basin.

A more accurate chronology of the Tertiary events has been recently proposed by Campbell et al. (2006) and generalized to the whole upper Amazon Basin using stratigraphic unconformities and subsequent depositional features at widely separated areas within the Andes of Bolivia, Peru and Ecuador. A Pan-Amazonian surface has been identified and related to major erosion events leading to the formation of the Ucayali Peneplain. Peneplanation within the upper Amazon Basin likely started at the mid-Miocene, i.e. 15 Ma ago at the end of Quechua I, and terminated abruptly near the beginning of the late Miocene Quechua II orogenic event at ~ 9.5 Ma. This was followed by the late Tertiary sedimentation, which starts blanketing the lowlands and forms ultimately deltaic and lacustrine deposits of moderate to low energy within a giant lake (*Lago Amazonas*) following the closure of the gates to the Pacific ocean, in both the South and North directions. These deposits previously assimilated to the Solimões Formation in Brazil are now differentiated from the latter and assigned to the Içá formation (DNPM, 1981). This last continental sedimentation ends up in the late Pleistocene at ~ 2.5 Ma with the birth of the modern Amazon River system.

Detailed and regional surveys on soils derived from the Içá formation in the North region of PortoVelho (Fritsch et al., 2007) reveal less weathered materials and thinner soils (≤ 1 m) than those exposed on the Ucayali Peneplain of the Manaus (Fritsch et al., 2004) or São Gabriel da Cachoeira (Montes et al., 2007) regions (2 - 15 m), suggesting therefore younger soils. On this regards, datation of kaolinite, a ubiquitous clay mineral of tropical soils, using radiation-induced defects, could not be done for the youngest soils due to the presence of residual primary minerals (mostly mica) but gave an age ranging from 25 to 65 Ma for saprolitic materials of deeply weathered soils (Ferralsols) of the Manaus region (Balan et al., 2005). This apparent age is much older than that attributed to the late Tertiary sedimentation (2.5 Ma) and thus ignition of soil weathering on the Içá formation. It is also older than that related to the late orogenic events of the Quechua I (15 Ma) and indicates the formation of deeply weathered lateritic materials prior to the implementation of the Ucayali Peneplain.

The buried Peneplain, described by Campbell et al. (2006) on river cut-banks, separates eroded, often folded, faulted, and weathered, moderately to well consolidated materials from the unconsolidated, near horizontal, upper Tertiary deposits (Içá formation in Brazil). Spectacular faulting through deeply weathered lateritic profiles developed on the Alter do Chão, with hectometric uplifted and sunken blocks are observed on all road cuts of the Manaus region (Fritsch et al., 2004). It thus indicates that the Ucayali Peneplain is exposed at the surface in this region. It also suggests that faulting in old lateritic materials is likely

contemporary to Quechua II orogenic events and attributed to reactivation of the deepest faults of the Amazon graben (Hasui et al., 1984; Bezerra, 2003).

The end of Quecha II, with the ultimate formation of the Andes, is closely followed by the birth of the modern Amazon River System. This is nearly coincident with the onset of the Plio-Pleistocene glacial climatic regime and the lowest sea level stands since the latest middle Miocene (Campbell et al., 2006). This climatic event is likely at the origin of the deepest cuts in the riverbeds and incisions of the edges of the newly formed plateaux. River cuts show strong tectonic controls in the investigated catchment, more specifically at the extremity of the Amazon trough with dominant N45°W and N70°E lineaments in the lower Negro River catchment and N70°W and N-S lineaments in the middle one (Fig. 2). In the main drainage system of the Negro River, major sunken blocks linked to reactivation of deep faults of the Amazon graben has led to the formation of two archipelagos, separated by narrow river corridors with rock outcrops (Latrubesse and Franzinelli, 2005).

The formation of the Andes has also led to the establishment of a climatic gradient, oscillating from humid to dry during the Quaternary. The present climate is hot and humid. Mean annual temperature is elevated and almost constant throughout the Negro River catchment, decreasing slightly from the East (27 ^{o}C) to the West (25 ^{o}C) (Costa et al., 1977; Yamazaki et al., 1978). Mean annual precipitations present significant seasonal and regional changes. They increase westwards, from 1750 mm to more than 3500 mm. At Manaus (lower catchment) the average month precipitations are uni-modal, with a maximum on April (319 mm) and a minimum on August (43 mm) (Yamazaki et al., 1978). At São Gabriel da Cachoeira (upper catchment) precipitations are bi-modal, with maximum on January (289 mm) and April (339 mm) and minima on February (282 mm) and August (124 mm) (Costa et al., 1977).

5.3. Materials and methods

Pedo-geomorphologic investigations were carried at three major scales: (i) at global scale in the Northwestern part of the upper Amazon Basin in order to display the relative distribution of Podzols in the landscapes of the Negro River catchment, (2) at regional scale in two selected sites of the catchment to display contrasted abundance of Podzols in these landscapes and (3) at local scales in both selected sites to show gradual changes of colour and texture in well-drained upland soils observed along selected transects as well as abrupt ones along soil catena (lateral appearance of waterlogged Podzols).

Global scale

For the Negro River catchment, the data sources were the soil, geological, vegetation and geomorphological maps at 1:1.000.000 scale of the RADAM Project, and the Landsat TM satellite images. The three maps generated from these data using GIS softwares display soil types in relation with major geological and geomorphological units (Fig. 2). They revealed the distribution and relative abundance of waterlogged soils (Gleyic Plinthosols and Hydromorphic Podzols) in relation to better-drained ones (Ferralsols and Acrisols) of the uplands as well as the extent of Quaternary and modern deposits in terraces and riverbeds (Gleysols). The tendency of an orderly distribution of Podzols in the landscape and spatial expansion in an ESE-WNW direction, more specifically between two major rivers of the upper Amazon Basin, i.e. the Solimões and Negro Rivers, oriented the selection of two sites for detailed pedo-geomorphological investigations. The two sites belong to the low elevation plateaux of the basin. The first one (Jaú site), located in the lower Rio Negro catchment, marks the appearance of waterlogged Podzols in the uplands. The second one (Curicuriari site), 650 km upstream, belongs to the upper Rio Negro catchment. It is an almost completely podzolized soil landscape. The Jaú site is located within a National Park and the Curicuriari site inside an Indigenous Reserve. Accordingly, the impact of human activities on soil landscapes is negligible.

Regional scale

For each site, the relative distribution and the abundance of well-drained and waterlogged soils of the uplands (low elevation plateaux) and lowlands (terraces) in relation with major geological formations were estimated from digitized soil and geological maps at 1:100.000 of the RADAM Project (Fig. 2a,b and Fig 3a,b). More detailed maps (Fig. 2c and 3c) and block diagrams (Fig. 2d and 3d) of soil and vegetation in relation to major landforms were elaborated from aerial photographs (1980) for the Jaú site and from Ikonos satellite images (2005) for the Curicuriari site. The mapping was based on the photograph/image texture and tonality and on the degree of relief dissection that are function of vegetation type, soil drainage conditions and intensity of river incision, respectively. Field surveys were carried out in these selected areas to check map unit demarcations and to obtain precise altimetric data using topographic GPSs Topcon Hiper and a pair of Paulin Altimeters under vegetation cover. Aerial photographs or satellite images coupled with topographic GPS and altimeter data allowed the elaboration of the block-diagrams for each site using 3D design softwares.

Local scale

Detailed topographic and soil surveys in pits or drilling cores were conducted in the two sites. They were particularly abundant along two transects, extending from the margin of the river Jaú or Curicuriatri to the central part of the plateaux (Fig. 2e and Fig. 3e). The transects illustrate gradual changes of colour and texture in the soils and underlying deeply weathered rock formations (saprolites). They are 4.3 km long at the Jaú site and 1.6 km long at the Curicuriari site. In the latter, five profiles (P1, P2, P3, P4 and P5 in Fig. 3e), developed on a granitic rock basement, were selected to better illustrate and interpret the vertical and lateral changes of colour and texture in soils and saprolites. Soil colour was determined in the laboratory on dry fine earth samples (< 2 mm) by spectroscopy measurements in the visible range. The samples were gently grounded, oven-dried at 60^{o}C overnight during 24 h, put into a 27 mm diameter hole in an Al disk 3 mm thick and then gently pressed against a quartz glass. Diffuse reflectance spectra were taken from from 360 to 830 nm at 1 nm steps using a Varian Cary 5G UV/Vis/NIR spectrophotometer. The CIE tristimulus values were calculated using the colour matching functions of the CIE standart illuminant C (Wyszecki & Stiles, 1982) and a software was used to convert these values into Munsell notations (H for Hue, C for Chroma and V for Value). Particle-size distribution was determined by sieving of sand fractions and of clay-silt by pipetting after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. The particle size classes are: clay (< 0.2 µm), silt (20 – 50 µm), fine sand (50-200 µm) and coarse sand (200 – 2000 µm).

Soil and mineralogical investigations were also performed along two soil catena. The soil catena is 120 m long at the Jaú site and 80 m long at the Curicuriari site. They both exhibit the spectacular lateral transition between freely-drained, clay depleted soils (Acrisols) in upslope positions and waterlogged Podzols in downslope or low-lying positions (Fig. 4). Soil were described in pits or trenches (in particular at the transition) and photographed. Soil horizon or feature demarcations were then extended on the whole soil catena using graphic softwares (Rinder et al. 1994). Detailed geochemical, mineralogical and petrographic investigations were performed on each soil catena (e.g. see Methods in Do Nascimento et al. 2004). In the Curicuriari site, a detailed soil and topographic survey was also conduced in highly incised podzolised area (50 m spaced grid on 32.5 ha) and a ground penetrating radar (GPR) survey was carried out during the early rainy season (Novembre 2006).

5.4. Results

5.4.1 Soil landform distributions at global scale: the Negro River catchment

Figure 2 displays the major geological formations (Fig. 2a), geomorphic landforms (Fig. 2b) and soil units (Fig. 2c) of the Rio Negro catchment. Archean gneisses, granites and migmatites of the Guyana Shield are exposed in the Northern part of the catchment (Fig. 2a). They are covered in the South by the sediment pile of the upper Amazon Basin. The oldest sediments of the catchment outcrop in the East. They belong to Paleozoic (Properança, Trombetas) and Cretaceous (Alter do Chão) deposits, which have filled up the Amazon graben and are now exposed at the margin and central part of the Amazon trough (only the extremity of this Amazon trough is seen in Fig 2a). The Southern part of the catchment is predominantly covered by the Içá formation, the youngest Tertiary deposits overlying the weathered materials of the Guyana Shield in the North and those of the Solimões formation in the South and the West. Four types of erosion and sedimentation surfaces may be identified in the catchment (Fig. 2b): (1) the Ucayali Peneplain, i.e. the widest surface of erosion, (2) the Içá formation, which marks the late Tertiary sedimentation in the Amazon lowlands, (3) the depressions, drains or plains assigned to chemical erosion or physical erosion in former drainage networks of the Içá formation or both and, (4) the incisions and deposits (alluvial terraces) of the modern Amazon River system.

Hydromorphic podzols of the upper Amazon basin are mainly concentrated in the Negro River catchment (Fig. 2c), where they cover 200.000 km^2 of the lands, i.e. 33% of the surface of the catchment. They are formed on different geological formations (Fig. 2a), which are assigned to two major geomorphic surfaces: (i) the depositional surface of the Içá formation, mainly in the lower and middle Negro River catchment and (ii) the Ucayali Peneplain in the upper Negro River catchment (Fig. 2b). Hydromorphic Podzols display similar distribution pattern than Gleyic Plinthosols in the lower and middle Negro River catchment (I and II, respectively in Fig. 2c). Indeed, both kinds of waterlogged soils are lying in ramified networks of drains and depressions, and are both surrounded by slightly higher elevated and better-drained lateritic soils (Ferralsols and Acrisols). As suggested elsewhere by Fritsch et al. (2007), they most likely mark the emplacement of former drainage systems of the Içá formation. Widely extended in the southern part of our investigated region (between the Negro and Madeira rivers), this ancient drainage system is locally cross cut by the modern one, more specifically by the Quaternary alluvial deposits of major Andean rivers (see for example those of the River Solimoes in Fig.2b). This suggests that the development of both

kinds of soils and associated weathering processes (i.e. hydromorphy and podzolisation) in this major sedimentary structure could be prior to the birth of the Amazon River system (i.e. 2.5 Ma).

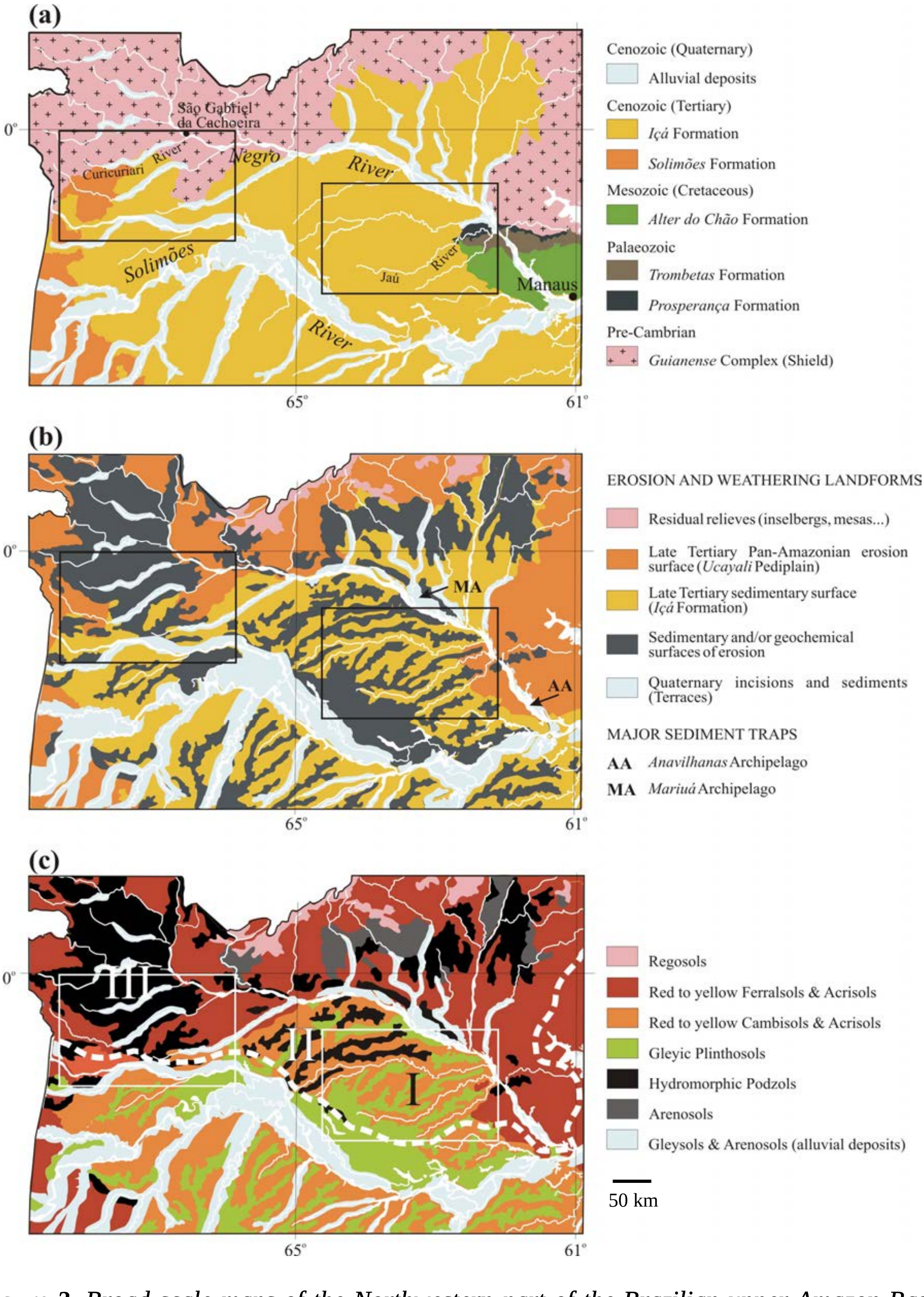


Figure 2*. Broad scale maps of the Northwestern part of the Brazilian upper Amazon Basin showing the major: (a) geological formations (reduced and simplified from DNPM geological*

map at 1:2.500.000), (b) geomorphic landforms (adapted from (a)) and (c) soil units (reduced and simplified from IBGE soil map at 1:5.000.000) of the Negro River catchment. Thick dashed white line refers to the water divide of the Negro River catchment, black or white rectangle inserts refers to regional maps of the Jaú and Curicuriari sites (Figure 3 and 4, respectively).

Figure 2c shows that the superficies covered by Hydromorphic Podzols increase in a Northwestern direction. Such a trend can be related to the establishment of a major climatic gradient after the definitive implementation of the Andean cordillera, with a total annual rainfall that reaches nowadays 1750 mm downstream of the Negro river (Manaus) and becomes greater than 3500 mm upstream. In the lower Negro River catchment (I in Fig. 2c), Hydromorphic Podzols are scarce and scattered whereas Gleyic Plinthosols are widely present in the ramified depressions of the plateaux. The reverse trend is observed in the middle Negro River catchment (II in Fig. 2c), the Gleyic Plinthosols giving rapidly place to hydromorphic Podzols. In the upper Negro River catchment (III in Fig. 2c), the Hydromorphic Podzols, formed on different geological formations of the Ucayali Peneplain, are widely developed on right side of the Negro River and drained by its major tributaries.

In the investigated region, the implementation of the modern river system (Fig. 2) is tectonics controlled and inherited from reactivation of deep structures of the Amazon graben during: (i) the separation of the Gondwanaland and (ii) the early to late Miocene Quechua I and II orogenic events (formation of the Andes). Headwater incisions of the lands by rivers has formed low elevations plateaux but produced weak quantity of sediments in the riverbanks, as the Negro River catchment mostly drained low elevated lands and strongly weathered soils. This is quite different from the major Andean rivers in the South (e.g. the Solimões River in Fig. 2c), which exhibited large alluvial terraces mostly related to active headwater erosion of weakly weathered soils in upstream high elevated Andean lands. However, two major sediment traps have been recognized in the main corridor of the Negro River: (i) the Mariuá Archipelago in the middle catchment (MA in Fig 2c) with white sandy deposits and (ii) the Anavilhanas Archipelago in the lower catchment (AA in Fig. 2c) with dominant clayey or muddy deposits (Latrubesse and Franzinelli, 2005).

5.4.2 Soil landform distribution at regional scale

Jaú River subcatchment (lower Negro River catchment)

Figure 3a better displays at regional scale, the ramified network of waterlogged soils (Gleyic Plinthosols and Hydromorphic Podzols) in the depressions of the plateaux as well as the alluvial deposits in major corridors of the Negro River tributaries. Both kinds of hydromorphic formations are dissociated and separated by better-drained lateritic soils (Ferralsols and Acrisols) on the plateau edges. Soils on the plateaux have formed on different geological formations of the Ucayali Peneplain in the East (Guianense complex, Prosperança and Trombetas formations of the Paleozoic, Alter do Chão Formation of the Cenozoic) and on deposits of the Içá formation elsewhere (Fig. 3b). Headwater incisions have intensely reworked the edges of the plateaux in numerous hills via a dense network of brooks (*igarapés)* and locally built up alluvial terraces (*Igapó*) in narrow river corridors (Fig. 3c,d,e). The brook incisions are less abundant towards the centre of the plateaux. They locally drain the waterlogged Podzols of the depressions (Fig. 3c,d).

This high diversity of soils and associated landforms is also manifest in surface water quality and colour (Do Nascimento et al. 2008, Fritsch et al. in review). Clear waters in brooks are dominant in the region and draining waterlogged areas of lateritic soils (Ferralsols and Acrisols) as well as, near the surface, those of Gleyic Plinthosols. Black waters are restricted to the brooks that drained the waterlogged Podzols in depressions of the plateaux. Both kinds of waters are almost free of suspended clay minerals. By contrast, surface waters of the Jaú River are brown and richer in suspended clay minerals. In the lower course of the Negro River and its major tributaries, suspended particulate phases in surface waters were mostly related by spectroscopic methods to poorly ordered kaolinite and tiny Fe-oxide mineral phases (Allard at al. 2002, 2004), i.e. the ubiquitous minerals systematical identified in the topsoil of deep lateritic profiles from the same region (Balan et al. 2005; Fritsch et al. 2005). This clearly reveals the origin of the deposits in the alluvial terraces of major tributaries of the Negro River. However, plateau edges are colonized by evergreen forest nowadays and do not exhibit wide, fresh eroded lands. Therefore, remobilisation of clay minerals in major river systems of the medium and low Negro River catchment seems to result from the more recent erosion of the alluvial terraces, which have likely contribute to the formation of the Anavilhanas Archipelago, one of the major sediment trap recognized in the lower course of the Negro River (AA on Fig. 2c).

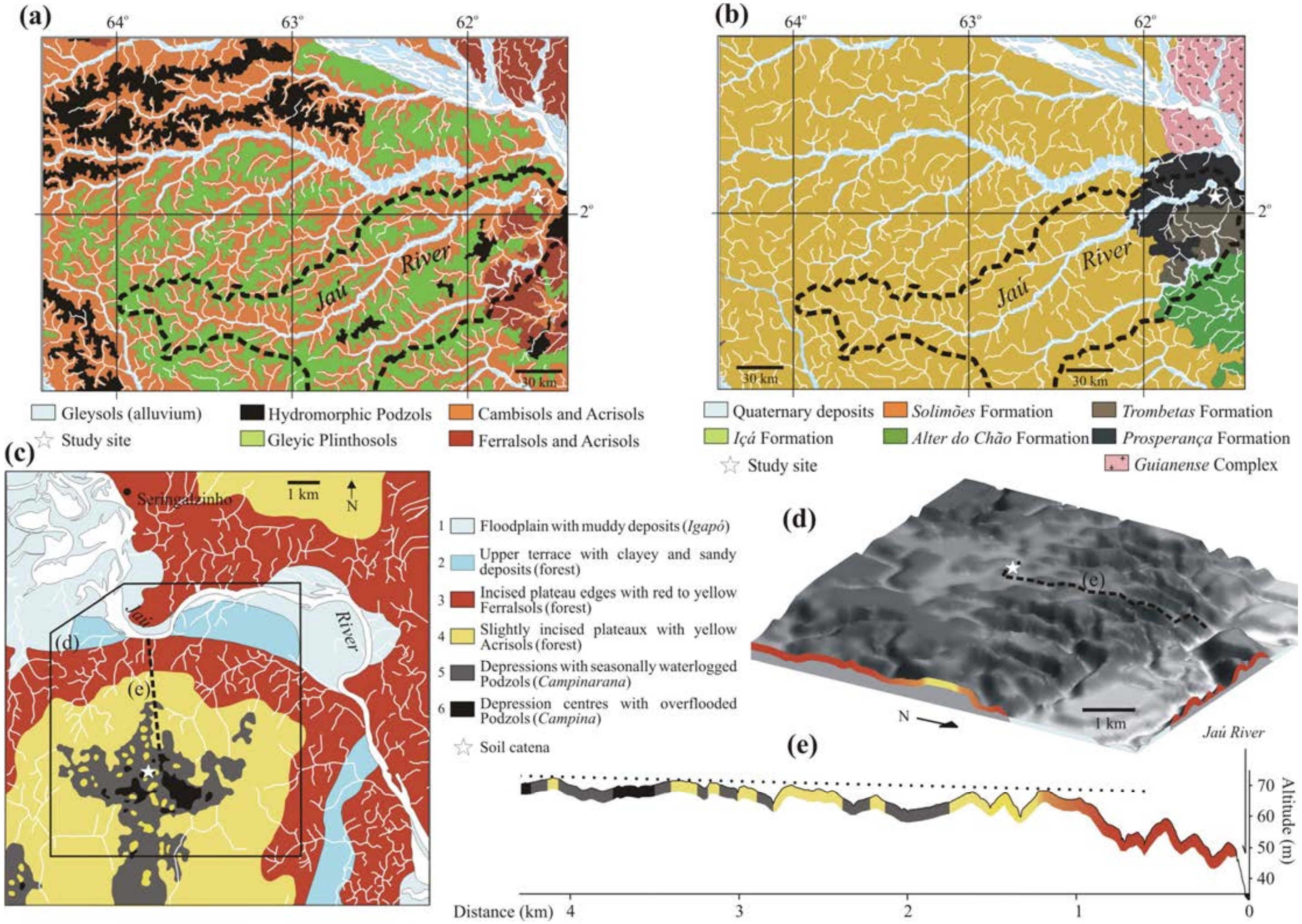


Figure 3. *(a) Regional soil map and (b) geological map of the Jaú site (extracts from the Radam Brazil maps at 1:1000.000 and modified from the DNPM geological map at 1:2.500.000) plus documents elaborated from aerial photographs and detailed field surveys: (c) map showing major soil landform units and corresponding vegetation covers (see star in (a) and (b) for site location), (d) 3D representation of the same area (see black rectangle insert in (c) for location of the selected zone), (e) soil transect (see dashed line in (c) and (d) for transect location).*

Within the Jaú catchment, waterlogged Podzols in ramified depressions of the plateaux only represent 5% of the lands. One of them has been investigated in detail downstream and on the right bank of the Jaú River (star in Fig. 3a,b, Fig. 3c,d,e). In the study site, soils (Fig. 3a) have formed on sandstones of the Prosperança formation (Fig. 3b). The plateau surface is almost at 40 m above the average water levels of the Jaú River (Fig. 3e). The deeply incised edges of the plateau are bearing reddish-yellow, clayey, low activity clay soils (Ferralsols), covered by evergreen forests (unit 3 in Figure 3c). These clayey soils have built up the Ancient and Recent alluvial terraces in the twisted corridor of the Jaú River (units 1 and 2 in Fig. 3c, respectively). Towards the centre of the plateau, the low activity clay soils turn yellow in their upper part and become progressively depleted in fine particles (Acrisols). They are still covered by the evergreen forest and are weakly incised by a diffuse network of brooks (unit 4 in Fig. 3c). An elongated and ramified depression, locally drained by the brooks, marks the extent of the podzolic area in the centre of the plateau. It is 5 m lower than the plateau surface. The margin of the podzolic area (unit 5 in Fig. 3c) is periodically waterlogged, slightly incised by numerous rills of less than 0.2 m depth and covered by a high density population of smaller trees (*Campinaranas*). The centre of the podzolic area (unit 6 in Fig. 3c) is permanently inundated during the rainy season and covered by a shrub savannah (*Campinas*). Small hill-like landforms bearing Acrisols with evergreen forest and altitudes equivalent to that measured on the plateau are abundant in the depression (Fig. 3c). They have to be considered as lateritic remnants in strongly podzolised lands and thus highlights the contribution of specific processes in the chemical erosion of the lands.

Curicuriari River subcatchment (upper Negro River catchment)

Figure 4a reveals the large extent of Hydromorphic Podzols in the upper Negro River catchment. Podzols occupy huge inundated plains and are thus directly connected to major tributaries of the Negro River. All these tributaries belong to black water systems and are then almost devoid of suspended clay particles (Allard at al. 2002, 2004). As for the Jaú region but at a much larger scale, remnants of freely drained lateritic soils (Ferralsols and Acrisols) are restricted to some dissected plateau edges, near major river corridors, and residual hills or "islands" in huge and weakly elevated inundation plains (Fig. 4a). Podzols in the region are supposed to have formed on weathering products of the *Guianense* shield in the North and the Solimões formation in the West that are both related to the Ucayali Peneplain but also on the Içá formation in the South (Fig. 4b). However, the accumulation of unconsolidated sands in

these huge inundated plains makes difficult the recognition of their parent materials. This is in particular highlighted by the soil map patterns (Fig. 4a), which display certain inconsistencies with that allowed to geological formations (Fig. 4b). Indeed, this study tends to assign the “dendritic” pattern of waterlogged soils developed on the low elevation plateaux (Gleyic Plinthosols and Hydromorphic Podzols) to domains covered by the Içá formation, and therefore to admit the lack of such a pattern for waterlogged soils developed on eroded lands of the Ucayali Peneplain.

As for the other parts of the Negro River catchment, the production of deposits in river beds is limited. However, headwater erosion by the brook and major tributaries of the Negro River now act in unconsolidated sandy materials of Podzols, highly prone to physical denudation. Accordingly, bright white sands are carried in the black waters of the region during periods of high water falls. They have formed waving sandy benches on each side of the rivers. They have also built up the major sandy deposits of the Mariuá Archipelago (MA in Fig. 2b), the other major sediment trap of the Negro River. These bright sandy deposits are certainly one of the most striking features of these highly degraded lands.

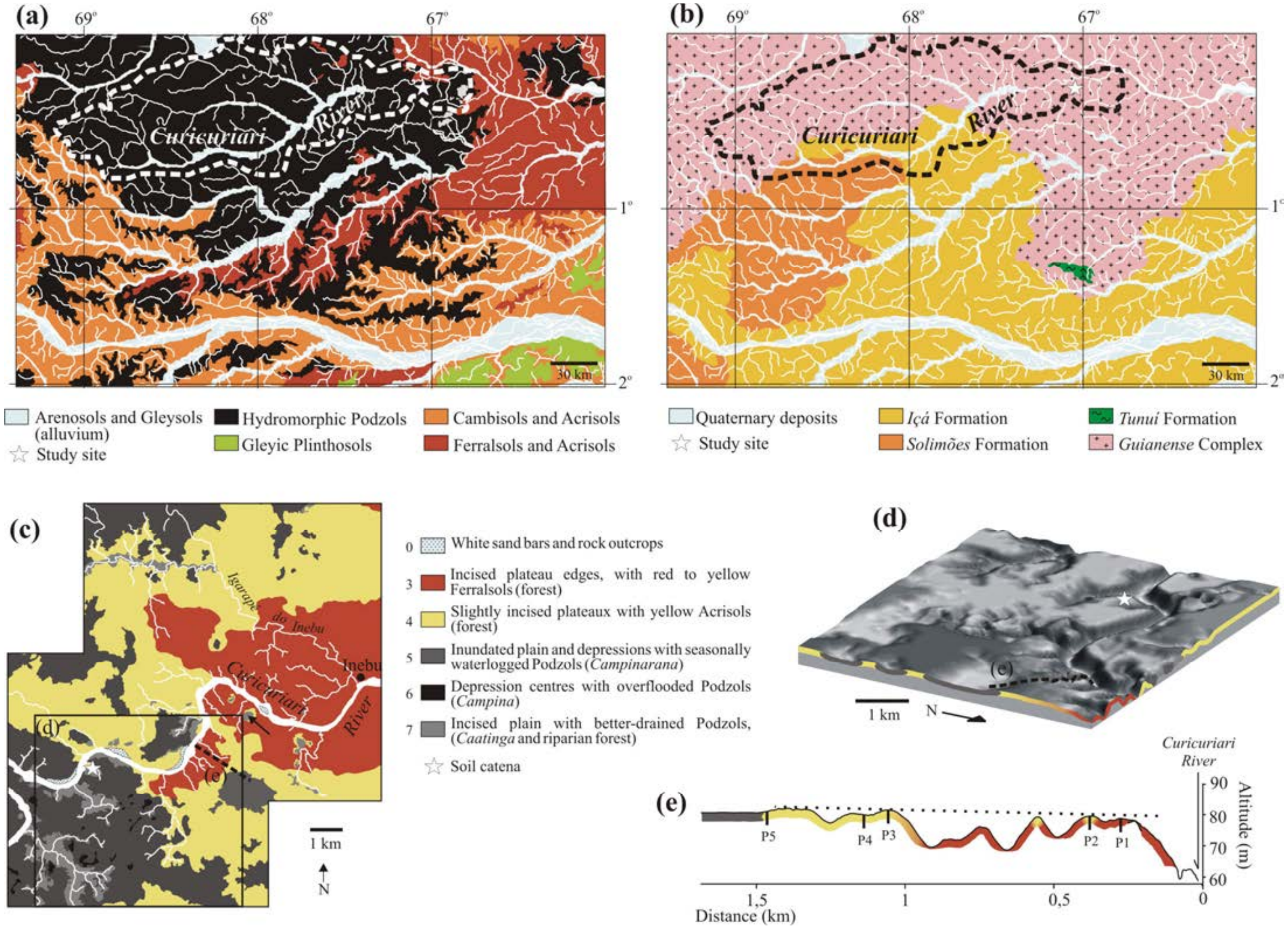


***Figure 4**. (a) Regional soil map and (b) geological map of the Curicuriari site (extracts from the Radam Brazil maps at 1:1000.000 and modified from the DNPM geological map at 1:2.500.000) plus documents elaborated from satellite images and detailed field surveys: (c) map showing major soil landform units and corresponding vegetation covers (see star in (a) and (b) for site location), (d) 3D representation of the same area (see black rectangle insert in (c) for location of the selected zone), (e) soil transect (see dashed line in (c) and (d) for transect location) with selected profiles (from P1 to P5) for colorimeric and particle size distribution of soil and saprolite samples (see Fig. 5).*

Waterlogged podzols cover 95% of the surfaces of the Curicuriari River subcatchment. Detailed field surveys were conducted downstream of the Curicuriari River at the transition between the huge inundated plain with Podzols in the West and the better drained, low activity clay laterites (Ferralsols and Acrisols) in the East (Fig. 4c,d,e). Both types of soils are developed on granitic rocks. Their transition is strongly indented and also characterized by the occurrence of spots of waterlogged Podzols in the freely drained and clay-depleted low activity clay soils (Acrisols). As for the Jaú site, these Podzols are lying in depressions of different sizes and shapes and are thus precursors of the huge podzolised plain (Figure 4c,d). They are 3 to 7 m lower than the low elevation plateau and the latter is about at 20 m above the average water level of the Curicuriari River (Fig. 4e), which is about half of that measured in the lower Negro River catchment (Jaú site). Landform units similar to that recognized in the Jaú site were also identified from the freely drained Ferralsols under the forest to the Hydromorphic Podzols of the depressions or inundated plains under tree or shrub savannahs (units 1 to 5 in Fig. 4c,d,e). One major difference is however reported and assigned to the incisions of the podzolic areas by brook and rivers that drained these areas and enable the development of an open forest (*Caatinga*) (unit 6 in Fig. 4c,d,e).

5.4.3 Detailed soil distributions along transect and catena

Pre-weathering processes along transects: Iron and clay-depletion

In both study sites (Jaú and Curicuriari), the freely drained, reddish-yellow, low activity clay soils (Ferralsols) turn yellow and become progressively depleted in fine particles (Acrisols), before to be podzolised in waterlogged depressions or large inundated plains (Figs 3c,d and 4c,d). Clay-depletion thus appears to be as a pre-existing and necessary process for soil podzolisation (Lucas et al., 1989; Bravard & Righi, 1990; Do Nascimento et al., 2004). Mineralogical, geochemical investigations and mass balance calculations carried out in 5 selected profiles of a 1.6 km long transect (Bueno et al. submitted) illustrating these gradual colorimeric and textural changes in the Curicuriari site (P1 to P5 in Fig. 4e) first indicate a total loss of alkali and alkaline earth elements at the base of the profiles and the residual accumulation of Si, Fe and Al in clay and oxide minerals, mainly kaolinite, gibbsite and Fe-oxides (data not shown). The losses in Fe and Al are enhanced vertically between the saprolite (> 2.2 m) and the overlying soil (0 - 2.2 m) and laterally from P1 to P5. They are mostly assigned in the field to colorimeric (for Fe speciation and content) and textural (for Al

contents) changes. The lack of sedimentary structures, geochemical and mineralogical unconformities and the gradual losses in Fe and Al let us to assign these changes to chemical erosion.

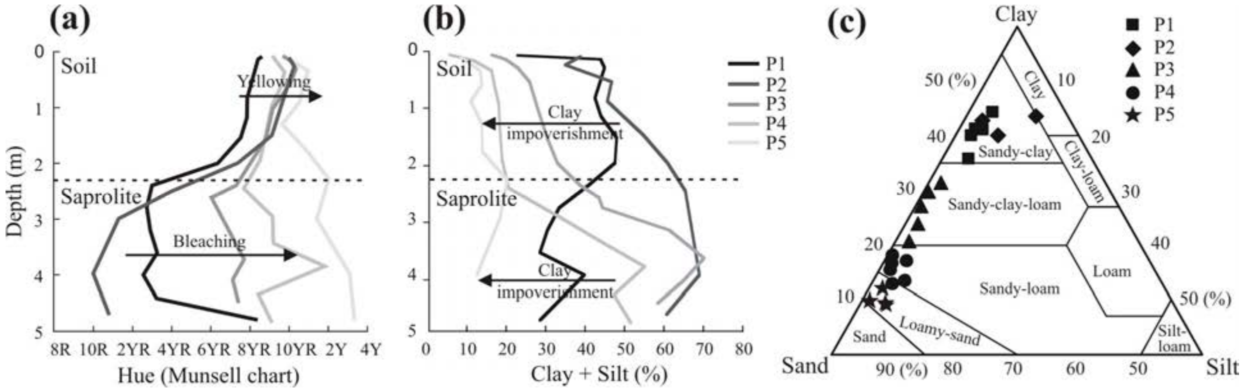


***Figure 5**. (a) Hue of the Munsell colour chart calculated from spectroscopic data in the visible range (H) versus depth, (b) clay + silt (< 50µm) weight percent versus depth, and (c) ternary representation of the percentage of clay, silt and sand in soil samples (B horizons) of the five profiles (from P1 to P5) selected in the transect of the Curicuriari site (see (e) in Fig. 4).*

Colorimeric (Fig. 5a) and textural (Fig. 5b,c) changes affect separately soils and saprolites. Soil yellowing (increase of Hue value in Fig. 5a) and Fe losses first affects the upper part of the weathered profiles that conserve the same type of texture (between P1 and P2 in Fig. 5b). Significant losses of clay minerals occur later on in soils and are related to gradual changes of texture from sandy-clay to loamy-sand (P2 to P5 in Fig. 5c). Soil yellowing first results from selective dissolution of Fe-oxides, first hematite than goethite (Fritsch et al., 1989, 2004; Peterschmitt et al. 1996), whereas the ultimate clay depletion is mostly assigned to the dissolution of Al-bearing minerals, mostly kaolinite and gibbsite (Chauvel, 1977; Fritsch et al., 1989; Bravard & Righi, 1990). Such processes indicate greater water activity and soil leaching in Acrisols than in Ferralsols due to larger periods of soil wetting and reduction in unsaturated soils.

At greater depth, the bleaching of red saprolites (between P2 and P4 in Fig 5a) is mainly assigned to a massive dissolution of Fe-oxides and exportation of ferrous iron by groundwater in waterlogged and strongly reduced environment. Close to the podzolic area (P5), the upper part of the saprolite, bleached by the groundwater, becomes also strongly clay-depleted (Fig. 5b). Clay depletion could either be due to the dissolution or the eluviation of clay minerals and associated with greater trough flows in groundwater (Bueno et al. submitted).

Accordingly the gradual lateral losses of matter from Ferralsols to Podzols, via the intermediate Acrisols, increase at two levels in highly weathered laterites: (i) in the soil from the soil surface (unsaturated zone) and at depth in the upper part of the saprolite (saturated one). They favor at macro-scale the formation of a double tongue-like transition and the development at micro-scale of macrovoids between adjacent quartz (Fritsch et al., 1989) that will favor the migration of humus compounds in soils and thus allow the formation of Podzols in waterlogged environments.

Weathering fronts along soil catena: Podzolisation

Structural and mineralogical investigations were carried out along soil catena at the transition between Acrisols and Podzols in both study sites (Jaú and Curicuriari) (Do Nascimento *et al.* 2004 ; Bueno *et al.* submitted). The soil catena of the Jaú site (Fig. 6a) belongs to a waterlogged depression of a plateau partly drained by small brooks (Fig. 3c). It presents a concave sloping side and extends from a small remnant of a forest on a hill-top to a periodically inundated shrub savannah (*Campina*) in a low-lying position. It is 120 m long and the depression is about 2 m lower than the hill-top. The soil catena of the Curicuriari site (Fig. 6b) marks the transition between the inundated podzolic plain and the upslope well-drained Acrisols. It is close from the Curicuriari River and is incised by a brook in low-lying positions (Figure 4c). It presents a convex sloping side and extends from a forest on a hill-top to a *Caatinga* in the midslope position and an inundated riparian forest close to the brook. This soil catena is 80 m long and the hill-top is 5 m higher than the brook. Many similarities exist for both soil catena suggesting highly representative structures and bio-chemical patterns, assigned to soil podzolisation, that could be extended to the whole upper Amazon basin. However remarkable differences are also reported between each site. They will be attributed to brook incisions that have altered the hydrological regime of Podzols.

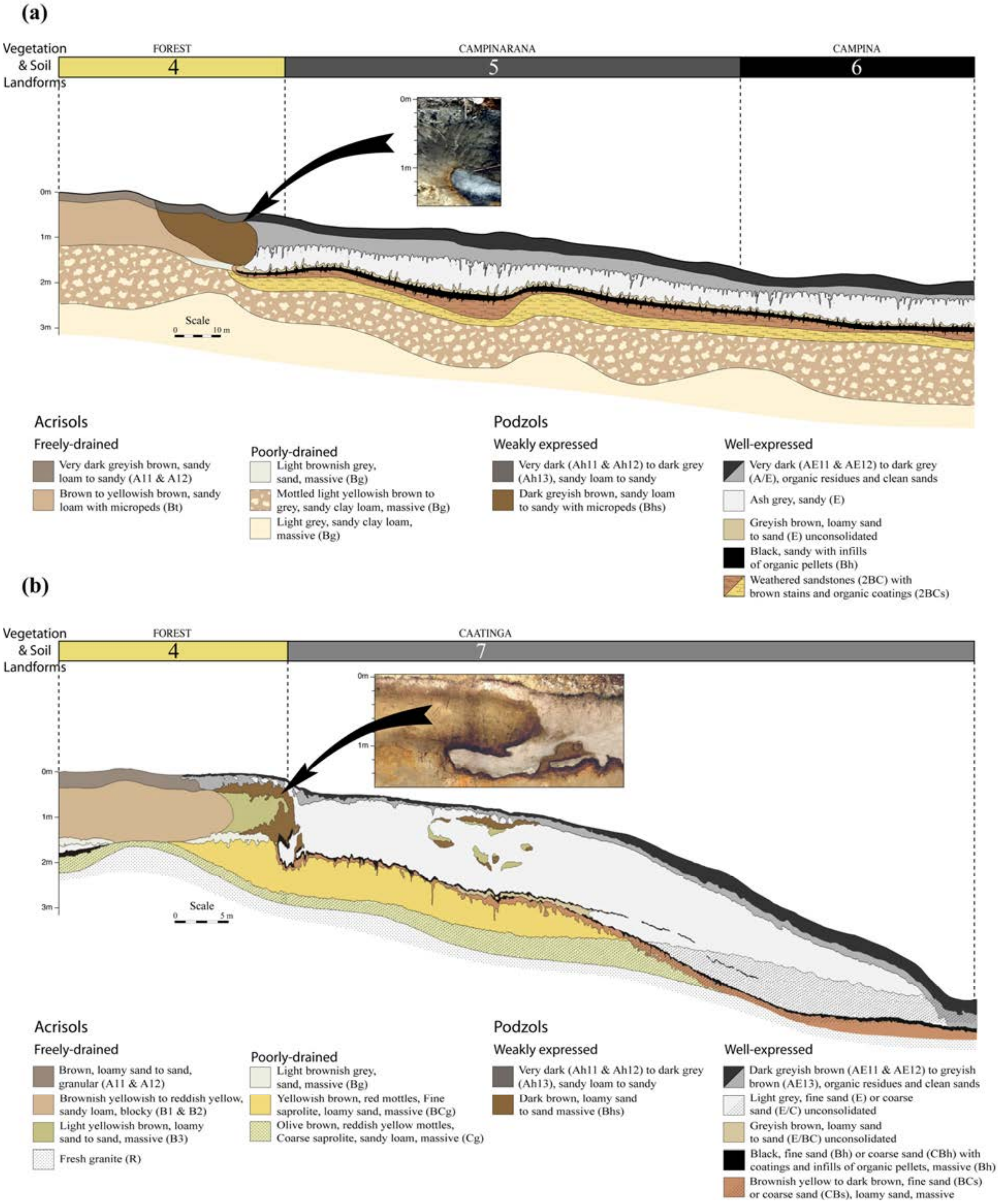


Figure 6. *Soil catena of the (a) Jaú site in a depression of a plateau (see star in Fig. 3c for catena location) and (b) Curicuriari site at the margin of an incised inundated plain (see star in Fig. 4c for catena location) showing the main types of vegetation and soil horizons according to topographic gradient.*

In both study sites, a double tongue-like shaped transition marks the transition between the upslope Acrisols and the downslope Podzols. This kind of transition has been systematically observed elsewhere at the margin of podzolic areas (Lucas et al., 1989; Bravard & Righi, 1990; Veillon 1990; Dubroeucq et al., 1999; Do Nascimento et al., 2004). The upper tongue is associated with shallow and weakly expressed humus Podzols, which form on top of Acrisols. In such a place, the organic compounds accumulate and deeply impregnate the clay-depleted soils, which contain predominantly quartz but also residual kaolinite, gibbsite and goethite. The organic acids enhance the weathering of clay minerals and contribute to the downward accumulation of organo-metallic complexes (mainly Al and Fe). This first weathering step forms topsoil eluviated A horizons with numerous plant remains and clean sands over subsoil illuviated (or spodic) Bhs horizons with organic coatings (Bardy et al. 2008). In the Curicuriari site, a thin and discontinuous bleached E horizon is also formed between the A and Bhs. The lower tongue is related to the downward but also upslope expansions of Podzols into subsoil B-horizons of Acrisols. This second weathering step marks the almost total loss of clay minerals in AE and E horizons of better-expressed podzols and therefore the residual accumulation of bleached sands as well as the accumulation at greater depths of a second generation of organo-metallic complexes in well-differentiated Bh and BCs spodic horizons (Bueno et al. submitted). By expanding upslope into the clay-depleted and hydromorphic B-horizons of Acrisol, the eluviated E horizon forms the lower tongue of the transition. This horizon may even expand on more than 10 m upslope, at the favor of twisted channels (one of them is cut perpendicularly upslope in the Curicuriai catena, see Fig. 6b). It locally establishes a remarkable structural discontinuity in the vertical differentiation of horizons in Acrisols. This lateral soil differentiation is due to greater through flow in the upper part of the groundwater. Accordingly the convoluted shape of the transition between Acrisols and Podzols and the occurrence in the latter of remnants of B-horizons of Acrisols or Bhs horizons of weakly expressed Podzols (see midslope profiles in Fig. 6b) provide strong evidences of the upslope expansion of the latter into the former.

In both study sites, the development of Podzols is impeded vertically as soon as a more compact and less permeable material is reached. In the Jaú site, this is assigned to a thin slab of weakly weathered sandstones seated on top of a mottled sandy clay loam and loose subsoil. Such kind of material corresponds to the upper part of the saprolitic mantle developed on a granitic basement for the Curicuriari site. Accordingly, textural and structural contrasts in the vertical differentiation of weathered profiles seem to play a major control in the deepening of

Podzols. As soon as a less permeable layer is reached, the lateral development of Podzols will then start to become predominant. The most active weathering front will no longer act at the base of the podzolic areas but at their periphery (Do Nascimento *et al.* 2008). Podzolisation will then be considered as a soil change process (Faning and Faning, 1989) that expands laterally in the landscape (e.g. Sommer et al. 2000). Moreover, the textural contrast at the periphery and base of these podzolic areas will favor the physical fractionation of humus compounds during the spatial differentiation of Podzols, with the accumulation of the smallest fractions (mostly the dissolved organic carbon) in the outer and less permeable materials (respectively the B-horizons of the upslope Acrisols and the top of the underlying saprolitic layer) and the accumulation of coarser fractions (i.e. black organic colloids) at the periphery and base of the inner sandy horizons of Podzols (Fritsch et al. in review). This physical fractionation of humus compounds thus forms on one hand the dark brown Bhs and BCs horizons of Podzols and on another hand their black Bh horizons. Both types of organic accumulation will also reduce the hydraulic conductivity of the soil at the periphery of the podzolic areas and thus favor the development of reducing and acidic conditions in perched groundwaters. This led Do Nascimento et al. (2008) and Fritsch et al. (submitted) to link the formation of Podzols in the lateritic landscape of the upper Amazon basin to the development and dynamics of perched groundwaters. Perched groundwaters rise very quickly in sandy horizons of Podzols. They become enriched in dissolved and suspended organic loads (black waters) and rapidly feed the brooks and rivers of the region. In semi confined environments such as that investigated in the Jaú site (Do Nascimento et al. 2008), the perched groundwater seeps at the margin of the podzolic area and fluctuate in the upper tongue of weakly expressed Podzols during periods of major rainfalls of the wet season. It fluctuates at greater depth, within the lower tongue of better-expressed Podzols, in the early dry or wet seasons and exports large amounts of organic carbon and associated metals to the rivers.

In the Jaú site, Podzols are weakly incised by the river network and systematically observed in open depressions with concave sloping sides (Figs 3c and 6a). By contrast, the highly podzolised plain of the Curicuriari site appears deeply incised by major brooks and rivers. Highly podzolised lands then exhibit convex sloping sides with the river network (Figs 4c and 6b). Comparison of both soil catena (Fig. 6a,b), reveal that physical denudation of the downslope Podzols may have significant consequences on soil differentiation and vegetation cover. Two major differences are reported in soils (Bueno et al. submitted).

First of all, physical denudation of Podzols in low-lying positions may reactivate the deepening of Podzols and contribute to the formation of a second generation of eluviated and illuviated (or spodic) horizons. Indeed, as the slope gradient slowly increases toward the brook incision, a new bleached E horizon is formed just beneath the Bh horizon of the upslope Podzols (Fig. 6b). This sandy horizon expands downward in the saprolitic mantle. It first develops in a clay-depleted and strongly weathered fine saprolite (BC) and ultimately in a coarser, sandier and less weathered saprolite (C). The Bh horizon of the upslope Podzols is partly preserved in bleached E horizons, as a discontinuous line, and a second generation of spodic horizons is formed at greater depth on top of the fine and then of the coarse saprolite (CBh and CBs). Although eroded, the thickness of the Podzols then remains unchanged, or slightly increases donwslope, except in low-lying positions where greater incisions lead to rock outcrops in river beds. Soil survey in other parts of the landscape also shows that podzolisation is not reactivated when brook incisions cut deeper and more abruptly in the landscape (Figs 4c and 7a). Spodic horizons that sustain the perched groundwater on top of saprolitic materials then outcrop in major incisions of the low elevation plateau and numerous springs can be observed on the edges of these newly formed flat surfaces (Fig. 7b). GPR survey clearly reveals the soil organization with a dominant horizontal distribution of podzolic horizons on these incised plateaux as well as the position of the sustained groundwater in the early rainy season (Fig. 7c).

By lowering the local base-level, soil denudation has also significant impacts on the transient accumulation of organic compounds in Podzols. This accumulation of organic matter is much less in upslope positions, at the lateral weathering front between Acrisols and Podzols, and by contrast very important in downslope positions, in the newly formed Podzols. Indeed both the topsoil AE horizons and subsoil Bhs horizons of weakly expressed Podzols appear much thinner in the Curicuriari catena (Fig. 6b) than in the Jaú catena (Fig. 6a). By contrast, the thicknesses of the eluviated topsoil AE horizons and subsoil spodic horizons of better-differentiated Podzols increase significantly toward downslope positions (Fig. 6b). Such changes must be related to better drained environments in the upslope Podzols and the maintenance of waterlogged and reducing conditions in the downslope Podzols. Indeed shorter periods of waterlogging in the upslope Podzols will enhance the turnover of organic compounds whereas longer ones in low-lying positions will increase the residence time of organic compounds and thus favour their accumulation in soils. These changes have also major consequences on the physiognomy and dynamics of the vegetation cover. Indeed the

development of better-drained Podzols in the highly podzolised landscapes of the Curicuriari site enables the return of an open forest (*Caatinga*), which replaces the much denser forest (*Campinarana*) and shrub savannah (*Campina*) of the waterlogged Podzols observed in the weakly podzolised landscapes of the Jaú site.

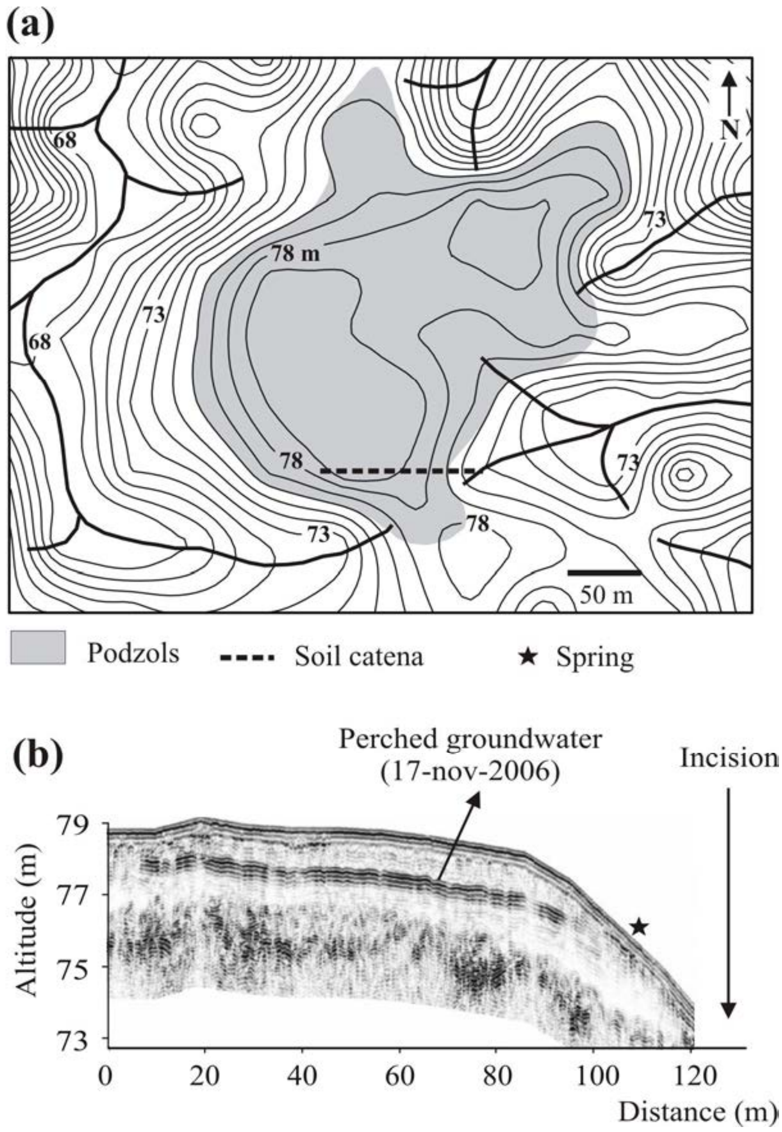


Figure 7. *(a) Small spot of Podzols on a low elevation plateau (see arrow in Fig. 4c for site location) deeply incised by brooks, (b) soil catena (see dashed line in (a)) showing a deep incision in the vertical differentiation of Podzols and groundwater seepage (spring) on the plateau edge in the early rainy season, and corresponding ground penetrating radar (GPR) image (from J. Porsani).*

5.5. Discussion

Pedo-geomorphic investigations carried out at three different scales, from the global scale to the very detailed field surveys, have permitted to recognize major landforms and processes associated with the development of highly degraded lands (mainly Podzols) in waterlogged environments of the Negro River catchment. Regional and detailed field surveys and related soil characterizations led us to propose a schematic model of soil landscape evolution that incorporate, in a sequence of block diagrams, major chemical and physical erosion processes and dominant trends in their spatial expansion (Fig. 8). The development of such processes in the different landforms recognized at regional and global scales are discussed in the frame of the most recent interpretations on the geological history of that part of the Amazon Basin to reveal the main sedimentary, tectonic and climatic controls in the development of these degraded lands.

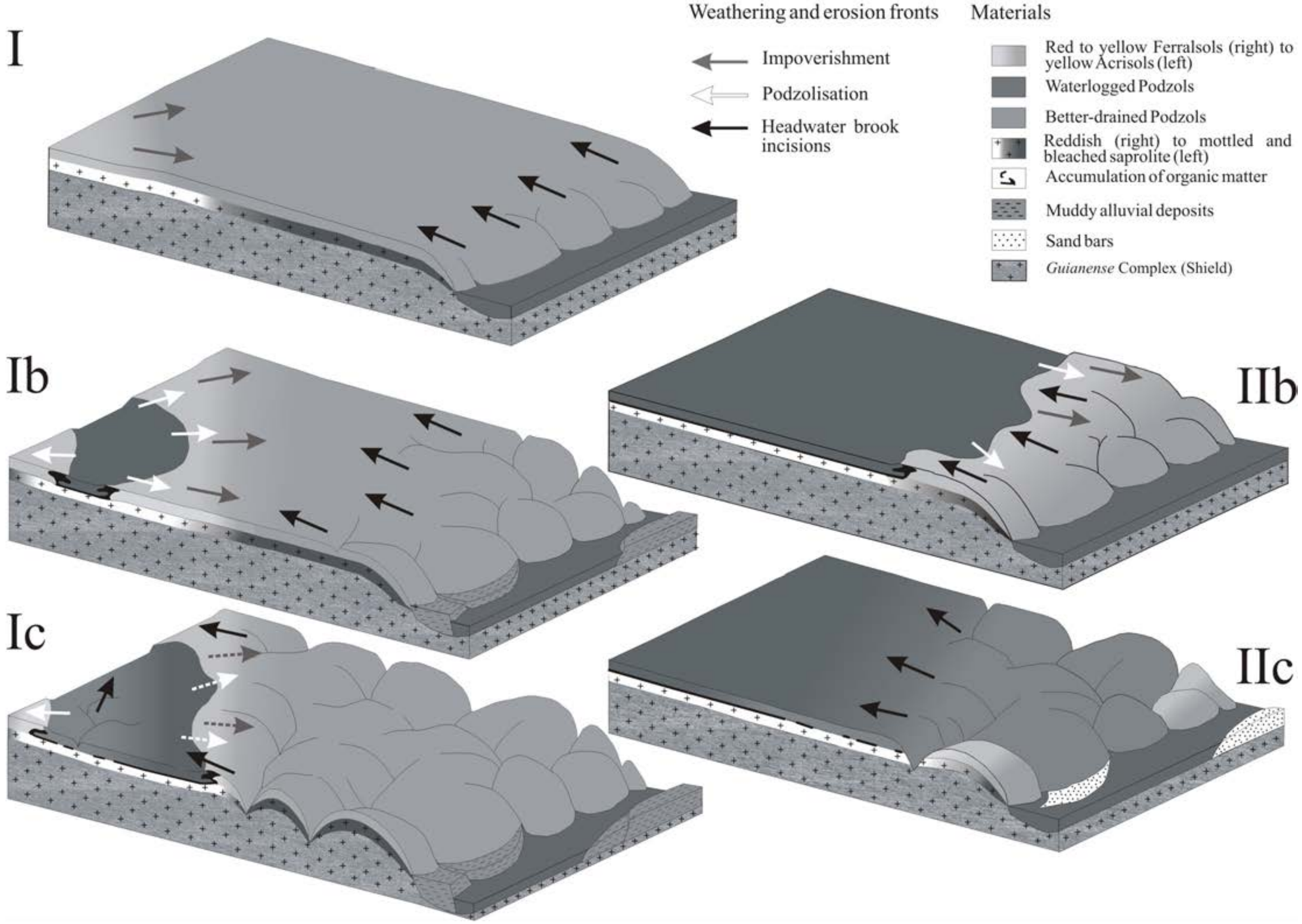


***Figure 8**. Schematic model of soil landform dynamics with their three major weathering and erosion processes: from the waterlogged podzols of the low elevation plateaux), iron and clay impoverishment (grey arrows) and podzolisation (white arrows); and from the river network, headwater brook incisions (black arrows), adapted for the lower and middle (Ia, Ib and Ic sequence), and for the upper (Ia, IIb, IIc sequence) Negro River catchment.*

The model opposes dominant weathering processes, which have first acted in the Amazon lowlands to major phases of incision and deposition associated with the birth of the modern Amazon River system, which has formed the low elevation plateaux and built up the alluvial terraces in the upper Amazon basin. According to Fanning and Fanning (1989) and Fritsch et al. (1994), weathering of continental surfaces is either ascribed to soil forming processes commonly observed in freely drained environments (i.e. lateritisation in tropical regions) or to soil change processes, which mainly result from altered water regimes, leading to the individualization of waterlogged environments. In the upper Amazon Basin, broad scale soil maps suggest that lateritisation has either acted on very long geological times or on shorter ones. Indeed, deeply weathered lateritic materials (Ferralsols also known as *Latosols* in Brazil) developed on different geological formations (rocks and sediments) were likely formed prior to the implementation of the Pan-Amazonian Ucayali Peneplain, i.e. before 15 Ma (Campbell et al., 2006). From the early Paleocene, they likely result from the intense weathering under warm and hot climate of rock basements of the *Guianense* and Brazilian shields and the erosion of weathered products at a period where the drainage system of the Amazon basin discharged sediments into a Pacific embayment and built up most of the continental deposits of the basin (mainly Alter do Chão and Solimões formations). This interpretation is in agreement with results of Balan et al. (2005) who provide an age ranging from 65 to 20 Ma for kaolinite of deeply weathered continental deposits of the Manaus region. It is also consistent with paleomagnetic results of Théveniaut and Freyssinet (2002) who attributed a Paleocene-Eocene age to the “Sul Americano” laterization cycles of paleo-surfaces from Guyana, with average relative ages of 60, 50 and 40 Ma. Such lateritic products either *in situ* (paleo-surfaces) or transported (sediments) were deeply faulted in the Amazon trough (Fritsch et al. 2004) during major Andean orogenic events (Quecha I and II) and partly washed out by erosion during the Ucayali Peneplanation. By contrast, less weathered lateritic materials (Cambisols or Acrisols also known as *Podzólicos* in Brazil) have formed on the Late Tertiary sediments accumulated in a huge lacustrine environment in the middle region of the upper Amazon basin (Içá formation), at a period were the Andean Cordillera was formed and at the beginning of the implementation of the modern Amazon River system, i.e. ~ 2.5 Ma (Campbell et al., 2006). This leads us to admit that deposits of the Içá formation came mainly from the erosion of weakly weathered soils of the Andes.

Soil change processes in the Negro River catchment are mostly assigned to: (1) iron and clay impoverishment, and (2) soil podzolisation. They have acted in the Tertiary Amazon

lowlands, including different geological formations of the Ucayali Peneplain and the late Tertiary sediments of the Içá formation. Iron impoverishment has acted alone in some parts of the catchment, leading to the formation of waterlogged clayey soils, namely Gleyic Plinthosols (Fritsch et al., 2007). It has been closely followed by clay impoverishment in podzolic environments. Both iron and clay impoverishment (i.e. development of Acrisols) are thus pre-existing and necessary steps to the ultimate formation of waterlogged sandy soils (i.e. Hydromorphic Podzols) in the Negro River catchment (Bueno et al., submitted) (see grey and white arrows in Fig. 8). Waterlogged Podzols have expanded in the Amazon lowlands in a Northwestern direction according to a major climatic gradient established following the definitive formation of the Andean cordillera. In the lower and middle Negro River catchment (I and II in Fig. 8), they have explored the most confined areas of the Içá formation, which were attributed to former drainage patterns by Fritsch et al. (2007). Podzols have expanded in a huge inundated area of the Pan-Amazonian Ucayali Peneplain in the upper catchment (III in Fig. 8). Development of these Podzols in the Amazon lowlands is related to geochemical erosion, which has contributed to the development of depressions, drains or inundated plains in the most confined areas of the landscapes.

Major incisions associated with the birth of the modern Amazon River system have formed low elevation plateaux in the upper Amazon basin and built up alluvial terraces during the Quaternary. Headwater incisions in the ramified brook networks of the tributaries of the Negro River have strongly reworked the edges of the incised plateaux in numerous hills. The rates of soil denudation on plateau edges and sedimentation in major river corridors was mostly controlled by difference in altitude between the plateau surface and the regional base-level, which was optimum in the early Quaternary during the first major glaciations. Nowadays, the difference of altitude from the plateau surface to the regional base-level increases gradually from upstream (20 m at the Curicuriari site) to downstream positions (40 m at the Jaú site and 50 m at Manaus), suggesting greater rates of soil denudation in the same direction. However, higher stage heights in the lowermost reaches of the Solimões River strongly reduced water discharge of the Negro River at the confluence (Meade et al., 1991). Moreover eroded lands on the plateau edges are actually covered by evergreen forest and most of the suspended clays in rivers most likely result from the rework of alluvial terraces. Suspended clays from major downstream tributaries (e.g. Jaú River) have accumulated in the *Anavilhanas* Archipelago, the major sediment trap recognized in the lower course of the Negro River. Incisions has also generated freely drained conditions in the soils of the plateau

edges and thus favoured the vertical development of laterites. Besides, such incisions (arrow 3 in Fig 8) have acted in an opposite direction that soil change processes (arrows 1 and 2 in Fig 8).

In the lower and middle Negro River catchment, iron and clay impoverishment (arrow 1) closely followed by soil podzolisation (arrow 2) has led to the formation of hydromorphic Podzols in depressions and drains of the plateaux (I in Fig. 8). Regional soil maps suggest that Hydromorphic Podzols have replaced Gleyic Plinthosols from the lower to the middle Negro River catchment (from I to II in Fig. 2c). The weak expansion of Podzols on these landforms must be related to the nature of their underlying geological substrate (i.e. the Içá formation) and the relatively youngest ages of the soils on which they have formed (less than 2.5 MA). Accordingly, the greater rates of soil denudation on plateau edges and the smaller rates of geochemical erosion in more confined areas of the Içá formation thus restrict the lateral expansion of Podzols on the plateaux and therefore their drainage by the river network (I in Fig. 8). Podzols thus remain strongly waterlogged and become deeply impregnated by organic acids, more specifically at the lateral weathering front with their clay-depleted, lateritic upslope counterpart (Acrisols).

The reverse trend can be reported for the upper Negro River catchment. Podzols there have predominantly formed on deeply weathered materials of the Ucayali Peneplain. This kind of materials is highly prone to podzolisation, more specifically in the low elevation plateaux (small water storage capacity in soils) and high rainfall regions of that part of the catchment. Geochemical erosion then acts on a much greater scale and forms huge inundated plains of Podzols that become drained by the brooks and tributaries of the Negro River (II in Fig. 8). Physical erosion of the unconsolidated topsoil horizons of Podzols then provides bleached sands to river systems in periods of high water stages, leading with time to the formation and displacement of wavy sandy bars in major river corridors. This transfer has built up the major sandy repository of the Mariuá Archipelago (MA in Fig. 2b), the second major sediment trap of the Negro River just downstream of the largest podzolised and incised area of the upper catchment. In the lower section of the trap, input of sands from the Branco River has built an internal delta that largely contributes to the accretion of sands in the upper trap. We also reveal that freely-drained Podzols can form from waterlogged ones close to major river incisions. By lowering the groundwater table in Podzols, this will in return restrict the lateral expansion of the podzolised plain but enhance the exportation of organic colloids and associated metals in rivers. Podzolisation will no longer act efficiently at the margin of the

podzolised plain but in low-lying positions and close to major river incisions, expanding then vertically in less permeable weathered materials such as saprolites.

The almost lack of Podzols in the incised landforms of the Quaternary, particularly in the middle and lower Negro River catchment is an additional argument to reveal the great age of the Podzols observed on the low elevation plateaux, which could have started to form on strongly weathered materials at the end of the Ucayali Peneplaination, i.e. 9.5 Ma ago. However and contrary to geological formations, soil change process such as podzolisation, which might have been initiated some Ma ago, could also have been reactivated more recently in some part of the landscapes. This process is also still on-going nowadays, as indicated by the large amount of organic colloids and associated metals transferred to the black waters of the Negro River. This points out the difficulty or impossibility to date weathering processes. Nevertheless, we have also some strong evidences that podzolisation has been reactivated at some times in the past. This led to the formation of Podzols in foot slope positions of Quaternary incised landforms or alluvial terraces. This second generation of Podzols is widely spread downstream of the Negro River, more specifically in footslope positions of the deeply incised plateaux of the Manaus Region (Lucas et al., 1984; 1988; Righi 1990). As reported in this paper, it has also been initiated on incised landforms of the inundated plains of the upper Negro River catchment.

At least, the study also highlights that the development of waterlogged and acidic conditions and the ultimate return to better-drained conditions in podzolic and incised landforms have also a remarkable effect on the dynamics of the vegetation cover. Indeed the first trend will favours the development in the forest of shrub savannah on inundated Podzols (*Campina*), whereas the second one will, on the opposite, lead to the development of an open forest (*Caatinga*) in better-drained Podzols. Soils and vegetations have therefore similar dynamics in the Negro River catchment, which not necessary result from climatic changes during the Quarternary, as stated by some authors (Haffer, 1969).

5.6. Conclusion

The major weathering and erosion processes were replaced in the frame of the main geomorphic surfaces implemented during the Cenozoic history of the Amazon Basin. The detailed mineralogical and structural approach applied in this study has been used in the past on small landscape units to reveal major processes and hydro-geochemical cycles in degraded

landscapes (e.g. Fritsch et al. 1992, 1994). Fritsch et al. (2007) have recently used this approach with detailed and broad scale soil maps to interpret the formation of waterlogged soils on the the Içá formation, which is commonly related to the implementation in the past of a giant lascustrine area (*Lago Amazonas*) and to the switch of the Amazon river drainage system. We used in this paper the same procedure at continental scale, on different geomorphic surfaces, which have formed in the past and are still forming highly degraded landforms in waterlogged and acidic environments, i.e. in the podzolic lands of the Negro River catchment.

We bring new insights on the formation and development of these degraded lands. In particular, we reveal the main controls of geomorphic surfaces and associated geological formations in the development of weathering and erosion processes, which are driving processes in our study site to (1) lateritisation, (2) iron and clay impoverishment, (3) podzolisation, and (4) headwater incisions or regressive erosion in freely-drained and waterlogged lands. We also highlight the contribution of climatic and tectonic factors, closely related to the formation of the Andean Cordillera during the Tertiary, in the development of these processes. We are conscientious of the restrictions imposed by the lack of detailed cartographic documents and believe that integration of major soil patterns in geological and geomorphic maps would greatly improve our understanding on the formation and evolution of the continental surfaces of the Amazon Basin. On this regards, we suggest to restrict the extend of the Içá formation to low elevation plateaux with shallow (~1m deep), weakly weathered soils developed on near horizontal, mottled and compact deposits as well as to occurrence on the plateaux of ramified drains and depressions with waterlogged soils (Fritsch et al. 2007). Indeed, this soil pattern is consistent with an Andean origin of the sediment (weakly weathered), a deposition in lacustrine environment and the relatively young age of the soils (< 2.5 Ma). It is easily recognised in the field and is assigned on all Brazilian soil maps (Radam Brazil, 1972-78; EMBRAPA, 1981; IBGE, 2001) to a vast area in the central part of the upper Amazon Basin. This definition led us to revise the geomorphic map presented in Figure 2c and restrict the extent of the Içá formation to the right bank of the Negro River (Fig. 9).

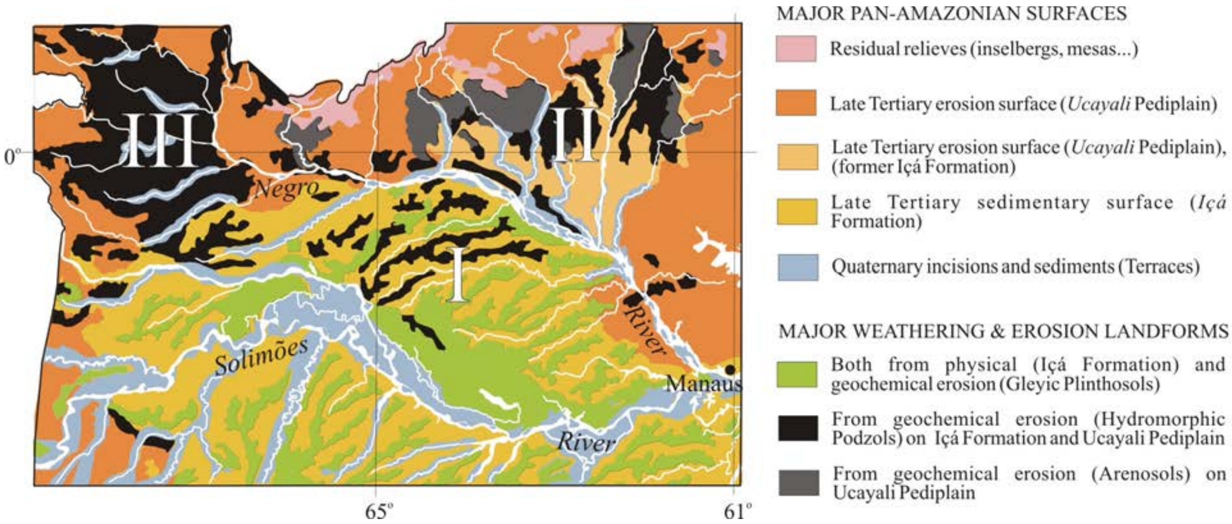


***Figure 9**. Re-interpretation of the major geomorphic landform units presented in Figure 2b for the Northwestern part of the Brazilian upper Amazon Basin from results and interpretations given in this study.*

Figure 9 reveals thee major land surfaces with hydromorphic Podzols (I, II and III). The first one in the South (I in Fig. 9) corresponds to the Içá formation. Podzols less than 2.5MA old are weakly present and lying in the ramified drains and depressions of the formation. They are replacing other waterlogged soils (Gleyic Plinthosols) in higher rainfall areas of the Negro River catchment. By contrast, Podzols are widely spread on the two other land surfaces (II and III in Fig. 9). They have formed on much older and deeply weathered materials (either *in situ* or transported) exposed at the surface after the late Pan-Amazonian Ucayali Peneplaination. Unit II is easily differentiated from unit III, as it comprises large and elongated regions of Podzols alternating with wide strips of deep sands (Arenosols), closely related in the North to residual relieves (inselbergs) of the crystalline rocks of the Guyana Shield. This unit, with its characteristic strip river pattern, comprises most of the giant Podzols of the Negro River catchment. It most likely results from exposure and podzolisation of coarse grained saprolitic materials of old lateritic formations following the Ucayali Peneplaination. Accordingly, weathering processes enhance on continental surfaces geological and geomorphic patterns acquired on geological times. They also contribute by intense chemical weathering to the development of eroded landforms (depressions, plains), which are abundant in the highly degraded podzolic regions of the Negro River catchment (Fig. 9). These eroded landforms are much widely expressed on old lateritic land surfaces (II and III in Fig. 9) than on younger ones (I in Fig. 9) and may also explore structures acquired

during sedimentary processes (e.g. Içá formation). Further remote sensing and field investigations are required to better reveal these structures and the contribution of weathering and erosion processes in the redistribution of major and trace elements in river systems, more specifically in key areas of units I and II.

Acknowledgements

This work benefits from the financial support of CAPESCOFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l'Univers du CNRS), through the "Ecosphère continentale" programme: "Podzolisation des latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)". We gratefully acknowledge J. Porsani who performed the ground penetrating radar (GPR) survey in our study site.

CONCLUSIONS GENERALES ET PERSPECTIVES

Cette étude contribue à une meilleure connaissance des environnements podzoliques amazoniens. Ces environnements extrêmes (engorgements prolongés, résidus sableux peu fertiles, forte acidité des eaux, faible activité et diversité biologique) associés à des paysages insolites d'une grande beauté mais d'un intérêt économique plus limité sont particulièrement bien développés dans la partie nord du haut bassin amazonien qui reçoit les plus fortes précipitations du bassin. Ils couvrent un tiers de la superficie du bassin du Rio Negro. Ce bassin d'une superficie de 600.000 km2 présente la plus grande concentration de rivières à eaux noires et exporte de ce fait des quantités considérables de matières organiques et de métaux à l'océan. Nous nous sommes dès lors intéressés aux processus et fonctionnements associés à la dynamique évolutive de ces podzols dans les paysages. Nous avons étudié ces processus et fonctionnement à la fois aux échelles locales dans des positions clés de ces paysages et à des échelles régionales afin de resituer cette évolutive dynamique des podzols dans un contexte géodynamique plus global, associé à la formation des Andes et aux grandes surfaces d'érosion du bassin sédimentaire attenant. Cette démarche multi-échelle et fortement pluridisciplinaire nous a amené à utiliser des approches très variées pour acquérir nos données. Ces approches débutent avec les outils spectroscopiques pour la caractérisation des phases minérales du sol et s'achèvent avec les outils de la télédétection pour l'identification des principales facettes des paysages et des grands ensembles structuraux du bassin du Rio Negro, sans oublier bien sûr l'approche structurale essentielle pour la reconnaissance des organisations pédologiques sur le terrain que nous avons utilisée lors des nombreuses missions sur nos sites d'étude. Comme nous l'avons déjà signalé en introduction, les documents cartographiques du projet RadamBrasil ont été décisifs dans le choix de ces sites et la reconnaissance des grandes unités structurales du bassin. À l'échelle des profils d'altération et des séquences de sols, des approches géochimiques couplées à des calculs des fonctions de transfert ont permis d'apprécier l'importance des pertes de matières lors de la transformation ou dégradation des couvertures latéritiques.

Les travaux présentés dans ce mémoire apportent une contribution majeure à la compréhension des dégradations successives qu'ont subi ces couvertures latéritiques au court du temps. Ces dégradations sont essentiellement attribuées à des pertes de matières (principalement Fe et Al en régions tropicales) qui peuvent être sélectives, conjointes, très progressives ou brutales. Elles témoignent des changements des conditions d'altération et de

drainage qui se relayent dans l'espace et se succèdent aussi dans le temps. Dans le bassin amazonien, ces dégradations suivent deux grandes voies. Dans la première voie, les pertes de matières sont ménagées et concernent essentiellement Fe. Elles sont de ce fait attribuées à des engorgements et au développement de conditions réductrices provisoires ou plus permanentes dans les profils d'altération (oxydo-réduction). La caractérisation de ces systèmes (Latosols-Gleysols) sort des objectifs de cette étude. Elle a toutefois été abordée de façon très détaillée dans des études antérieures de séquences de sols à la fois sur des formations latéritiques très épaisses (sur la surface d'érosion de Manaus) ou beaucoup plus minces et moins altérées (sur les sédiments de la Formation Içá au Nord de Porto Velho).

La deuxième voie est celle que nous avons abordée et étudiée dans le cadre de cette thèse. Elle est associée à des pertes de matières beaucoup plus importantes et se réalise en deux grandes étapes (appauvrissement et podzolisation). Dans le cadre de l'appauvrissement (cf article du Chapitre 3), les pertes de matières s'expriment différemment suivant qu'on se situe en milieu non saturé (partie supérieure des profils latéritiques) ou en milieu saturé (partie inférieure de ces profils). Dans la partie inférieure des profils latéritiques, les pertes de matières liées à la fluctuation et aux écoulements de nappes sont brutales. Elles sont d'abord attribuées à l'exportation massive du fer (dissolution des oxydes de fer) puis de minéraux argileux (vraisemblablement par soutirage ou lessivage latéral) lorsque les conditions de drainage de la partie supérieure des nappes est accrue. Dans la partie supérieure de ces profils latéritiques, les pertes de matières sont à l'inverse très progressives. Elles sont saisonnières et vraisemblablement attribuées à des périodes d'hydratation plus prolongées. Elles sont sélectives et affectent d'abord l'hématite (jaunissement du sol) puis les minéraux argileux (kaolinite et goethite) vraisemblablement par des mécanismes de dissolution et lixiviation dominants. Ces exportations de matière en surface mais aussi en profondeur aboutissent à l'individualisation à l'aval des versants de réservoirs sableux dont la bordure latérale présente une forme caractéristique en double langue. Le développement de ces réservoirs très poreux et perméables est propice à la migration des matières organiques et de ce fait à la podzolisation ultime des latérites (cf article du Chapitre 4 et aussi articles en annexe). Cette étape ultime marque le colmatage de la bordure des réservoirs sableux par les substances organiques acides qui altèrent les minéraux résiduels argileux et forment des complexes organo-métalliques. Elle est de ce fait étroitement associée à la mise en place de nappes perchées et de conditions réductrices qui favorisent l'accumulation de matières organiques dans ces sols et leur exportation au réseau hydrographique. Le calcul des fonctions de transfert dans ces systèmes

montre que les exportations de matières (Fe et Al) sont minimes lors de la podzolisation et à l'inverse bien plus importantes lors de l'étape préalable d'appauvrissement des latérites en minéraux argileux. Toutefois, la podzolisation marque un changement de spéciation drastique pour les métaux, qui deviennent alors étroitement liés aux matières organiques.

Nous avons également étudié l'effet des incisions linéaires sur la morphologie et dynamique des podzols (rabattement des nappes perchées, érosion des matériaux sableux des podzols). Cette étude minéralogique et structurale réalisée dans la région de São Gabriel da Cachoeira (cf article du Chapitre 4) a de ce fait été comparé à celle entreprise antérieurement sur des systèmes podzoliques à nappe non incisés (région du Jaú). Dans ces podzols drainés par les incisions du réseau hydrographique, le rabattement des nappes à l'amont des systèmes podzoliques favorise la minéralisation des matières organiques dans les fronts latéraux de podzolisation et de ce fait la libération des métaux préalablement accumulés. Cette minéralisation accrue, liée à une oxygénation plus marquée de ces sols, entraîne une nette réduction de l'épaisseur des horizons organiques de ces podzols, en surface (dans les horizons éluviés à résidus organiques) mais aussi en profondeur dans les fronts de podzolisation (horizons illuviés à complexes organo-métalliques). Cette oxygénation du sol peut aussi favoriser la formation d'oxydes de fer mal cristallisé dans les systèmes hydromorphes qui jouxtent les podzols de l'amont. Enfin l'érosion régressive des bas de versants, qui alimente en sables blancs les lits des rivières, peut favoriser la descente des fronts de podzolisation dans niveaux altéritiques moins perméables et de ce fait initier la formation d'une nouvelle génération d'horizons illuviés (ou spodiques) à l'aval. A ce niveau, le maintien de conditions anoxiques en milieu faiblement acide est propice à une grande accumulation de complexes organo-métalliques. Les métaux initialement présents à l'amont de ces systèmes podzoliques s'accumulent à l'aval dans une seconde génération d'horizons spodiques. Cette étude comparative montre aussi que les podzols sont associés à des systèmes de nappe et que le drainage de ces podzols marque une étape ultime dans leur évolution qui permet aussi (soit de façon naturelle soit de façon artificielle) de limiter leur expansion dans l'espace.

Dans une dernière et ultime étape, nous avons resitué ces processus et fonctionnement à l'échelle du bassin amazonien, plus particulièrement dans la région où les podzols sont les plus abondants : le bassin versant du Rio Negro (cf article du Chapitre 5). Cette étape décisive dans la compréhension de la mise en place de ces formations et de leur expansion dans les paysages s'est avérée très riche d'informations. Nous avons ainsi pu montrer que leur expansion dans l'espace était à la fois contrôlée par la nature du support sur laquelle elles se

forment et par les apports pluviométriques. Leur expansion est en effet très nettement accrue dans la partie Nord et Nord Ouest, c'est-à-dire dans les zones les plus pluvieuses et sur la surface d'aplanissement *Ucayali* qui exposent localement les latérites les plus altérées et anciennes du bassin. A l'inverse, elles sont beaucoup moins abondantes dans la partie sud du bassin, plus particulièrement sur la Formation Içá où elles occupent, comme les sols hydromorphes plus classiques (les Gleysols), les parties déprimées des plateaux. La grande expansion des systèmes podzoliques sur ces surfaces Tertaires et leur bien moindre abondance sur les surfaces d'incision et de dépôt du Quaternaire suggèrent fortement que ces systèmes aient pu être mis en place sur le bassin avant la naissance du réseau modern de drainage du fleuve Amazone, il y a prêt de 2.5 Ma. Par ailleurs, l'incision des surfaces basses du bassin par ce réseau de drainage a permis de drainer les aires les plus podzolisées situées au Nord Ouest de ce bassin, de stopper l'expansion de ces podzols ou limiter fortement leur expansion dans les paysages et d'alimenter en sables les lits des rivières.

Suite aux travaux réalisés dans le cadre de cette étude, deux incertitudes majeures subsistent. En effet, nous montrons qu'il existe deux voies possibles dans l'érosion chimique des couvertures latéritiques qui sont toutes deux associées, lors de leur évolution ultime, à la mise en place de systèmes de nappes dans les paysages. Dans la première voie, l'érosion chimique est sélective (dissolution des oxydes de fer) et les sols blanchissent mais restent argileux et peu perméables (formations des Gleys à nappes). Dans la deuxième voie, l'érosion chimique beaucoup plus importante (dissolution de l'ensemble des minéraux argileux) est propices à l'appauvrissement des latérites et ultérieurement à leur podzolisation (formations des Podzols à nappes). Sur la Formation Iça, les deux types de sols (Gleys et Podzols) occupent les mêmes positions topographiques (dépressions et chenaux des plateaux) et se relayent du Sud Est (Gleys) vers le Nord Ouest (Podzols). Quels sont les facteurs qui permettraient d'expliquer l'évolution vers l'une ou l'autre de ces voies à partir d'un même matériau parental ? N'y aurait-il pas içi l'influence de structures sédimentaires (e.g. dépôts plus sableux) qui pourrait favoriser l'une de ces voies plutôt que l'autre (e.g. podzolisation) ? La seconde incertitude correspond aux principaux processus à l'origine de la formation des nombreuses dépressions et chenaux de la Formation Içá. Faut-il y voir içi la marque d'anciennes structures fluvio-lacustres comme ça semble être le cas lorsqu'on les observe à petites échelles ou le résultat d'une fonte géochimique dans les parties centrales les moins bien drainées de ces plateaux, avec l'individualisation ultime de sols à nappes (Gley et Podzols) ?

L'ensemble de ces données permet également de dégager quelques perspectives dans l'optique d'une meilleure connaissance de ces systèmes. La première consisterait à mieux dissocier à méso-échelles les structures sédimentaires de celles attribuées à l'altération et la pédogenèse sur des sites clés de la Formation Içá de façon à mieux répondre aux précédentes incertitudes. La seconde viserait à mieux caractériser les matières organiques et leur charge en métaux dans les podzols drainés du site de São Gabriel da Cachoeira de façon à faire également une étude comparative avec ce qui a été établi au Jaú pour des podzols à nappe. En effet, il serait bon d'attribuer à ces changements de régime hydrique des facies pédologiques différents et des signatures spectrales tranchées pour la matière organique et les métaux, ce qui a encore jamais été réellement fait à notre connaissance. Enfin, il serait aussi souhaitable d'aborder le problème de l'age et de la dynamique de ces systèmes podzoliques par datation (^{14}C) et par des approches isotopiques (^{13}C, ^{15}N) et ce dans les différents ensembles structuraux reconnus aux échelles locales (séquence de sols) et régionales (eaux, sédiments). Des travaux dans ce sens sont en cours. Ils montrent des temps de résidence très contrastés des matières organiques dans les horizons des podzols et des fractionnements isotopiques opposés par rapport à ceux attribués aux environnements minéraux, comme les latérites (pour C, N mais aussi pour les métaux tels que Fe).

CONCLUSÕES GERAIS E PERSPECTIVAS

Este estudo vem contribuir para um melhor conhecimento dos meios podzolizados amazônicos. Estes meios extremos (encharcamentos prolongados, resíduos arenosos pouco férteis, forte acidez das águas, fraca atividade e diversidade biológicas) associados a paisagens insólitas de grande beleza, mas de interesse econômico limitado, são particularmente bem desenvolvidos na parte norte da alta bacia amazônica, que recebe os maiores volumes de precipitação pluviométrica da bacia. Eles cobrem um terço da superfície da bacia do Rio Negro. Essa bacia, com uma superfície de 600.000 km^2, apresenta a maior concentração de rios de águas negras e exporta por isso quantidades consideráveis de matéria orgânica e metais para o oceano. Os processos e funcionamentos associados à dinâmica evolutiva destes podzóis na paisagem nos chamaram a atenção. Estes processos e funcionamentos foram estudos tanto nas escalas locais, em posições-chave destas paisagens, quanto em escalas regionais, visando reconstituir a evolução dinâmica dos podzóis em um contexto geodinâmico mais global, associado à formação dos Andes e às grandes superfícies de erosão da bacia sedimentar. Essa ***démarche*** multiescalar e fortemente pluridisciplinar nos conduziu a utilizar abordagens diversificadas para obtenção dos dados. Essas abordagens se iniciaram pelas análises espectroscópicas para a caracterização das fases minerais do solo e terminaram com o estudo de produtos do sensoriamento remoto para a identificação das principais unidades de paisagem e dos grandes conjuntos estruturais da bacia do Rio Negro, sem deixar de lado, é claro, a abordagem estrutural, essencial para o reconhecimento das organizações pedológicas na escala de campo. Como já assinalado na Introdução, os documentos cartográficos do Projeto RadamBrasil foram decisivos para a escolha dos sítios de estudos e para o reconhecimento das grandes unidades estruturais da bacia. Na escala dos perfis de alteração e das seqüências de solos, abordagens geoquímicas acopladas a cálculos de funções de transporte permitiram a constatação de importantes perdas de matéria durante a transformação ou degradação das coberturas lateríticas.

Os trabalhos aqui apresentados contribuem para a compreensão das degradações sucessivas que as coberturas lateríticas sofreram ao longo do tempo. Estas degradações são essencialmente atribuídas a perdas de matéria (principalmente Fe e Al na região tropical) que podem ser seletivas, conjuntas, progressivas ou brutais. Elas testemunham mudanças das condições de alteração e drenagem que variam no espaço e se sucedem no tempo. Na bacia amazônica estas degradações seguem duas vias. Na primeira via as perdas de matéria são

menos intensas e afetam essencialmente o Fe. Elas são, por isso, atribuídas à saturação hídrica e ao desenvolvimento de condições redutoras provisórias ou mais permanentes nos perfis de alteração (óxido-redução). A caracterização destes sistemas (Latossolos-Gleissolos) vai além dos objetivos deste estudo. Ela foi realizada de forma bastante detalhada em estudos anteriores de seqüências de solos, tanto sobre formações lateríticas espessas (da superfície de erosão da região de Manaus) quanto sobre formações lateríticas delgadas e menos alteradas (sobre os sedimentos da Formação Içá, na região de Porto Velho). A segunda via é aquela que abordamos e estudamos nesta tese. Ela é associada a perdas de matéria muito mais importantes e acontece em duas grandes etapas (empobrecimento e podzolização). Quanto ao empobrecimento (tratado no Capítulo 3), as perdas de matéria se exprimem diferentemente segundo a posição no perfil: na parte inferior, em meio saturado, as perdas associadas à flutuação e ao escoamento dos lençóis são intensas. Elas são inicialmente atribuídas à exportação maciça do ferro (dissolução dos óxidos e lixiviação) e depois dos minerais de argila (aparentemente por lessivagem lateral), desde que aumentem os fluxos na parte superior dos lençóis. Na parte superior dos perfis lateríticos, não saturadas, as perdas são menos progressivas. Elas são sazonais e aparentemente associadas a períodos de hidratação mais prolongados. Elas são seletivas e afetam inicialmente a hematita (amarelecimento do solo) e depois a goethita e os minerais de argila, provavelmente por mecanismos de dissolução e lixiviação. Estas exportações de matéria na superfície, mas também em profundidade, conduzem à individualização, na parte de jusante das vertentes, de reservatórios arenosos cujos limites têm a forma de “dupla língua”. O desenvolvimento destes reservatórios bastante porosos e permeáveis é propício à migração da matéria orgânica e, assim, à podzolização última dos solos lateríticos (tratadas no Capítulo 4 e também em artigos no Anexo). Esta última etapa marca a colmatação da borda dos reservatórios arenosos por substâncias organo-metálicas. Ela é, assim, estreitamente associada ao aparecimento de lençóis suspensos e de condições redutoras que favorecem a acumulação de matéria orgânica nos solos e sua exportação para a rede hidrográfica. O cálculo das funções de transporte nestes sistemas mostra que as exportações de matéria (Fe e Al) são mínimas durante a podzolização, mas são muito mais importantes durante a etapa antecedente, de empobrecimento dos solos lateríticos em minerais argilosos. Entretanto, a podzolização marca uma mudança drástica na especiação dos metais, que passam a se associar à matéria orgânica.

Foram também estudados os efeitos das incisões lineares sobre a morfologia e a dinâmica dos podzóis (rebaixamento dos lençóis suspensos, erosão dos materiais arenosos dos podzóis).

Este estudo mineralógico e estrutural realizado na região de São Gabriel da Cachoeira (apresentado no Capítulo 4) foi comparado àquele feito anteriormente sobre sistemas podzolizados com lençol suspenso e pouco afetados pelas incisões dos canais de drenagem (região do Jaú). Nestes podzóis drenados pelas incisões, o rebaixamento dos lençóis na parte de montante dos sistemas podzólicos favorece a mineralização da matéria orgânica nas frentes laterais de podzolização e, conseqüentemente, a liberação dos metais previamente acumulados. Esta mineralização mais intensa, ligada a uma maior oxigenação destes solos, conduz a uma clara redução da espessura dos horizontes orgânicos destes podzóis, em superfície (nos horizontes eluviais com resíduos orgânicos), mas, também, em profundidade, nas frentes de podzolização (horizontes iluviais com complexos organo-metálicos). Esta oxigenação do solo pode também favorecer a formação de óxidos de ferro mal cristalizados nos sistemas hidromórficos que afetam os podzóis de montante. Enfim, a erosão regressiva na base das vertentes, que alimenta com areias brancas os leitos dos rios, pode favorecer o aprofundamento das frentes de podzolização sobre os saprolitos menos permeáveis e, assim, iniciar a formação de uma nova geração de horizontes iluviais (ou espódicos). Neste nível, a permanência de condições anóxicas em meio fracamente ácido é propícia a uma grande acumulação de complexos organo-metálicos. Os metais inicialmente presentes na parte de montante dos sistemas podzólicos se acumulam na parte de jusante, em uma segunda geração de horizontes espódicos. Este estudo comparativo mostra, também, que os podzóis estão associados a sistemas de lençol e que a drenagem destes podzóis marca uma etapa última na sua evolução, podendo, de forma natural ou artificial, limitar sua expansão no espaço.

Numa última etapa, os processos e funcionamentos foram discutidos na escala da bacia amazônica, particularmente na região onde os podzóis são mais abundantes: a bacia do Rio Negro (Capítulo 5). Esta etapa, decisiva para a compreensão da gênese destas formações e de sua expansão nas paisagens, trouxe importantes informações. Foi possível, assim, mostrar que sua expansão espacial é condicionada tanto pela natureza do substrato sobre o qual se formam quanto pela pluviometria. Sua expansão é, de fato, claramente mais importante nas partes norte e noroeste, isto é, nas zonas mais pluviosas e sobre a superfície de aplanamento *Ucayali*, coberta pelos perfis lateríticos mais alterados e antigos da bacia. Ao contrário, elas são muito menos abundantes na parte sul da bacia, particularmente sobre a formação Içá, onde ocupam, ao lado dos solos hidromórficos mais clássicos (Gleissolos), as partes deprimidas dos platôs. A grande expansão dos sistemas podzólicos sobre estas superfícies terciárias e sua menor incidência sobre as superfícies mais recentes, do Quaternário, sugerem fortemente que estes

sistemas podem ter se desenvolvido na bacia antes da instalação da rede de drenagem moderna do Rio Amazonas, há aproximadamente 2.5 Ma. Além disso, a incisão desta rede fluvial sobre as superfícies baixas foi responsável pela drenagem das áreas mais podzolizadas da parte noroeste da bacia, pela interrupção ou a limitação da expansão destes podzóis nas paisagens e pelo fornecimento de areias brancas para os canais fluviais.

Após os trabalhos realizados no âmbito deste estudo, duas incertezas maiores persistem. De fato, foi mostrado que existem duas vias possíveis para a erosão química das coberturas lateríticas. Estas duas vias estão associadas, na sua evolução final, ao aparecimento de sistemas de lençóis na paisagem. Na primeira via, a erosão química é seletiva (dissolução dos óxidos de ferro) e os solos se tornam mais brancos, mas permanecem argilosos e pouco permeáveis (formação de Gleissolos com lençóis). Na segunda via, a erosão química mais importante (dissolução do conjunto dos minerais argilosos) é propícia ao empobrecimento dos solos lateríticos e posteriormente à sua podzolização (formação de Podzóis com lençol). Sobre a Formação Içá, os dois tipos de solos (Gleissolos e Podzóis) ocupam as mesmas posições topográficas (depressões e canais mal drenados dos platôs) e se alternam do sudeste (Gleissolos) para noroeste (Podzóis). Quais são os fatores que permitiriam explicar a evolução rumo a uma ou outra destas duas vias a partir de um mesmo material de origem? Não haveria aqui a influência de estruturas sedimentares (ex: depósitos mais arenosos) que poderiam favorecer uma destas vias em detrimento da outra (ex: podzolização)? A segunda incerteza corresponde aos principais processos que explicam a origem das inúmeras depressões e canais mal drenados dos platôs da Formação Içá. É necessário verificar se se trata de antigas estruturas flúvio-lacustres, associadas a antigas redes de drenagem, como parece ser o caso quando observadas em pequena escala, ou o resultado de uma perda geoquímica mais acentuada nas partes centrais de pior drenagem destes platôs, seguida da individualização última de solos com lençóis (Gleissolos e Podzóis).

O conjunto destes dados permitiu igualmente apontar algumas perspectivas na ótica de um melhor conhecimento destes sistemas. A primeira consistiria em melhor dissociar, em meso-escala, as estruturas sedimentares daquelas atribuídas à alteração e à pedogênese sobre sítios-chave da Formação Içá, para melhor responder às referidas incertezas. A segunda visaria uma melhor caracterização das matérias orgânicas e de sua carga em metais nos podzóis drenados do sítio de São Gabriel da Cachoeira, para fazer um estudo comparativo com aquele realizado no sítio do Jaú sobre os podzóis com lençol. De fato, seria bom atribuir, a estas mudanças de regime hídrico, diferentes fácies pedológicas e assinaturas espectrais para a matéria orgânica e

para os metais, o que não foi ainda feito segundo nosso conhecimento. Enfim, seria também desejável abordar o problema da idade e da dinâmica destes sistemas podzólicos por datação (^{14}C) e por abordagens isotópicas (^{13}C, ^{15}N), isto para os diferentes conjuntos estruturais identificados nas escalas locais (seqüências de solos) e regionais (águas e sedimentos). Trabalhos neste sentido estão em curso. Eles indicam tempos de residência da matéria orgânica muito contrastados nos horizontes dos podzóis e fracionamentos isotópicos muito diferentes daqueles atribuídos aos meios minerais, como os solos lateríticos (para C, N, mas, também, para metais como o Fe).

BIBLIOGRAFIA

Anderson H.A., Berrow M.L., Farmer V.C., Hepburn A., Russel J.D., Walker A.D. (1982). A reassessment of podzol formation processes. *J. Soil Sci*. **33**, 125-136.

Allard T., Ponthieu M., Weber T., Filizola N., Guyot J.L., and Benedetti M. (2002). Nature and properties of suspended solids in the Amazon Basin. *Bull. Soc. Géol. France* **173**, 67-75.

Allard T., Menguy N., Salomon J., Calligaro T., Weber T., Calas G., Benedetti M.F. (2004). Revealing forms of iron in river-borne material from major tropical rivers of the Amazon Basin (Brazil). *Geochimica et Cosmochimica Acta* **68**, 3079-3094.

Aubert G. (1954). Les sols latéritiques. *Actes et Comptes Rendus du V^e Congrès International de la Science du Sol.* Léopoldville **1**, 103-118.

Balan E., Allard T. Boizot B., Morin G., Muller J.P. (1999). Structural Fe^{3+} in natural kaolinites: new insights from electron paramagnetic resonance spectra fitting at X and Q-band frequencies. *Clays and Clay Minerals* **47**, 605-616.

Balan, E., Trocellier , P., Jupille, J., Fritsch, E., Muller, J.-P., Calas, G. (2001). Surface chemistry of weathered zircons. *Chemical Geology* **181**, 13-22.

Balan E., Allard T., Fritsch E., Sélo M., Falguères C., Chabaux F., Pierret M.C., Calas G. (2005). Formation and evolution of lateritic profiles in the middle Amazon basin: Insights from radiation-induced defects in kaolinite. *Geochimica et Cosmochimica Acta* **69**, 2193-2204.

Bardy M., Bonhomme C., Fritsch E., Maquet J., Hajjar R., Allard T., Derenne S., Calas G. (2007). Al speciation in tropical Podzols of the upper Amazon basin : a solid-state ^{27}Al MAS and MQMAS NMR study. *Geochimica et Cosmochimica Acta* **71**, 3211-3222.

Bardy M., Fritsch E., Derenne S., Allard T., Do Nascimento N.R., Bueno G.T. (2008). Micromorphology and spectroscopic characteristics of organic matter in waterlogged Podzols of the upper Amazon basin. *Geoderma* **14**, 222-230.

Beaudou A.G. & Chatelin Y. (1972). Les mouvements d'argile dans certains sols ferrallitiques centrafricains. ORSTOM, 9p.

Bedidi, A., Cervelle, B., Madeira, J., Pouget, M. (1992). Moisture effects on visible spectral characteristics of lateritic soils. *Soil Science* **153**, 129-141.

Bezerra P.E.L., (2003). Compartimentação morfotectônica do Interflúvio Solimões-Negro. Tese de doutorado, 335p**.**

Bish D.L. & Reynolds J. (1989): Sample preparation for X-ray diffraction. *Reviews in Mineralogy : Modern Powder Diffraction*, Vol. 20, Mineralogical Society of America, Washington, 73-99.

Benedetti M.F., Mounier S., Filizola N., Benaim J., Seyler P. (2003a). Carbon and metal concentrations, size distributions and fluxes in major rivers of the Amazon Basin. *Hydrological Processes* **17**, 1363-1377.

Benedetti M.F., Ranville J.F., Allard T., Bednar A.J., Menguy N. (2003b). The iron status in colloidal matter from the Rio Negro, Brasil. Colloids and Surfaces A. *Physicochem. Eng. Aspects* **217**, 1-9.

Bigarella J.J. & Andrade G.O. (1965). Contribution to the study of the Brazilian Quaternary. In: WRIGHT H.E. Jr., FREY D.G. (eds.). *International Studies on the Quaternary. Geological Society of America Special Papers* **94**, 433-451.

Blancaneaux P. (1981). Essai sur le milieu naturel de la Guyane Française. Travaux et Documents de l'ORSTOM, 137, 126p.

Bocquier G. (1971). Genèse et évolution de deux toposéquences de sols tropicaux du Tchad – Interprétation biogéodynamique. *Cah. ORSTOM* **9**, 509-515.

Boulet R. (1974). Toposéquences de sols tropicaux en Haute-Volta. Equilibres dynamiques et bio-climatiques. Thèse Sci. Strasbourg, Mémoire ORSTOM, 85, 1978, 272p.

Boulet R., Bocquier G., Millot G., (1977). Géochimie de la surface et formes du relief : 1. Déséquilibre pédobioclimatique dans les couvertures pédologiques de l'Afrique tropicale de l'Ouest et son rôle dans l'aplanissement des reliefs. *Sciences Géologiques Bulletin* **30** (4), 235-243.

Boulet R., Chauvel A., Humbel F.X., Lucas Y. (1982). Analyse structurale et cartographie en pédologie: I - Prise en compte de l'organisation bidimensionnelle de la couverture pédologique: les études de toposéquences et leurs principaux apports à la connaissance des sols. *Cah. ORSTOM* **19**, 309-321.

Boulet R., Lucas Y., Fritsch E., Paquet H. (1993). Géochimie des paysages : le rôle des couvertures pédologiques. *In* Coll. "Sédimentologie et Géochimie de la Surface" à la mémoire de Georges Millot. H. Paquet et N. Clauer eds., Les colloques de l'Académie des Sciences et du Cadas, Paris, 55-76.

Boulet R., Lucas Y., Fritsch E., Paquet, H. (1997). Geochemical processes in tropical landscapes: role of the soil covers. In: Paquet, H. & Clauer N. (Eds). Soils and Sediments - Mineralogy and Geochemistry, Springer-Verlag, Heidelberg, 67-96.

Bousserrhine N, Gasser U.G., Jeanroy E., Berthelin J. (1998). Bacterial and chemical reductive dissolution of Mn-, Cr- and Al-substituted goethithes. *Geomicrobiology Journal* **16**, 245-258.

Bravard S. & Righi D. (1989). Geochemical differences in an oxisol-spodosol toposéquence of Amazonia, Brazil. *Geoderma* **44**, 29-42.

Bravard S. & Righi D. (1990). Podzols in Amazonia. *Catena* **17**, 461-475.

Brimhall G.H. & Dietrich W.E. (1987). Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis. *Geochimica et Cosmochimica Acta* **51**, 567-587.

Braun, J.J., Pagel, M., Herbillon, A., Roisin, C. (1993). Mobilization and redistribution of REEs and thorium in a syenitic lateritic profile. A mass balance study. *Geochimica et Cosmochimica Acta* **57**, 4419-4434.

Braun J.J., Ngoupayou J.R.N., Viers J., Dupre B., Bedimo J.P., Boeglin J.L., Robain H. Nyeck B., Freydier R., Nkamdjou L.S., Rouiller J., Muller J.P. (2005). Present weathering rates in a humid tropical watershed : Nsimi, South Cameroon. *Geochimica et Cosmochimica Acta* **69**, 357-387.

Bravard, S. & Righi, D. (1989). Geochemical differences in an Oxisol-Spodosols Toposequence of Amazonia, Brazil. *Geoderma* **44**, 29-42.

Bravard S. & Righi D. (1990). Podzols in Amazonia. *Catena* **17**, 461-475.

Brewer R. (1964). Fabric and mineral analysis of soils. J. Wiley and Sons, N.Y., Sydney, 470p.

Brimhall, G.H., Lewis, C.J., Ford, C., Bratt, J., Taylor, G., Warin O. (1991). Quantitative geochemical approach to pedogenesis: importance of parent material reduction, volumetric expansion, and eolian influx in lateritization. *Geoderma* **51**, 51-91.

Brinkman R. (1970). Ferrolysis, a hydormorphic soil forming process. *Geoderma* **3**, 199-206.

Bruand A., Braudeau E., Fritsch E. (1990). Evolution de la géométrie de l'espace poral des sols lors du passage du domaine ferrallitique au domaine ferrugineux et hydromorphe : exemple du bassin de Booro Borotou. *In* Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, Paris, 90-96.

Büdel J. (1957). Die “Doppelten Einebnungsflächen” in den feuchten Tropen. *Z. Geomorphol.* **1**, 201-228.

Buurman P. (1987). pH-dependent character of complexation in podzols. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 191-186.

Buurman P. & Jongmans A.G. (2005). Podzolisation and soil organic matter dynamics. *Geoderma* **125**, 71-83.

Campbell K.E. Jr., Frailey C.D., Romero-Pittman L. (2006). The Pan-Amazonian Ucayali Peneplain, late Neogene sedimentation in Amazonia, and the birth of the modern Amazon River system. *Palaeogeography, Palaeoclimatology, Palaeoecology* **239**, 166-219.

Chadwick O.A., Brimhall G.H., Hendricks D.M. (1990). From a black to a grey box: a mass balance interpretation of pedogenesis. *Geomorphology* **3**, 369-390.

Chauvel A., Bocquier G., Pedro G. (1977). Géochimie de la surface et formes du relief III. Les mécanismes de la disjonction des constituants des couvertures ferrallitiques et l’origine de la zonalité des couvertures sableuses dans les régions intertropicales de l’Afrique de l’Ouest. *Sci. Géol., Bull.* **30**, 255-263.

Chauvel A., & Pedro G. (1978). Genèse de sols beiges (ferrugineux tropicaux lessivés) par transformation des sols rouges (ferrallitiques) de Casamance (Sénégal) – Modalités de leur propagation, *Cah. ORSTOM* **16**, 231-249.

Chauvel A., Lucas Y., Boulet R. (1987). On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. *Experientia* **43**, 234-241.

Colin F., Vieillard P., Ambrosi J.P. (1993). Quantitative approach to physical and chemical old mobility in equatorial rainforest lateritic environment. *Earth Planet. Sci. Let.*, **114**, 269-285.

Cornu S., Lucas Y., Lebon E., Ambrosi J.P., Luizão F, Rouiller J, Bonnay M, Neal, C. (1999). Evidence of titanium mobility in soil profile Manaus, central Amazonia. *Geoderma* **91**. 281-295.

Costa R C.R., Natali Filho T., Oliveira A.A.B. (1978). Projeto RADAMBRASIL – Geomorfologia. Manaus, 18, 165-244.

De Coninck F. (1980). Major mechanisms in formation of spodic horizons. *Geoderma* **24**, 101-128.

DNPM. (1981). Mapa geológico do Brasil, Brasília, escala 1:2.500.000.

Dubroeucq D. & Volkoff B. (1988). Évolution des couvertures pédologiques sableuses à podzols géants d'Amazonie (Bassin du Haut rio Negro). *Cahiers ORSTOM, Série Pédologie* **26** (3), 191-214.

Dubroeucq D. & Volkof B. (1998). From Oxisols to Spodosols and Histosols: evolution of the soil mantles in the Rio Negro basin (Amazonia). *Catena* **32**, 245-280.

Dubroeucq D., Volkoff B., Faure P. (1999). Les couvertures pédologiques à Podzols du Bassin du Haut Rio Negro. *Étude et Gestion des Sols* **6**, 131-153.

Duchaufour P. (1972). Processus de formation des sols. Biochimie et Géochimie. Nancy : Editions CRDP, Coll. Etudes et Recherches, 182 p.

Duchaufour P. (1982). Pedology: Pedogenesis and Classification. London: George Allen and Unwin, 481p.

EMBRAPA. (1981). Mapa de Solos do Brasil. Brasília. escala 1:5.000.000.

Fanning D.S. & Fanning M.C. (1989). Soil, morphology, genesis and classification. John Wiley & Sons, New York, 395p.

FAO. (1998). World Reference Base for Soil Resources. World Soil Resources Report n° 84. Rome, 172p.

Farmer V.C., Russel J.D., Berrow M.L. (1980). Imogolite and proto-imogolite alophane in spodic horizons: evidence for a mobile aluminium silicate complex in podzol formation. *J. Soil Sci.* **31**, 673-784.

Farmer V.C. (1987). The role of inorganic species in the transport of aluminium in podzols. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 187-194.

Fauck R. (1972). Les sols rouges sur sables et sur grès d'Afrique Occidentale. Mémoires ORSTOM, 261p.

Fernandes P.E.C.A, Pinheiro S.S., Montalvão R.M.G., Issler R.S., Abreu A.S.; Tassinari C.C.G. (1977). Geologia. Içá, 14. DNPM/Projeto Radambrasil, 19-123.

Fitzpatrick, E.A., (1970). A technique for preparation of large thin sections of soils and unconsolidated materials. In: Osmond, D.A. & Bullocck, P. (Eds.), Soil Survey of England and Wales, Harpenden, Technical Monograph. Micromorphological Techniques and Applications, vol. 2, 3-13.

Franco E.M.S., Moreira M.M.M.A, Barbosa G.V. (1977). Projeto RADAMBRASIL – Geomorfologia. Içá, 14, 127-180.

Fritsch E., Bocquier G., Boulet R., Dosso M., Humbel F.X. (1986). Les systèmes transformants d'une couverture ferrallitique de Guyane française. Analyse structurale d'une formation supergène et mode de représentation. *Cah. ORSTOM* **22**, 361-395.

Fritsch E., Herbillon A.J., Jeanroy E., Pillon P., Barres O. (1989). Variations minéralogiques et structurales accompagnant le passage "sols rouges - sols jaunes" dans un bassin versant caractéristique de la zone de contact forêt-savane de l'Afrique occidentale (Booro-Borotou, Côte d'Ivoire). *Sci. Géol. Bul.* **42**, 65-89.

Fritsch E., Valentin C., Morel P., Leblond P. (1990a). La couverture pédologique : interactions avec les roches, le modelé et les formes de dégradation superficielles. In : Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 31-57.

Fritsch E., Chevallier P., Janeau J.L. (1990b). Le fonctionnement hydrodynamique du bas de versant. In : Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 185-206.

Fritsch E, Peterschmitt E., Herbillon A.J. (1992). A structural approach to the regolith: Identification of structures, analysis of structural relationships and interpretations. *Sci. Géol. Bul.* **45** (2), 77-97.

Fritsch E. & Fitzpatrick R.W. (1994). Interpretation of Soil Features Produced by Ancient and Modern Processes in Degraded Landscapes. I. A new method for constructing conceptual soil-water-landscape models. *Aust. J. Soil Res.* **32**, 889-907.

Fritsch E., Montes-Lauar C.R., Boulet R., Melfi A.J., Balan E., Magat Ph. (2002). Lateritic and redoximorphic features in a faulted landscape near Manaus, Brazil. *European Journal of Soil Science* **53**, 203-218.

Fritsch E., Morin G., Bedidi A., Bonnin D., Balan E., Caquineau S., Calas G. (2005). Transformation of haematite and Al-poor goethite to Al-rich goethite and associated yellowing in a ferralitic clay soil profile of the middle Amazon basin (Manaus, Brazil). *European Journal of Soil Science* **56**, 575-588.

Fritsch E., Herbillon A. J., Nascimento Do N. R., Grimaldi, M., Melfi M. J. (2007). From Plinthic Acrisols to Plinthosols and Gleysols : iron and groundwater dynamics in the tertiary sediments of the upper Amazon basin. *European Journal of Soil Science* **58**, 989-1006.

Fritsch E., Allard T., Benedetti M.F., Bardy M., Nascimento Do N. R., Li, Y., Calas G. (2009). Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. *Geochimica et Cosmochimica Acta*, (doi: 10.1016/j.gca.2009.01.008).

Fritsch E., Allard T., Benedetti M.F., Bardy M., Do Nascimento N. R., Li, Y., Calas G. Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. *Geochimica et Cosmochimica Acta*, (submitted).

Gombeer R. & D'Hoore H. (1971). Induced migration of clays and other moderately mobile soil constituents. III. Critical soil/water dispersion ratio, colloid stability and electrophoretic mobility. *Pedologie* **21**, 311-342.

Grybos M., Davranche M., Gruau G., Petitjean P. (2007). Is trace metal release in wetland soils controlled by organic matter mobility or Fe-oxyhydroxides reduction? *Journal of Colloid and Interface Science* **314**, 460-501.

Gouveia S.E.M., Pessenda L.C.R. Aravena, R. Boulet R., Roveratti R., Gomes B.M. (1997). Dinâmica de vegetações durante o Quaternário recente no sul do Amazonas, indicada pelos isótopos do carbono (^{12}C, ^{13}C, ^{14}C) do solo. *Geochimica Brasiliensis* **11**, 355-367.

Gustafsson J.P., Bhattacharya P., Karltun E. (1999). Mineralogy of poorly crystalline aluminium phases in the B horizon of Podzols in southern Sweden. *Applied Geochemistry* **14**, 707-718.

IBGE. (2001). Mapa de solos do Brasil, Rio de Janeiro, escala 1: 5.000.000.

Jansen B., Nierop K.G.J., Verstraten J.M. (2003). Mobility of Fe(II), Fe(III) and Al in acidic forest soils mediated by dissolved organic matter: influence of solution pH and metal/organic carbon ratios. *Geoderma* **113**, 323-340.

Jeanroy E., Rajot J.L., Pillon P., Herbillon A.J. (1991). Differential dissolution of hematite and goethite in dithionite and its implication on soil yellowing. *Geoderma* **50**, 79-94.

Jenny H. (1941). Factors of soil formation. New York: McGraw-Hill, 109p.

King L.C. (1953). Canons of landscape evolution. *Bull. Geol. Soc. Am.* **64**, 721-752.

Klinge H. (1965). Podzol soils in the Amazon Basin. *Journal of Soil Sci.* **16**, 95-103.

Kronberg B. & Melfi,A. J. (1987). The geochemical evolution of lateritic terranes. *Z Geomorph N F Suppl Bd*. **64**, 25-32.

Kosmas, C.S., Curi, N., Bryant, R.B. & Franzmeier, D.P. (1984). Characterization of iron oxide minerals by second derivative visible spectroscopy. *Soil Science Society of America Journal* **48**, 401-405.

Latrubesse E.M., Franzinelli E., (2005). The Late Quaternary evolution of the Negro River, Amazon, Brazil : Implications for island and floodplain formation in large anabranching tropical systems. *Geomorphology* **70**, 372-397.

Linton D.L. (1955). The problem of tors. *Geogr. Journal*. **121**, 470-487.

Lucas, Y. (1989). *Systèmes pédologiques en Amazonie brésilienne. Equilibres, déséquilibres et transformations*. Thèse de Doctorat, Université de Poitiers, 157p.

Lucas Y., Chauvel A., Boulet R., Ranzani G., Scatolini F. (1984). Transição latossolos-podzóis sobre a Formação Barreiras na região de Manaus, Amazônia. *Revista Brasileira de Ciência do Solo* **8**, 325-335.

Lucas, Y., Boulet, R., Veillon, L. (1987). Systèmes sols ferrallitiques – podzols en région amazonienne. In: *Podzols et Podzolisation* (eds D. Righi & A. Chauvel), Association Française pour l'Etude du Sol, INRA, 53-65.

Lucas Y., Boulet R., Chauvel A. (1988). Intervention simultanée des phénomènes d'enfoncement vertical et de transformation latérale dans la mise en place des systèmes de sols de la zone tropicale humide. Cas des systèmes sols ferrallitiques-podzols de l'Amazonie Brésilienne. *C. R. Academie des Sciences de Paris* **306**, 1395-1400.

Lucas Y., Nahon D., Cornu S., Eyrolle F. (1996). Genèse et fonctionnement des sols en milieu équatorial. *C. R. Acad. Sci. Paris* **322**, 1-16.

Lundström U.S. (1993). The role of organic acids in soil solution chemistry in a podzolized soil. *J. Soil Sci.* **44**, 121-133.

Lundström U.S., van Breemen N., Bain, D. (2000). The Podzolisation process. A review. *Geoderma* **94**, 91-107.

Macias-Vasquez F, Fernandez-Marcos M.L., Chesworth W. (1987). Transformations minéralogiques dans les podzols et les sols podzoliques de Galice (NW. Espagne). In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 163-177.

Magnago H., Barreto R.A.A., Pastore U. (1978). Vegetação. Manaus, Projeto RadamBrasil, 18, 413-530.

Maurin J.C., Gilbert F., Robert M., Churlaud C. (2005). L'érosion chimique et l'érosion mécanique à long terme du substrat granitique (Vendée, France). *C. R. Geosciences* **337**, 841-848.

Malengreau, N., Beddidi A., Muller, J.P., Herbillon, A.J. (1996). Spectroscopic control of iron oxide dissolution in two ferralitic soils. *European Journal of Soil Science* **47**, 13-20.

Meade R., Rayol J.M., Da Conceição S.C., Natividade J.R., (1991). *Environmental Geologic Water Science* **18** (2), 105-114.

Mehra, O.P. & Jackson, M.L. (1960). Iron oxide removal from soils and clays by a dithionite-citrate buffered with sodium bicarbonate. *Clays and Clay Minerals* **7**, 317-327.

Melfi A.J. & Pedro G. (1977). Estudo geoquímico dos solos e formações superficiais do Brasil. Parte 1 - Caracterização e repartição dos principais tipos de evolução pedogeoquímica. *Revista Brasileira de Geociências* **7**, 271-286.

Middelburg J.J., Van der Weijden C.H., Woittiez J.R.W. (1988). Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks. *Chemical Geology* **68**, 253-273.

Millot G. (1983). Planation of continents by intertropical weathering and pedogenetic processes. In: Melfi A.J. & Carvalho A. Lateritisation Processes – Proceedings of the II International Seminar on lateritisation processes, 53-64.

Montes C.R., Lucas Y., Melfi A.J., Ishida D.A. (2007). Systèmes sols ferrallitiques–podzols et genèse des kaolins / Ferralsols–podzols soil systems and kaolin genesis. *C. R. Geosciences* **339**, 50-56.

Mortland M.M. (1968). Protonation of compounds at clay minera1 surfaces. *Transactions IX Int. Cong. Soi1 Sciences*, Adelalde (Australie) 1, 691-699.

Nahon, D.B. (1991). *Introduction to the Petrology of Soils and Chemical Weathering*. New York: John Wiley & Sons, 313p.

Nascimento Do N.R., Bueno G. T., Fritsch E., Herbillon A.J., Allard Th., Melfi A.J., Astolfo R., Boucher H., Y. Li. (2004). Podzolisation as a deferralitization process. A study of an Acrisol-Podzol sequence derived from Paleozoic sandstones in the northern upper Amazon Basin. *European Journal of Soil Science* **55**, 523-538.

Nascimento Do N.R., Fritsch E., Bueno G.T., Bardy M., Grimaldi C., Melfi A.J. (2008). Podzolization as a deferralitisation process: dynamics and chemistry of ground and surface waters in an Acrisol–Podzol sequence of the upper Amazon Basin. *European Journal of Soil Science* **59**, 911-924.

Oliva P., Viers J., Dupré B., Fortuné J.P., Martin F., Braun J.J., Nahon D.B., Robain H. (1999). The effect of organic matter on chemical weathering : Study of a small tropical watershed : Nsimi-Zoétélé site, Cameroon. *Geochimica et Cosmochimica Acta* **63**, 4013-4035.

Patel-Sorrentino N., Lucas Y., Eyrolle F., Melfi A.J. (2007). Fe, Al and Si species and organic matter leached off a ferrallitic and podzolic soil system from Central Amazonia. *Geoderma* **137**, 444-454.

Pedro G. (1987). Podzols et Podzolisation: un problème pédologique fort ancien, mas toujours d'actualité. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 1-10.

Peterschmitt E., Fritsch E., Rajot J.L., Herbillon A.J. (1996). Yellowing bleaching and ferritization in a hydrotoposequence of the Western Ghâts, South India. *Geoderma* **74**, 235-253.

Petersen L. (1984). The Podzol concept. In: Buurman, P. (Ed.), Podzols. New York: Van Nostrand Reinhold Company, 12-19.

Plaisance G. & Cailleux A. (1958). Dictionnaire des Sols. Paris: La Maison Rustique, 604 p.

Planchon O., Fritsch E., Valentin C. (1987). Rill development in a wet savannah environment. *Catena sup*. **8**, 55-70.

Projeto Radam (or Radam Brazil) (1972-78). *Levantamento de Recursos Naturais.* Vol. 1 - 15. Ministério das Minas e Energia. Departamento Nacional da Produção Mineral. Rio de Janeiro, Brazil.

Rinder G.E., Fritsch E., Fitzpatrick R.W. (1994). Computing procedures for mapping soil features at sub-catchment scale. *Aust. J. Soil Res*. **32**, 909-913 (colour figs 886-887).

Robinson G.W. (1949). *Soils, their origin, constitution and classification*. London: Thomas Murby and Co., 573p.

Sampaio, A. & Northfleet, A. (1973). Estratigrafia e correlação das bacias sedimentares brasileiras. In: Ann. 27 Congr. Soc. Bras. Geol., Aracajú, 3, 189-206.

Schwartz D. (1987). Les podzols tropicaux sur sable Batéké en R.P du Congo:description, caracterisation et genèse. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 25-36.

Ségalen P. (1966). Le processus de ferrallitisation et ses limites. ORSTOM s.n., 15-20.

Silva F.C.F., Jesus R.M., Ribeiro A.G. (1977). Vegetação. Içá, 14. DNPM/Projeto Radambrasil, 229-396.

Simonson, R.W. (1959). Outline of a generalized theory of soil genesis. *Soil Sci. Soc. Am. Proc.* **23**, 152-156.

Soil Survey Staff. (1975). Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S. Dept. of Agric. Handb. 436p.

Taboada T., Cortizas A. M., García C., García-Rodeja E. (2006). Particle-size fractionation of titanium and zirconium during weathering and pedogenesis of granitic rocks in NW Spain. *Geoderma* **131**, 218-236.

Tardy Y. (1993). *Pétrologie des latérites et des sols tropicaux*. Paris : Masson, 459p.

Théveniaut, H. & Freyssinet, Ph. (2002). Timing of lateritzation on the Guiana Shield: synthesis of paleomagnetic results from the French Guiana and Suriname. *Palaeogeography, Palaeoclimatology, Palaeoecology* **178**, 91-117.

Thompson C.H. (1992). Genesis of Podzols on Coastal Dunes in Southern Queensland. I. Field Relationships and Profile Morphology. *Australian Journal of Soil Research,* **30**, 593-613.

Torrent J., Schwertmann U., Barron V. (1987). The reductive dissolution of synthetic goethite and hematite in dithionite. *Clay Miner*. **22**, 329-337.

Trescases J.J. (1975). L'évolution géochimique supergène des roches ultrabasiques en zone tropicale. Formation des gisements nickélifères de Nouvelle-Calédonie. *Mém. ORSTOM* 78, 259p.

Turenne, J.F. (1975). *Modes d'humification et différenciation Podzolique dans deux toposéquences guyanaises*. Thèse de Doctorat, Université Nancy I, 185p.

Turenne J.F. (1977). Modes d'humification et différenciation podzolique dans deux toposéquences Guyanaises. *Mém. ORSTOM* 84, Paris, 174p.

Ugolini F.C. & Dahlgren R. (1987). The mechanism of podzolisation as revealed by soil solution studies. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 195-203.

Valentin C. & Fritsch E. (1990). Un résumé des processus pédologiques ouest-africains. *In* Structure et fonctionnement hydropédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 227-232.

Van Breemen N. (1985). Effects of seasonal redox-processes involving Fe on the chemistry of periodically reduced soils. In: Stucki J. W., Goodman A., Schwertmann O. (Eds.) Iron in soils and clay minerals. Bad Windsheim: Nato Advanced Study Institute, 858-875.

Van der Weijden C.H. & Van der Weijden R. (1995). Mobility of major, minor and some redox-sensitive trace elements and rare-earth elements during weathering of four granitoids in central Portugal. *Chemical Geology* **125**, 149-167.

Van Hees P.A.W. & Lundström U.S. (2000). Equilibrium models of aluminium and iron complexation with different organic acids in soil solution. *Geoderma* **94**, 201-221.

Van Ranst F. & De Coninck F. (2002). Evaluation of ferrolysis in soil formation. *European J. Soil Science* **53**, 513-520.

Viers J., Dupré B., Polvé M., Schott J., Dandurand J.L., Braun J.J. (1997). Chemical weathering in the drainage basin of a tropical watershed (Nsimi-Zoetele site, Cameroon): comparison between organic poor and organic rich waters. *Chem. Geol.*, **140**, 181-206.

Wesemael B., Verstraten J.M., Sevink J. (2005). Pedogenesis by clay dissolution on acid, low-grade metamorphic rocks under mediterranean forests in southern Tuscany (Italy). *Catena*, **24**, 105-125.

Wyszecki, G. & Stiles, W.S. (1982). Color science: Concepts and Methods, Quantitative Data and Formulae. John Wiley & Sons, New York, 950p.

Yamazaki D.R., Costa A.M.R., Azevedo W.P. (1978). Projeto RADAMBRASIL – Pedologia. Manaus, 18, 245-410.

UNIVERSIDADE ESTADUAL PAULISTA

Instituto de Geociências e Ciências Exatas

Campus de Rio Claro

EMPOBRECIMENTO E PODZOLIZAÇÃO DE SOLOS LATERÍTICOS DA BACIA DO RIO NEGRO E GÊNESE DOS PODZÓIS NA ALTA BACIA AMAZÔNICA

GUILHERME TAITSON BUENO

Orientadores: Nádia Regina do Nascimento (UNESP-Brasil)
Emmanuel Fritsch (IPGP-França)

Tese elaborada junto ao Programa de Pós-Graduação em Geografia, Área de Concentração em Análise Espacial (UNESP-Brasil), e ao Programa de Pós-Graduação em Ciências da Terra, Área de Concentração em Geoquímica Fundamental e Aplicada (IPGP-França) (regime de co-tutoria, convênio CAPES-COFECUB) para obtenção do título de Doutor em Geografia e em Ciências da Terra

Rio Claro (SP)
2009

551.41 Bueno, Guilherme Taitson
B928e Empobrecimento e podzolização de solos lateríticos da bacia do Rio Negro e gênese dos podzóis na alta Bacia Amazônica / Guilherme Taitson Bueno. - Rio Claro : [s.n.], 2009
157 f. : il., gráfs., tabs., fots., mapas

Tese (doutorado) - Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas
Orientador: Nádia Regina do Nascimento
Orientador: Emmanuel Fritsch

1. Ciência do solo. 2. Podzóis da Amazônia. 3. Podzolização. 4. Mineralogia. 5. Geoquímica. 6. Evolução da paisagem. I. Título.

Ficha Catalográfica elaborada pela STATI - Biblioteca da UNESP
Campus de Rio Claro/SP

Comissão Examinadora

Profa. Dra. Nádia Regina do Nascimento (orientadora)

Dr. Emmanuel Fritsch (orientador)

Dr. Marc Benedetti

Prof. Dr. Antônio José Teixeira Guerra

Dr. Georges Calas

Dr. Ary Bruand

Prof. Dr. Adolpho José Melfi

Dra. Sylvie Derenne

Guilherme Taitson Bueno
Aluno (a)

Paris, 6 de maio de 2009

Resultado: aprovado

RESUMO

Os podzóis (espodossolos) apresentam horizontes arenosos sobre níveis pouco permeáveis enriquecidos em matéria orgânica e metais. Ocupam grandes superfícies da alta bacia amazônica, sob influênica de lençóis suspensos e meios redutores e ácidos. Este trabalho trata da: (i) pré-podzolização, ou empobrecimento prévio dos solos lateríticos (latossolos); (ii) formação de podzóis sobre platôs, posteriormente dissecados pelos rios; (iii) dinâmica dos podzóis na escala da bacia do Rio Negro. Integra abordagens geoquímicas, petrográficas e mineralógicas, estudos de solos e de unidades de paisagem. A erosão química, mas, também, particulada, dos solos lateríticos, crescente da borda ao centro podzolizado dos platôs, afeta, separadamente, solos e saprolitos. O amarelecimento e o empobrecimento do solo devem-se à dissolução dos óxidos de Fe (hematita e depois goethita), e da caolinita. O desenvolvimento de lençóis suspensos no saprolito favorece o empalidecimento dos materiais e, os escoamentos laterais, a eluviação. Produzem reservatórios arenosos, explorados pela podzolização. A posterior incisão dos podzóis hidromórficos ativa a mineralização da matéria orgânica, a oxidação do Fe, e o aporte de areias aos rios. O desenvolvimento dos podzóis na bacia pode ser anterior à rede de drenagem moderna do Amazonas (2,5 Ma BP). Sua posterior incisão posterior teria limitado sua expansão lateral e fornecido areias brancas ao Rio Negro.

Palavras-chave: Amazônia, podzolização, mineralogia, geoquímica, evolução da paisagem

ABSTRACT

Podzols present spectacular morphology, with sandy horizons over less permeable and organo-metallic compartments. They occupy important surfaces of the upper Amazon basin, under the influence of perched watertables and reducing/acidic environments. This work focuses on: (i) lateritic soils impoverishment before podzolisation; (ii) hydromorphic podzol development on the plateaux and their latter incision; and (iii) podzol dynamics in the Rio Negro catchment scale. It associates geochemical, petrographic and mineralogical approaches, with investigations of soil catena and landscapes units. The increasing chemical but also particulate erosion of lateritic soils from the edge to the podzolised plateaux centre affect, separately, soils and saprolites. Selective dissolution of iron oxydes (hematite, then goethite), and ultimately of kaolinite, are associated with soil yellowing and impoverishment. In the saprolites, the groundwater promotes the material bleaching, and lateral flows, close to podzols, its eluviation. Chemical and physical erosions generate sandy horizons explored by podzolisation. River incisions into podzols enhance organic matter mineralisation, iron oxidation and the sand transport to the rivers. The apparition of podzols may preceed the formation of modern Amazon River system (2,5 Ma BP). Ultimate incisions of podzols restrict their spatial expansion and fill with white sands the Rio Negro sediment traps.

Keywords: Amazônia, podzolisation, mineralogy, geochemistry, landscape evolution

RÉSUMÉ

Les podzols sont des sols à morphologie spectaculaire présentant des horizons sableux sur des niveaux peu perméables, enrichis en matière organique et métaux. Ils occupent de grandes surfaces dans le haut bassin amazonien. Leur formation est attribuée à l'existence des nappes propices à des accumulations organo-métalliques en milieu réducteur et acide. Le travail traite: (i) de la pré-podzolisation (appauvrissement préalable des latérites); (ii) de la formation des podzols sur plateaux, posterieurement incisés par le reseau hydrographique; (iii) de la dynamique de ces podzols dans le bassin du Rio Negro. Il intègre des approches géochimiques, pétrographiques et minéralogiques, des études de séquences de sols et d'unités de paysages (terrain et traitement d'images). L'érosion chimique mais aussi particulaire des latérites, accrue depuis la bordure vers le centre des plateaux à podzols affecte séparément sols et saprolites. Le jaunissement et l'appauvrissement des sols sont attribués à la dissolution des oxydes de fer (hématite puis goethite) puis des kaolinites. Le développement des nappes dans les saprolites favorise le blanchiment et, leurs écoulements latéraux, l'éluviation. Ces érosions génèrent des réservoirs sableux en "double langue" qui vont être exploités par la podzolisation. L'incision posterieure de ces podzols hydromorphes par le reseau hydrographique active la minéralisation des matières organiques, l'oxydation du fer et l'apport de sable aux rivières. La distribution des podzols est fortement controlée par la pluviometrie et la géologie. Leur apparition peut être antérieure à l'établissement du réseau moderne de drainage de l'Amazone (2,5 Ma BP). L'incision posterieure des aires podzolisées aurait limitée leur expansion et alimentée en sable blanc le Rio Negro.

Mots-clés: Amazônia, podzolisation, mineralogie, géochimie, évolution du paysage

SUMARIO

Página

INTRODUCTION

Le bassin amazonien est l'un des plus grands bassins des surfaces émergées de la planète, avec une superficie totale d'environ 6,5 millions de km^2. Situé dans la zone tropicale forestière et en grande partie protégé des activités anthropiques, ce bassin contrôle les principaux cycles biogéochimiques de la planète (dont le cycle du carbone). Il constitue de ce fait une région emblématique pour aborder l'étude de ces cycles, et révéler d'une part les processus majeurs qui contrôlent la dynamique des métaux et des matières organiques et d'autre part l'impact du forçage anthropique (déforestation, effets de serre et changement climatique) sur la dynamique de ces processus et sur les re-mobilisations de matières aux interfaces atmosphère, biosphère, hydrosphère et lithosphère. Le fleuve Amazone exporte par ailleurs des quantités considérables de matières à l'océan (13,5 t/sec). Si les quantités de matières exportées par l'Amazone à l'océan Atlantique sont essentiellement attribuées à la surrection et érosion des Andes, des études récentes tendent à montrer que d'importantes quantités de matières ont pu également être remobilisées au sein des couvertures latéritiques du bassin et être exportées par érosion chimique au réseau hydrographique. Les processus associés à de telles exportations agissent essentiellement dans les régions amont les plus pluvieuses du bassin et la podzolisation marque le stade ultime de cette "fonte géochimique". La diversité des processus d'altération et d'érosion mis en jeu dans ce bassin est illustrée par la très célèbre "rencontre des eaux" ("*encontro das águas*") de la région de Manaus (partie centrale et amont du moyen basin amazonien) (Fig. 1a). Sur plusieurs kilomètres se rejoignent sans se mélanger les eaux brunes issues de l'érosion physique des sols andins et les eaux noires qui, comme nous le verrons par la suite, sont étroitement reliés à une érosion chimique et interne du sol et au développement de podzols au sein des paysages latéritiques du haut bassin amazonien.

Sur les 6,5 millions de km^2 du bassin, 4 millions de km^2 appartiennent au Brésil, ce qui représente prêt de la moitié de la surface de ce pays. Si les connaissances sur le milieu naturel des régions Sud, Sud Est et Nord Ouest du Brésil, qui regroupent la majeure partie de la population et des activités économiques du pays, sont très détaillés, celles portant sur les milieux amazoniens restent encore éparses. Le premier inventaire systématique des ressources naturelles de cette immense région forestière, souvent difficile d'accès, a été programmé dans les années 1970 par le gouvernement brésilien dans le cadre du Projet RadamBrasil. Ce projet a nécessité des moyens logistiques importants (dont avions et hélicoptères) et a mobilisé un nombre considérable de chercheurs de toutes disciplines (botanistes, géologues, pédologues,

géomorphologues, hydrologues…). Il a permis d'évaluer les ressources de cette grande région naturelle, où prédominent des plateaux de faibles altitudes associés à d'immenses réserves d'eau, et de révéler par la même occasion toute la diversité et complexité d'organisation de ses différentes composantes (roches, sédiments, végétations, sols et paysages) (Figs 2a et b).

Figure 1*. La rencontre des eaux (a) à l'amont du fleuve Amazone et à l'aval de la ville de Manaus où les eaux noires du Rio Negro (à droite) rejoignent les eaux brunes du Rio Solimões (à gauche) (provenance Th Allard) et (b) au niveau d'une confluence de ruisseaux dans les bas plateaux (région de São Gabriel da Cachoeira) où les eaux noires des aires podzoliques (à droite) rejoignent les eaux claires des latérites (à gauche).*

La diversité des structures et ressources de cet écosystème est illustrée par les nombreux documents cartographiques et légendes élaborés dans le cadre de ce projet. La carte, établie à l’échelle 1 :2.500.000, permet d’avoir une perception d’ensemble du milieu physique et biologique du bassin. Des cartes plus détaillées à l’échelle 1 :1.000.000 donnent une vision plus précise des organisations régionales. Comme nous allons le voir dans ce mémoire, ces documents riches d’informations très variées sont à l’origine de travaux plus détaillés, en particulier sur les sols. Ces dernières entreprises sur des sites pilotes comprenant petites unités de paysages (ou bassin versants élémentaires) et séquences de sols, orientées sur des axes de plus forte pente (le plus souvent d’un pôle haut et bien drainé vers un pôle bas et mal drainé), sont de plus en plus nombreuses (Lucas *et al.,* 1984; 1988; 1996; Bravard & Righi, 1989; 1990; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1998; Nascimento *et al.,* 2004; Montes *et al.,* 2007). Elles ont révélé les processus associés à la mobilité des éléments majeurs et en traces dans différents types d’écosystèmes, mais ont également montré, dans certains cas, l’inexactitude des documents RadamBrasil dans la caractérisation de certaines structures ou les interprétations qu’on en donne. Cela a en particulier amené le Département National de Recherche Minérale (Departamento Nacional de Pesquisa Mineral : DNPM) à réviser la carte géologique du bassin en différentiant au sein de la formation Solimões une nouvelle formation plus récente : la formation Içá. Cette dernière marque l’un des derniers épisodes sédimentaires du Tertiaire. Comme nous le verrons par la suite, elle aura une importance considérable sur la compréhension de la genèse des sols du bassin.

Les documents du Projet RadamBrasil et les images satellitaires de plus en plus nombreuses et variées montrent que l’idée d’une Amazonie couverte par une forêt homogène et monotone est fausse. La forêt sempervirente, qui recouvre sur de très grandes surfaces les bas plateaux et les versants creusés par le réseau de drainage, est localement associée à des couverts végétaux plus bas, quelquefois étonnamment ouverts, où les sols sont exposés à l’érosion hydrique et éolienne. A ce titre, des paysages tout à fait insolites ont été reconnus dans le haut bassin du Rio Negro où de vaste étendues dépourvues de végétation font apparaître des dunes de sables blancs. La comparaison des différents documents cartographiques du Projet RadamBrasil suggère que la diversité du couvert forestier reflète des hétérogénéités lithologiques, des gradients pluviométriques mais surtout et aussi, une grande diversité d’altérites et de sols. Les cartes du projet RadamBrasil et les études plus ponctuelles sur séquence de sols montrent en effet qu'il existe une distribution ordonnée des sols à l'échelle des paysages et également une distribution ordonnée de ces paysages à l'échelle du bassin amazonien (Fig. 3).

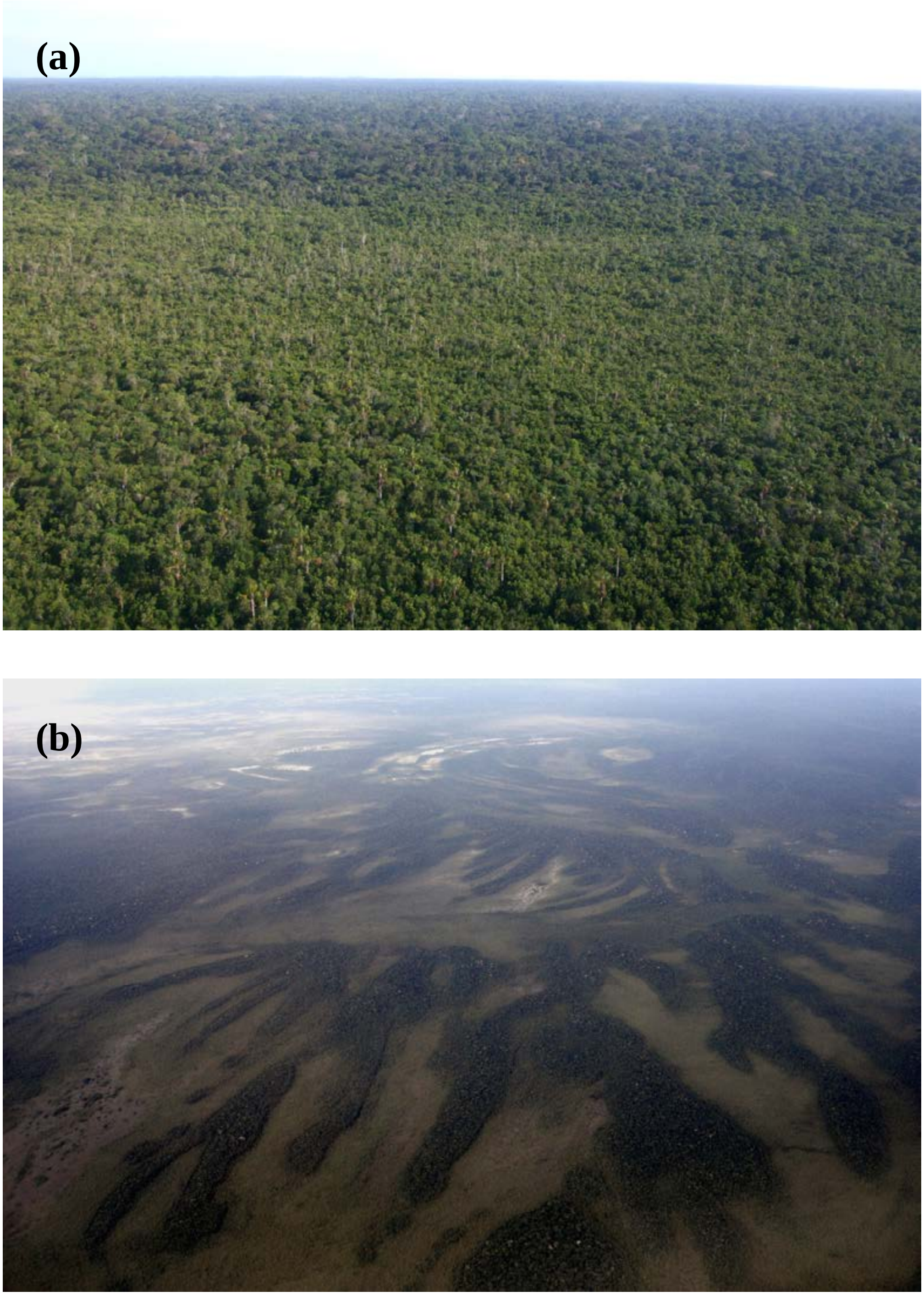


Figure 2. Diversité des paysages amazoniens : (a) Végétations de caatinga sur podzols (premier plan) et de fôret sur latérites (arrière plan), bas plateaux de la région de São Gabriel da Cachoeira ; (b) Bandes végétales en concordance avec les structures sédimentaires fluvio-lacustres de la formation Içá, région de Barcelos.

Les sols latéritiques les plus typiques (Latosols ou Ferralsols rouges, argileux et bien drainés) sont essentiellement présents à la périphérie du bassin et sont associés à des sols

hydromorphes (Gleys) dans les principaux axes de drainage et plaines alluviales. Ces latérites épaisses ont tendance à jaunir dans la partie centrale du bassin.

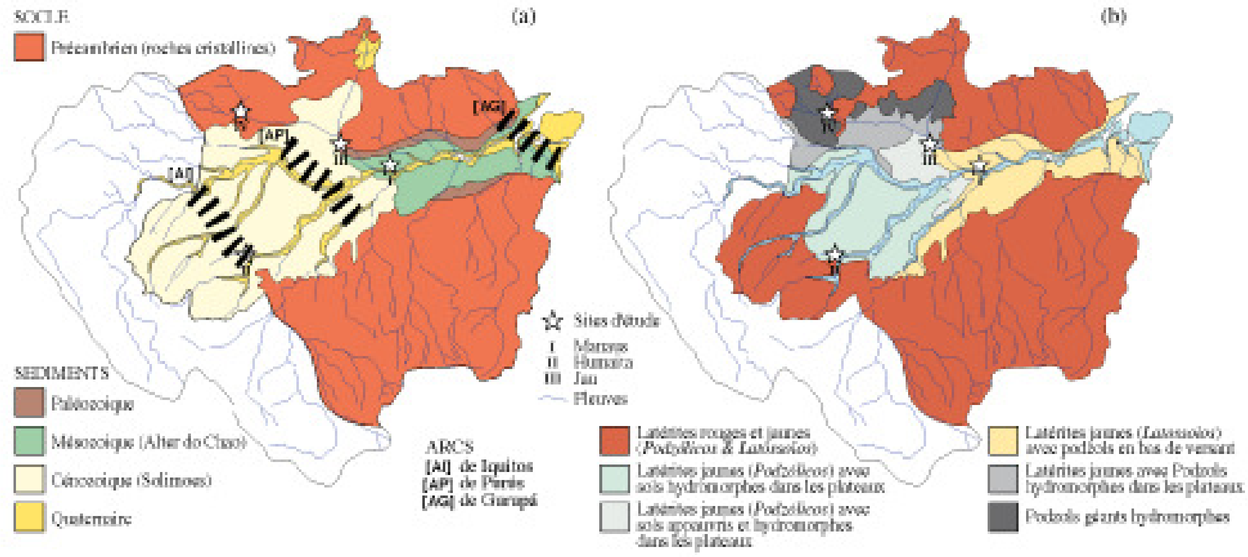


Figure 3*. Les roches (a) et les sols (b) du bassin amazonien brésilien (documents réduits et simplifiés à partir des cartes RadamBrasil au 1 :2.500.000) montrant l'extension des formations sédimentaires, la distribution des latérites rouges et jaunes et l'extension des zones hydromorphes et podzoliques dans la partie amont et centrale du bassin. (Fritsch et al., 2002).*

Sur des formations continentales plus récentes du haut bassin amazonien (Formation Içá), les formations latéritiques moins épaisses des bas plateaux amazoniens sont étroitement associées à des sols hydromorphes (Plinthosols, Gleys). Plus au nord dans le bassin du Rio Negro, les latérites s'appauvrissent en éléments fins (Ultisols) et se podzolisent (Podzols hydromorphes). Les podzols sont généralement situés sur les bas plateaux amazoniens. Dans la partie médiane du bassin du Rio Negro, ces podzols sont peu développés et s'observent, comme les sols hydromorphes (Gleys), dans les dépressions de ces plateaux (région du Jaú). Dans sa partie amont et plus pluvieuse (région de São Gabriel da Cachoeira), les podzols ont une extension beaucoup plus importante et sont directement connectés aux axes de drainage principaux du bassin du Rio Negro. Ils occupent alors de vastes pénéplaines inondées et les sols latéritiques n'apparaissent plus que sous la forme de collines résiduelles ou de reliques de rebords de plateaux. Dans la partie aval du bassin du Rio Negro (région de Manaus), les podzols sont généralement absents des plateaux. Ils sont par contre identifiés dans les bas de versants de ces plateaux. Ces distributions relatives de sols dans les paysages montrent ainsi que la mise

en place et la dégradation ultérieure des latérites du bassin amazonien peuvent être reliées à quatre processus majeurs : (1) la latéritisation, (2) l'appauvrissement, (3) l'oxydo-réduction et (4) la podzolisation.

Dans l'optique d'une meilleure connaissance de ces processus, des sols et des fonctionnements hydro-biogéochimiques qui leur sont associés, des projets scientifiques conjoints entre chercheurs brésiliens et français ont été élaborés. Ces projets étaient engagés de longue date dans les régions de Manaus et São Gabriel da Cachoeira (Lucas *et al.,* 1984, 1988, 1996; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1999). Ils ont été étendus en 1996 à l'ensemble du haut bassin amazonien dans le cadre d'un accord de coopération CNPq/IRD associant le Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera de l'Université de São Paulo et l'Unité de Recherche 12 "Géoscience de l'Environnement Tropical" du Département TOA de l'IRD (ex ORSTOM) sur un projet de recherche intitulé "Organisation et fonctionnement hydro-biogéochimique des couvertures latéritiques d'Amazonie" (Dylat Amazonie). Ils ont été ultérieurement financés par des projets FAPESP, PRONEX, et ECCO, et ont aussi reçu l'appui de l'Institut de Minéralogie et de Physique des Milieux Condensés (IMPMC) de Paris dans le cadre de la caractérisation minéralogique et spectroscopique des échantillons de sols. En 2004, ces travaux se sont progressivement focalisés sur l'étude des systèmes podzoliques d'Amazonie plus particulièrement dans le cadre d'un projet CAPES-COFECUB intitulé : "Podzolisation des latérites du haut bassin amazonien : Etudes des mécanismes et facteurs contrôlant la dynamique évolutive des podzols et les exportations de matières dans les têtes de rivières du bassin versant du Rio Negro et des dépôts de kaolins associés".

Les travaux, engagés dans le cadre de ces projets, correspondent essentiellement à des études multi-échelles de quatre sites pilotes (étoiles dans Fig. 3) : (1) région de Manaus, (2) région de Porto Velho, (3) région du Jaú et (4) région de São Gabriel da Cachoeira. Les sites (1) et (2) ont permis de mieux caractériser les processus de latéritisation et d'oxydo-réduction (Fritsch *et al.,* 2002, 2007). Dans le site (1) (région de Manaus), la latéritisation a été attribuée à des paragenèses affectant les principales phases minérales de ces sols, i.e. les kaolinites (Balan et al. 2005) et les oxydes de fer (Fritsch *et al.,* 2005). Cette latérisation a transformé des formations sédimentaires très anciennes (formation Alter do Chão, fin Crétacé – début Tertiaire) en latérites très épaisses (Latosols). Les latérites montrent de nombreuses failles normales liées à la réactivation de failles plus profondes, elles-mêmes associées à la mise en place du graben amazonien. Ces latérites sont localement affectées par l'hydromorphie

(développement au sein de ces latérites de poches réduites au-dessus de raies ferrugineuses) (Fritsch *et al.,* 2002). Dans le site (2) (région de Porto Velho), les latérites se sont formées sur des formations sédimentaires beaucoup plus récentes (Formation Içá) et sont de ce fait beaucoup moins épaisses (< 1m). A l'inverse, l'hydromorphie est beaucoup plus développée, en particulier dans les dépressions des bas plateaux amazoniens (Fritsch *et al.,* 2007). Les sites (3) et (4) ont par ailleurs permis d'étudier plus en détail l'appauvrissement et la podzolisation des couvertures latéritiques. L'étude du site (3) (région du Jaú), à laquelle j'ai contribué, a permis dans un premier temps de définir les grandes étapes dans la mise en place des "îlots" podzoliques des bas plateaux amazoniens (Nascimento *et al.*, 2004). La mise en place de ces podzols a pu être reliée au développement de nappes perchées en milieu réducteur et acide et la caractérisation géochimique de ces nappes a permis de mieux comprendre les mécanismes associés à la mobilisation des matières organiques et des métaux au sein des sols et des eaux noires qui les drainent (Nascimento *et al.*, 2008). Cette compréhension dans le fonctionnement hydro-biogéochimique de ces podzols hydromorphes a été fortement améliorée dans le cadre de la caractérisation des principaux groupements fonctionnels des matières organiques du sol (Bardy *et al.,* 2008) et dans l'étude de leur aptitude à complexer l'aluminium (Bardy *et al.*, 2007) et le fer (Fritsch *et al.*, 2009).

Figure 4*. Les eaux noires et les sables blancs (région de Barcelos) issus de l'érosion chimique et physique des vastes étendues podzolisées de la partie amont du bassin du Rio Negro (région de São Gabriel da Cachoeira).*

Les travaux présentés dans ce mémoire traitent essentiellement du site (4) (région de São Gabriel da Cachoeira). Ces travaux sont de ce fait complémentaires de ceux engagés dans le site (3) (région du Jaú). Comme nous l'avons déjà signalé, le site 4 est caractérisé par une extension optimale des podzols dans les paysages. Ces podzols sont alors directement reliés au réseau hydrographique principal du Rio Negro. Ils alimentent ce dernier en eaux noires mais aussi en sables blancs (Fig. 4). L'étude de ce quatrième site a permis de mieux comprendre les interactions entre les deux moteurs principaux de la morphogenèse des paysages dans cette partie du bassin amazonien : (1) la transformation des modelés en réponse à l'érosion chimique due à l'expansion latérale des systèmes podzoliques dans les paysages latéritiques, et (2) le processus d'incision des bas plateaux par le réseau hydrographique qui a de ce fait tendance à drainer ces formations hydromorphes. Nous avons par ailleurs étudié les mécanismes associés à l'appauvrissement préalable des couvertures latéritiques, comme processus majeur de pré-podzolisation. Enfin nous avons resitué ces processus d'appauvrissement et de podzolisation à l'échelle du haut bassin amazonien et ceci en relation avec l'histoire géodynamique de ce bassin. Cette étape ultime nous a amené à regrouper l'ensemble des travaux obtenus sur deux site-clés du bassin du Rio Negro ((3) et (4)), en associant études régionales (documents cartographiques) et études plus ponctuelles (de transects et séquences de sols sur des unités représentatives des paysages).

INTRODUÇÃO

A bacia amazônica é uma das maiores bacias hidrográficas da superfície emersa do planeta, com uma área total de cerca de 6,5 milhões de km^2. Situada na zona das florestas tropicais e em grande parte protegida das atividades antrópicas, essa bacia controla os principais ciclos biogeoquímicos do planeta (dentre eles o ciclo do carbono). Ela constitui, por isso, uma região emblemática para abordar o estudo destes ciclos e revelar, por um lado, os processos maiores que controlam a dinâmica dos metais e da matéria orgânica e, por outro, o impacto da pressão antrópica (desmatamento, efeito estufa e mudança climática) sobre a dinâmica destes processos e sobre a remobilização de matéria na interface atmosfera, biosfera, hidrosfera e litosfera. O rio Amazonas exporta quantidades consideráveis de matéria para o oceano (13,5 t/s). Se as quantidades de matéria exportadas pelo Amazonas para o oceano Atlântico são atribuídas essencialmente à orogênese e à erosão dos Andes, estudos recentes tendem a mostrar que importantes quantidades de matéria são também remobilizadas a partir das coberturas lateríticas da bacia e exportadas por erosão química para a rede hidrográfica. Os processos associados a estas exportações agem essencialmente nas regiões mais chuvosas da parte de montante da bacia e a podzolização marca o último estágio desta perda geoquímica. A diversidade de processos de alteração e de erosão que atuam nesta bacia é ilustrada pelo célebre “encontro das águas”, na região de Manaus (parte central da bacia amazônica) (Fig. 1a). Por mais de 60 km, as águas provenientes da erosão física dos Andes se encontram sem se misturar com as águas “negras” que, como veremos a seguir, estão estreitamente associadas à erosão química e interna do solo e ao desenvolvimento de podzóis nas paisagens lateríticas da alta bacia amazônica.

Dos 6,5 milhões de km^2 da bacia, 4 milhões de km^2 pertencem ao Brasil, o que corresponde a quase a metade da área deste país. Se o conhecimento dos meios naturais das regiões Sul, Sudeste e Nordeste do Brasil, que concentram a maior parte da população e das atividades econômicas do país, pode ser considerado satisfatório, o conhecimento dos meios amazônicos é ainda esparso e pouco detalhado. O primeiro inventário sistemático dos recursos naturais desta imensa região de florestas, quase sempre de difícil acesso, foi realizado nos anos 1970 pelo governo brasileiro no âmbito do Projeto RadamBrasil. Este projeto exigiu importantes meios de logística (como aviões e helicópteros) e a mobilização de uma vasta equipe de pesquisadores de diferentes áreas de conhecimento (botânicos, geólogos, pedólogos, geomorfólogos, hidrólogos...). Ele permitiu avaliar os recursos desta imensa região natural,

onde predominam platôs de baixas altitudes associados a imensas reservas de água, e revelar toda a diversidade e a complexidade de organizações de seus diferentes componentes (rochas, sedimentos, vegetações, solos e paisagens) (Fig. 2a e b). A diversidade das estruturas e recursos destes ecossistemas é ilustrada por numerosos documentos cartográficos e legendas elaborados por este amplo projeto. As cartas à escala 1:2.500.000 permitiram uma percepção do conjunto do meio físico e biológico da bacia. Cartas mais detalhadas, à escala 1:1.000.000 fornecem uma visão mais precisa das organizações regionais. Estes documentos, ricos em informações bastante variadas, serviram de base para trabalhos mais detalhados, particularmente sobre os solos. Estas investigações, realizadas em sítios-chave em pequenas unidades de paisagem (bacias elementares) e seqüências de solos ao longo de vertentes (frequentemente partindo de um pólo de montante, bem drenado, rumo a um pólo de jusante, mal drenado), são cada vez mais numerosas (Lucas *et al.*, 1984, 1988, 1996; Bravard & Righi, 1989, 1990; Dubroeucq & Volkoff, 1998; Dubroeucq *et al.*, 1999; Nascimento *et al.*, 2004; Montes *et al.*, 2007). Elas revelaram os processos associados à mobilidade de elementos maiores e em traços nos diferentes ecossistemas, mas mostraram, ainda, em alguns casos, as imprecisões dos documentos do Projeto RadamBrasil na caracterização ou na interpretação de certas estruturas. Este último fato justifica posteriores revisões destes documentos, como a realizada pelo Departamento Nacional de Pesquisa Mineral (DNPM) sobre a carta geológica da bacia, que propôs a diferenciação de uma nova formação, mais recente, no interior da formação Solimões: a formação Içá. Esta formação marca os últimos episódios sedimentares do Terciário. Como será visto adiante, ela tem grande importância para a compreensão da gênese dos solos da bacia.

Os documentos do Projeto RadamBrasil e as imagens de satélite cada vez mais numerosas e detalhadas mostram que a idéia de uma Amazônia coberta por uma floresta homogênea e monótona é falsa. A floresta sempervirente, que cobre amplas superfícies dos baixos platôs e das vertentes abertas pela rede de drenagem, é associada a coberturas vegetais mais baixas, algumas vezes surpreendentemente abertas, onde os solos são expostos à erosão hídrica e eólica. Campos de dunas de areias brancas sem cobertura vegetal (região de Santa Isabel do Rio Negro, por exemplo), em meio à floresta constituem paisagens insólitas da alta bacia do Rio Negro. A comparação de diferentes documentos cartográficos do Projeto RadamBrasil sugere que a diversidade da cobertura vegetal reflete as heterogeneidades litológicas, os gradientes pluviométricos mas, sobretudo, uma grande diversidade de materiais de alteração e de solos.

As cartas do Projeto RadamBrasil e os estudos pontuais sobre sequencias de solos mostram que existe uma distribuição ordenada dos solos na escala da paisagem e, igualmente, uma distribuição ordenada destas paisagens na escala da bacia amazônica (Fig. 3). Os solos lateríticos mais típicos (Latossolos ou Ferralsols vermelhos, argilosos e bem drenados) são presentes essencialmente na periferia da bacia e estão associados aos solos hidromórficos (Gleissolos) ao longo dos principais eixos de drenagem e planícies aluviais. Estes solos lateríticos espessos tendem a ficar mais amarelos na parte central da bacia. Sobre as formações continentais mais recentes da alta bacia amazônica (Formação Içá), as formações lateríticas menos espessas dos baixos platôs amazônicos estão estreitamente associadas a solos hidromórficos (Plintossolos e Gleissolos). Mais ao norte, na bacia do Rio Negro, os solos lateríticos se empobrecem em elementos finos (Ultisols) e se podzolizam (Podzóis hidromóficos). Os podzóis se encontram geralmente sobre os baixos platôs amazônicos. Na parte média da bacia do Rio Negro estes solos são pouco desenvolvidos e ocupam, como os solos hidromórficos (Gleissolos), zonas deprimidas sobre estes platôs (região do Jaú). Na parte de montante e mais chuvosa (região de São Gabriel da Cachoeira), os podzóis têm uma extensão muito mais importante e estão diretamente conectados aos eixos de drenagem principais da bacia do Rio Negro. Eles ocupam vastos peneplanos inundados onde os solos lateríticos aparecem apenas como colinas residuais ou faixas relictuais nas bordas dos platôs. Na parte de jusante da bacia do Rio Negro (região de Manaus), os podzóis geralmente não aparecem sobre os platôs. Eles existem nas partes baixas e médias de vertentes elaboradas pelas incisões da rede de drenagem nestes platôs. Esta distribuição relativa de solos na paisagem mostra que a elaboração e a degradação posterior dos solos lateríticos da bacia amazônica pode ser associada a quatro processos maiores: (1) lateritização, (2) empobrecimento, (3) óxido-redução e (4) podzolização.

Na ótica de um melhor conhecimento destes processos, dos solos e dos funcionamentos hidro-biogeoquímicos a eles associados, foram elaborados projetos científicos em que colaboram pesquisadores brasileiros e franceses. Estes projetos têm início a partir dos anos 80 para a região de Manaus (Lucas et al., 1984; 1988; 1996) e dos anos 90 para a região de São Gabriel da Cachoeira (Dubroeucq & Volkoff, 1998; Dubroeucq *et al.,* 1999). Eles foram estendidos em 1996 ao conjunto da alta bacia amazônica no âmbito de um acordo de cooperação BNPq/IRD associando o Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera de l'Université de São Paulo e a Unidade de Pesquisa 12 (Unité de Recherche 12 "Géoscience de l'Environnement Tropical") do Departamento TOA do IRD (ex-ORSTOM) em um projeto de

pesquisa intitulado “Organização e funcionamento hidro-bioquímico das coberturas lateríticas da Amazônia (Dylat Amazonie). Eles foram posteriormente financiados por projetos FAPESP, PRONEX e ECCO e receberam também o apoio do Instituto de Mineralogia e Física dos Meios Condensados de Paris (IMPMC) para a caracterização mineralógica e espectroscópica de amostras de rocha e solo. Em 2004 estes trabalhos passaram a focalizar particularmente o estudo dos sistemas podzólicos da Amazônia, mais particularmente no âmbito de um projeto intitulado “Podzolização das lateritas da alta bacia amazônica: estudos dos mecanismos e fatores que controlam a dinâmica evolutiva dos podzóis e as exportações de matéria nas cabeceiras de drenagem da bacia do Rio Negro e os depósitos de caolim associados”.

Os trabalhos desenvolvidos nestes projetos correspondem essencialmente a estudos em várias escalas de quatro sítios-chave (estrelas na Fig. 3): (1) região de Manaus, (2) região de Porto Velho, (3) região do Jaú e (4) região de São Gabriel da Cachoeira. Os sítios (1) e (2) permitiram melhor caracterizar os processos de lateritização e de óxido-redução (Fritsch *et al.,* 2002, 2007). No sítio (1) (região de Manaus), a lateritização foi associada às paragêneses que afetam as principais fases minerais destes solos, i.e. as caolinitas (Balan *et al.,* 2005) e os óxidos de Fe (Fritsch *et al.,* 2005). Esta lateritização transformou formações sedimentares muito antigas (Formação Alter do Chão, do final do Cretáceo-começo do Terciário em coberturas lateríticas muito espessas). Essas coberturas lateríticas móveis (ou solos lateríticos) apresentam numerosas falhas normais ligadas à reativação de falhas profundas, associadas ao estabelecimento do graben amazônico. Estes solos lateríticos são localmente afetados pela hidromorfia (desenvolvimento de zonas redutoras na forma de bolsas sobre camadas finas ferruginosas). No sítio (2) (região de Porto Velho), os solos lateríticos se formam sobre formações sedimentares muito mais recentes (Formação Içá) e são muito menos espessas (< 1 m). Inversamente, a hidromorfia é muito mais desenvolvida, particularmente nas depressões dos baixos platôs amazônicos (Fritsch *et al.,* 2007). Os sítios (3) e (4) permitiram o estudo mais detalhado do empobrecimento e da podzolização das coberturas lateríticas. O estudo do sítio (3) (região do Jaú), em que participei como colaborador, permitiu definir as grandes etapas da elaboração das “ilhas” podzolizadas dos baixos platôs amazônicos (Nascimento *et al.,* 2004). A instalação destes podzóis pôde ser associada ao desenvolvimento de lençóis suspensos em meio redutor ácido e a caracterização geoquímica destes lençóis permitiu uma melhor compreensão dos mecanismos associados à mobilização da matéria orgânica e dos metais nos solos e nas águas negras que os drenam (Nascimento *et al.,* 2008). Esta

compreensão do funcionamento hidro-biogeoquímico destes podzóis hidromórficos foi aprofundada com a caracterização das principais funções estruturais da matéria orgânica do solo (Bardy *et al.,* 2008) e com o estudo da aptidão das mesmas para a complexação do alumínio (Bardy *et al.,* 2007) e do ferro (Fristsch *et al.,* 2009).

Os resultados apresentados neste trabalho tratam essencialmente do sítio (4) (região de São Gabriel da Cachoeira). Estes trabalhos são complementares daqueles desenvolvidos no sítio (3) (região do Jaú). Como já assinalado, este sítio se caracteriza pela extensão máxima dos podzóis na paisagem. Estes podzóis estão diretamente ligados à rede de drenagem principal do Rio Negro. Eles alimentam este rio não somente em águas negras, mas, também, em areias brancas (Fig. 4). O estudo deste quarto sítio permitiu compreender melhor as interações entre os dois principais motores da morfogênese das paisagens nesta parte da bacia amazônica: (1) a transformação dos relevos em resposta à erosão química e à expansão lateral dos sistemas podzólicos nas paisagens lateríticas e (2) o processo de incisão dos baixos platôs pela rede hidrográfica, que tem como conseqüência a drenagem das formações hidromórficas. Foram estudados, ainda, os mecanismos associados ao empobrecimento dos solos lateríticos, como processo maior de pré-podzolização. Finalmente, os processos de empobrecimento e de podzolização foram situados espacialmente na escala da alta bacia amazônica e temporalmente na história geodinâmica desta bacia. Esta última etapa nos conduziu a reagrupar o conjunto dos trabalhos produzidos nestes dois sítios-chave da bacia do Rio Negro (3) e (4) associando estudos regionais (documentos cartográficos) e estudos pontuais (estudos de transeções e de seqüências de solos em unidades representativas das paisagens).

OS CINCO CAPITULOS DA TESE

Les résultats de cette étude sont regroupés dans cinq chapitres :

Le **Chapitre 1** est une brève revue bibliographique qui présente les podzols (distribution et horizons diagnostiques) et les mécanismes le plus souvent invoqués dans la mise en place de ces sols.

Le **Chapitre 2** présente le cadre naturel de cette étude. Il traite des grands ensembles structuraux du bassin amazonien, de ses sols et des processus majeurs (latérisation, appauvrissement, oxydo-réduction, podzolisation et incision du modelé) impliqués dans l'érosion chimique et physique des paysages.

Le **Chapitre 3** traite de l'appauvrissement des latérites comme étape préalable à la podzolisation. Cette étude a été réalisée dans la région de São Gabriel da Cachoeira (site (4)) à la bordure des aires fortement podzolisées du bassin versant du Curicuriari (bassin versant podzolisé sur prêt de 95% de sa superficie).

Le **Chapitre 4** présente les résultats d'une étude minéralogique et structurale d'une séquence de sols entreprise dans la même région (site 4) au niveau d'une relique de sols latéritique, dans un paysage fortement podzolisé et incisé par le réseau hydrographique. Cette étude a pour objectif de montrer les effets de ces incisions sur la morphologie des podzols et sur la dynamique de ces sols (rabattement des nappes perchées). Elle traitera en particulier des analogies et différences par rapport à ce qui a déjà été étudié sur le site (3) du Jaú.

Le **Chapitre 5** est un essai de reconstitution de la dynamique des podzols dans le bassin du Rio Negro à partir des études ponctuelles obtenues sur des séquences de sols (sites 3 et 4), de documents cartographiques obtenues à des échelles régionales et des connaissances actuelles sur l'histoire géodynamique et géologique du bassin amazonien.

VALORIZAÇÃO DOS RESULTADOS

Les résultats présentés dans cette thèse ont donné lieu à l'écriture de trois articles destinés à paraître dans des revues internationales. Ces articles constituent l'ossature de cette thèse. Ils sont brièvement introduits en début des Chapitres 3, 4 et 5 :

Chapitre 3

Yellowing, bleaching and clay depletion of laterites in the Negro River Catchment (upper Amazon Basin). Preliminary steps to Podzolisation. G. Bueno, E. Fritsch, N.R. DO Nascimento, M.E. Almeida & B.S. Arenare.

Chapitre 4

Podzolisation of clay depleted laterites and physical denudation of Podzols in the high rainfall region of the upper Negro River watershed. G. Bueno, E. Fritsch, N.R. DO Nascimento & A.J. Melfi.

Chapitre 5

Weathering and erosion in major Cenozoic land surfaces and genesis of waterlogged Podzols in the Negro River Catchment (upper Amazon Basin). G. Bueno, E. Fritsch, N.R. DO Nascimento, A.J. Melfi & G. Calas.

CAPITULO 1. PODZOIS E PODZOLIZAÇÃO

1.1. Définition

Le nom “Podzol” vient du russe “pod” pour sous et de “zola” pour cendre et caractérise de ce fait des sols présentant des horizons de sub-surface cendreux ou blanchis par des agents organiques acides (FAO, 1998). Ces sols sont vraisemblablement les plus connus de la planète du fait de leur morphologie spectaculaire avec la présence d’horizons éluviés, blanchis (aussi connu sous le terme d’horizons albiques) qui recouvrent plus en profondeur des horizons illuviés, brun foncé à brun rouge, enrichis en humus et parfois aussi en sesquioxydes (horizons également qualifiés de spodiques) (Fig. 5).

Le terme “Podzol” est utilisé dans la plupart des systèmes de classification des sols, en Russie bien sûr, mais aussi en Europe et par la FAO. La “Soil Taxonomy” américaine préfère néanmoins parler de “Spodosols” en référence aux horizons spodiques qui, comme nous le verrons, sont les horizons diagnostiques des podzols.

1.2. Morphologie et concept

Les podzols présentent deux catégories d’horizons : (1) des horizons supérieurs éluviés comprenant le plus souvent des horizons organiques de type Mor enrichis en résidus organiques (L, O, AE) et des horizons minéraux albiques (E), sans cohésion, essentiellement constitués de résidus quartzeux et minéraux lourds, et (2) des horizons inférieurs illuviés (Bh et Bs) enrichis en substances humiques acides susceptibles d’altérer les minéraux argileux du sol et de former des complexes organo-métalliques. Cette distribution relative indique ainsi des mécanismes de transfert (“chéluviation”) et d’accumulation (“chilluviation”). L’illuviation de substances organiques en profondeur est confirmée par la présence de revêtements ou cutanes qui coiffent les quartz ou remplissent les interstices ménagés par ces derniers (Bardy *et al.,* 2008). Ces revêtements sont très fins, brun rouge, souvent craquelés sur lames minces dans les horizons Bs les plus profonds des podzols. Ils sont noirs, plus grossiers (fibres ou boulettes), dans les horizons Bh qui les surmontent, à la base des réservoirs sableux (Buurman & Jongmans, 2005; Bardy *et al.,* 2008). Ces horizons illuviés, aussi qualifiés d’horizons spodiques, sont riches en humus et en métaux (Duchaufour, 1982; Petersen, 1984; Macias-Vasquez, 1987). Deux critères géochimiques majeurs sont généralement requis pour les horizons spodiques des podzols (FAO, 1998): (1) des teneurs en carbone organique supérieures à 6 g/kg et (2) des rapports Al_o+1/2Fe_o supérieurs à 5, où “Al_o” et “Fe_o” réfèrent respectivement aux quantités d’aluminium et de fer extraites par le traitement oxalate (c.a.d. aux formes complexées aux matières organiques et aux oxydes mal cristallisés). Ces horizons peuvent de ce fait être considérés comme des zones d’accumulation de métaux (principalement Al mais aussi Fe), qui sont majoritairement chélatés à des groupements organiques (formation de complexes organo-métalliques).

Les associations entre substances organiques et phases minérales résiduelles du sol sont très tranchées entre horizons éluviés et illuviés. Dans les horizons éluviés, les résidus organiques sont nettement dissociés des quartz blancs. Dans ces niveaux organo-minéraux de surface ou de subsurface, les horizons présentent alors un aspect “poivre et sel” très caractéristique (horizons humifères ponctués de blanc). Dans les horizons illuviés, les substances organiques, souvent assimilées à des humus de faible ou haut poids moléculaire (e.g. acides fulviques, acides humiques et humine), recouvrent les grains de quartz. En masquant les quartz, ces substances organiques peuvent ainsi nous amener à surestimer visuellement les quantités de matières organiques accumulées dans les horizons spodiques de ces sols (Nascimento *et al.,* 2004).

Figure 5*. Les podzols de la partie médiane des aires podzolisées (profile IV) de la séquence du Curicuriari (site 4) montrant en surface les horizons humifères éluviés (AE), puis l'horizon blanchi ou albique (E) et les horizons spodiques en profondeur: l'horizon noir Bh et les horizons brun rouge BCs (noter entre ces deux horizons la naissance d'un nouvel horizon éluvié, gris clair)*

Dans les horizons éluviés organiques et minéraux (AE et E), les pHs sont généralement bas (< 4), les groupements hydroxyles des composés organiques sont protonés (prédominance de fonctions carboxyliques, faible occurrence de carboxylates), les phases argileuses du sol ont pratiquement disparues et les résidus grossiers organiques et minéraux (surtout quartz mais aussi minéraux lourds, tels que zircon et oxydes de Ti) tendent à s'accumuler. Dans les horizons illuviés ou spodiques, les pHs sont généralement plus élevés (> 4) et les métaux sont complexés (chélatés) aux substances organiques (prédominance de carboxylates). Une partie non négligeable de métaux peut également précipiter sous forme de composés inorganiques faiblement cristallisés, les plus connus correspondant aux ferrihydrites (à deux ou six raies sur spectres DRX) pour Fe et aux produits allophaniques (allophane, proto-imogolite et imogolite) pour Al (Ross, 1980; Buurman, 1987; Macias-Vasquez, 1987; Lundström ***et al.,***

2000). Ces gradients soulignent de ce fait le rôle essentiel du pH dans l'immobilisation ou la remobilisation des métaux lors d'une lixiviation et acidification ultime de ces sols (principalement pour Al) (Nascimento *et al.* 2004, 2008).

1.3. Les deux grands types de podzols

Les horizons spodiques des podzols doivent apparaître sous des horizons éluviés organiques (AE) ou minéraux (E) et montrer des évidences d'accumulation de matières organiques et de métaux pour que le processus central de podzolisation puisse être invoqué (Petersen, 1984 ; Lundström et al., 2000). Dès lors, deux grands types de podzols peuvent distingués suivant l'épaisseur de ces sols et l'absence ou présence d'horizon albique.

Dans les podzols peu évolués, les horizons éluviés et organiques de surface (A, AE) surmontent des horizons spodiques faiblement différenciés (Bhs). Ces sols peu épais, dépourvus d'horizon albique, marquent de ce faite une première étape dans le développement de la podzolisation (Nascimento *et al.*, 2004). Ils ont été qualifiés de sols crypto-podzoliques (Duchaufour, 1972) ou de podzols humiques (Thompson, 1992). Des podzols plus épais et mieux différenciés sont le plus souvent observés dans les paysages. Dans ces podzols, les horizons organiques éluviés et illuviés sont séparés par des horizons blanchis (albiques). D'autre part, les horizons illuviés sont nettement différenciés en deux types d'horizons spodiques : (1) des horizons humiques noirs (Bh) surmontant (2) des horizons brun-rouge riches en sequioxydes (Bs).

Enfin une troisième catégorie de podzols pourrait éventuellement être distinguée. Cette dernière catégorie marque une étape ultime dans le développement vertical des podzols dans les paysages. Elle correspond aux podzols géants, qui ont été identifiés en abondance dans la zone tropicale, plus particulièrement dans le haut bassin amazonien. Ces podzols sont caractérisés par la très grande épaisseur de ces horizons blancs, sableux (albiques) qui rendent de ce fait difficile la reconnaissance à plus grande profondeur des horizons spodiques (les horizons albiques, dépourvus de cohésion, tendent en effet à s'effondrer dans les fosses pédologiques ou lors de sondages). De tels sols ne sont en fait plus considérés comme des podzols dans la plupart des systèmes de classification. Ils ont été qualifiés d'arénosols dans les cartes pédologiques du projet RadamBrasil.

1.4. Régime hydrique et morphologie des podzols

Ils existent très peu de données sur le fonctionnement hydrique des podzols et donc sur les conditions redox qui ont pu contribuer à la mise en place de ces sols. De telles conditions (i.e. alternance aux rythmes des saisons d'épisodes anoxiques et oxiques) sont toutefois reconnues comme l'un des facteurs majeurs dans la différenciation verticale des sols. Il est néanmoins admis qu'il existe des podzols à nappes et des podzols bien drainés sans qu'un lien génétique ait pu être établi entre ces deux types de sols.

Dans les podzols à nappe, les contrastes de couleur entre horizons sont parfois tenus. En effet, les couleurs sont plus fades et sont nettement dominées par l'abondance de composés organiques brun foncé à noirs. La présence d'une nappe à faible profondeur est propice au développement de conditions réductrices et de ce fait à une grande mobilité du fer au sein de ces formations. Cet élément est exporté sous forme dissoute ou en association avec les composés organiques au réseau hydrographique lors d'écoulements hydriques latéraux (Nascimento *et al.,* 2004, Fritsch *et al.,* 2009). Les eaux de nappe baignant ces podzols, mais aussi les eaux de surface qui drainent ces aires podzoliques, ont alors une coloration noire caractéristique (Fig. 1b), attribuée à la présence d'acides fulviques et de colloïdes organiques en suspension dans les eaux (FAO, 1998; Allard et al., 2002; Benedetti *et al*., 2003a).

Dans les podzols bien drainés, les contrastes de couleur entre horizons sont plus forts et la morphologie de ces sols est de ce fait plus spectaculaire. La plus grande minéralisation des composés organiques dans ces sols limite leur accumulation dans les horizons spodiques, plus profonds. Ces composés masquent de ce fait moins les hétérogénéités texturales et structurales de ces sols. Par ailleurs, le développement à certaines périodes de l'année de conditions oxiques est propice à la précipitation du fer qui donne des colorations brun rouge à rouge vif aux horizons spodiques les plus profonds de ces sols (Bs). Des phénomènes d'induration ont parfois été invoqués. Par contre, la nature des agents de cimentation reste incertaine et mal définie (oxydes de fer et de Mn, complexes organo-métalliques …).

1.5. Mécanismes communément invoqués pour la podzolisation

La formation des podzols est généralement attribuée à l'accumulation et migration des substances organiques, à l'altération des phases argileuses résiduelles du sol et à la formation de composés mal cristallisés associés ou non aux phases organiques de ces sols (Gustafsson *et al*., 1999; Lundström *et al*., 2000, Van Hees & Lundström, 2000, Nascimento et al., 2004). Il n'existe toutefois pas de véritables consensus sur les zones des profils ou ces mécanismes sont susceptibles d'agir et sur la nature des substances organiques susceptibles de migrer et de fixer les métaux libérés par l'altération. Ceci a amené les scientifiques à proposer plusieurs modèles conceptuels de formation des podzols.

D'après Petersen (1984), de Coninck (1980) et Buurman (1987), les acides organiques à faible poids moléculaire sont des agents de transport du Fe et de l'Al sous forme complexée. Ces complexes organo-métalliques peuvent être immobilisés en profondeur (1) au niveau de discontinuités lithologiques, (2) par la diminution du rapport C/(Al+Fe) au fur et à mesure que les complexes migrent à travers le profil, ce qui conduit à la saturation des sites d'échange de la matière organique, à la neutralisation de leurs charges négatives et à la précipitation des complexes, (3) après la biodégradation de certains complexes organo-métalliques, ce qui libère des cations métalliques qui peuvent saturer d'autres complexes, les faisant moins biodégradables, ou précipiter sous forme inorganique, ou (4) par adsorption des substances organiques à la surface des imogolites dans les horizons spodiques, suivant la diminution de la capacité complexante des groupements carboxyliques après la diminution du pH en profondeur.

D'après Farmer (1980), Anderson et al., (1982) et Farmer (1987), les cations Al et Fe libérés en surface par l'altérations des phases argileuses forment des gels de haut poids moléculaires (formation en particulier de proto-imogolites). Ces gels migrent en profondeur et s'accumulent dans les horizons spodiques sous forme de ferrihydrites et/ou de produits allophaniques (surtout imogolite). La matière organique (principalement les acides fulviques) migre en profondeur et s'adsorbe à la surface des imogolites.

D'après Ugolini & Dahlgren (1987) et Lundström (1993), l'imogolite se forme dans les horizons spodiques après hydrolyse des minéraux argileux dans un milieu à forte pCO_2. Ces imogolites adsorbent des complexes organo-métalliques (acides fulviques + métaux) qui migrent depuis la surface.

1.6. Conditions de formation et répartition géographique

Les conditions propices à la migration et accumulation de complexes organo-métalliques dans les sols sableux des surfaces continentales et de ce fait à la formation de podzols sont grandement favorisées par des climats froids et humides, par des environnements de hautes montagnes, par des matériaux parentaux sableux et des couverts végétaux acides (e.g.

conifères et landes) (FAO, 1998). Les Podzols peuvent se former sur n'importe quel type de matériaux parentaux (Buurman, 1984). Toutefois, les sédiments sableux sont très propices à la formation de ces sols lorsque les autres conditions du milieu s'y prêtent (Pedro, 1987). Ils peuvent également se développer à partir d'autres types de sols qui ont été au préalable appauvris en éléments fins argileux (Turenne, 1977; Lucas *et al.,* 1989). L'influence de systèmes de nappes semble également être un élément prépondérant dans l'accumulation des matières organiques et la mise en place de ces sols.

Les podzols sont les sols zonaux des régions boréales, où ils sont communément associés aux dépôts morainiques des glaciers et aux forets à *Taïga* (Buurman, 1984; Pedro, 1987). Bien que la podzolisation des sols affecte de très grandes superficies dans cette partie émergée des surfaces continentales, ce processus n'est pas limité à ces régions froides et humides. En effet, il est bien connu que ce processus est actif dans toutes les régions humides de la planète (FAO, 1998), plus particulièrement dans les régions tempérées (e.g. Buurman, 1984 ; Righi, 1987), mais aussi dans les régions tropicales (Klinge, 1965; Schwartz, 1987; Bravard & Righi, 1990; Dubroeucq & Volkoff, 1998; Thomas, 1999), où de nombreux exemples de podzols géants ont été décrits (e.g. Klinge, 1965). Les podzols tempérés et tropicaux ont été qualifiés d'intrazonaux par Buurman (1984) et de podzols secondaires par Duchaufour (1982).

Les Podzols des régions tropicales ne figurent pas sur la plupart des cartes pédologiques établis à l'échelle du globe, alors qu'ils semblent occuper des superficies importantes dans les zones les plus pluvieuses de cette partie de la planète (e.g. Amazonie, Afrique centrale et Indonésie). Ces sols, relativement peu connus dans ces régions, n'ont entre autres été décrits qu'assez récemment à partir des années 1960. Ils se forment sur des matériaux beaucoup plus altérés et souvent plus profonds. Ils présentent de ce fait une minéralogie plus simple que celle des podzols boréaux et tempérés. En particulier, les horizons éluviaux (AE et E) de ces podzols sont constitués presque exclusivement de quartz et de quelques minéraux lourds, résistants à l'altération (zircon, rutile, anatase…). Dans les horizons spodiques et à la bordure des aires podzoliques, les matières organiques sont généralement associées aux minéraux secondaires les plus communément rencontrés dans la zone tropicale (i.e. kaolinite, gibbsite et goethite) (Turenne, 1977; Schwartz, 1987, 1988; Lucas *et al.,* 1989; Bravard & Righi, 1990; Dubroeucq & Volkoff, 1998; Nascimento *et al.,* 2004). Comme l'ont souligné Nascimento et al. (2004), la présence de composés allophaniques (imogolite, allophane) dans les horizons spodiques des podzols tropicaux n'a encore jamais été démontrée, probablement du aux

faibles quantités des cations présents dans les nappes perchées de ces podzols hydromorphes (Si, Al et Fe), ainsi qu’à la forte lixiviation et acidification de ces sols.

CAPÍTULO 2. SOLOS E PROCESSOS MAIORES DE ALTERAÇÃO E PEDOGÊNESE NO ALTO RIO NEGRO

2.1. Histoire géodynamique du bassin et principaux ensembles structuraux

Situé sous les tropiques, le bassin forestier amazonien a focalisé l'attention de la communauté scientifique brésilienne et internationale par la diversité des processus mis en jeu et des facteurs qui ont pu contrôler la mise en place de ses principaux ensembles structuraux. Ces facteurs sont étroitement associés à la géodynamique de la plaque sud américaine et les processus à l'altération, l'érosion et la déformation (flexure et fracture) de cette plaque. La formation du graben amazonien a, entre autres, été reliée à l'érosion des socles brésilien et guyanais et à une sédimentation massive dans la partie centrale et ouest du bassin à une époque où les écoulements se faisaient vers le Pacifique (Fig. 3a). La majeure partie des sédiments accumulés dans ce bassin correspond ainsi de nos jours aux vastes pénéplaines à faible gradient topographique du haut bassin amazonien. La subduction de la plaque de Nazca a initié au Tertiaire la formation de la chaîne montagneuse des Andes sur la bordure Ouest du bassin. La surrection de cette chaîne, toujours actuelle, a joué un rôle déterminant sur le climat, l'érosion et changé de façon irréversible le sens des écoulements des eaux dans le bassin (vers l'Atlantique). Les changements climatiques et les variations des niveaux de base au Quaternaire ont favorisé l'incision des pénéplaines et de ce fait formé les bas plateaux qui dominent le modelé du bassin. Le basculement définitif du réseau hydrographique au Pliocène (~ 2,5 Ma) a contribué à l'individualisation de chenaux fossiles et de vastes étendues ennoyées dans les sédiments du haut bassin amazonien (Campbell ***et al.,*** 2006, Fritsch ***et al.,***

2007), dans une région soumise alors à de forts gradients pluviométriques (1,5 m/an à l'Est, jusqu'à 6 m/an au Nord Ouest).

L'histoire géodynamique de ce bassin est ainsi à l'origine de la mise en place de ses principales formations sédimentaires. Les formations les plus anciennes, issues de l'érosion des socles brésilien et guyanais, affleurent de nos jours au nord et au sud du graben central (Formations Prosperança et Trombetas), lui-même comblé par une puissante formation Crétacé (Formation Alter do Chão). Des sédiments plus récents ont recouvert ces dépôts dans le haut bassin amazonien. Ils correspondent à l'une des plus vastes formations Tertiaires de la planète (Fig. 3a). Des travaux récents (Campbell *et al.,* 2006) ont révélé deux grands cycles sédimentaires pan-américains au Tertiaire, séparés par une longue période d'aplanissement qui a tronqué toutes les structures géologiques exposées à la surface ("*the Ucayali Peneplain*"). Ces cycles, reliés à la surrection des Andes, sont associés à deux événements tectoniques majeurs: Quechua I et Quechua II. Le premier événement tectonique (Quechua I) s'est achevé approximativement au Miocène moyen. Il a contribué à la mise en place des épais sédiments de la Formation Solimões. Le second événement (Quechua II) est relié à la surrection définitive des Andes (~ 9,5 Ma) qui a définitivement obturé les écoulements vers le Pacifique. En initiant la formation d'un méga-lac dans la partie centrale et aval du haut bassin amazonien, il marque le début de l'ultime sédimentation Tertiaire (Formaton Içá). Cette sédimentation, essentiellement attribuée à l'érosion des Andes, s'est achevée vers 2,5 Ma avec la naissance du réseau hydrographique actuel, qui a pu explorer les anciens axes de drainage ou en créer de nouveaux en incisant de ce fait profondément les vastes plaines sédimentaires du bassin (Fig. 6).

L'observation de la Figure 3 montre que la distribution actuelle des sols se cale grosso modo sur ces structures géologiques et sédimentaires (N.B. la Formaton Içá, identifiée en 1981 par le DNPM, n'a pas été représentée sur la Fig. 3a, elle correspond toutefois à l'extension des latérites à sols hydromorphes de la Fig. 3b, cf aussi Fritsch *et al.,* 2007). On voit en particulier que les latérites rouges les mieux drainées (en rouge dans la Fig. 3b) se sont essentiellement développées au Nord et au Sud sur les roches cristallines des socles guyanais et brésilien. A l'inverse, les autres sols qui font apparaître soit une tendance plus ou moins affirmée au jaunissement et à l'appauvrissement de la partie supérieure des latérites, soit une tendance plus affirmée à l'hydromorphie et à la podzolisation se développent de préférence sur les formations sédimentaires de ce bassin. Les formations podzoliques (en gris ou noir sur la Fig. 3b) semble néanmoins échapper à cette règle puisqu'on les retrouve de part et d'autre de la

limite entre formations sédimentaires au Sud et cristallines au Nord, dans les zones les plus pluvieuses du bassin. Comme nous le verrons dans ce mémoire, les sols hydromorphes à Gleys ou à Podzols s'observent soit dans les dépressions des bas plateaux amazoniens (cas très fréquents de certaines unités de paysages) soit en positions plus basses, sur les bas de versants et les dépôts alluviaux (sableux ou argileux) du Quaternaire. Les premiers systèmes sont partiellement confinés (drainés par un réseau épars de petits ruisseaux) tandis que les seconds sont ouverts et directement connectés aux principales rivières du bassin. A ces systèmes peuvent être reliées des séquences ordonnées de sols qui partiront soit du rebord vers le centre des plateaux (cas des plateaux à dépressions) soit de l'amont vers l'aval sur les versants du rebord de ces plateaux.

2.2. Les grandes catégories de sols, de végétation et de régimes hydriques

Les sols du bassin Amazonien peuvent être regroupés dans deux grandes catégories suivant la nature des processus d'altération mis en jeu et les régimes hydriques qui leurs sont associés. La première catégorie de sols correspond aux latérites, formations également connues sous les termes de sols ferrallitiques, de Latosols, d'Oxisols ou de Ferralsols. Ces formations occupent généralement les positions hautes les mieux drainées des paysages et sont reliées à des écoulements libres verticaux. Ces écoulements sont propices à une horizonation des sols, et donc à un développement vertical des processus d'altération. Le processus majeur associé à la formation de ces sols argileux et bien structurés est la latéritisation (Melfi & Pedro, 1977; Fanning & Fanning, 1989: Fritsch *et al.*, 2002, 2005). La deuxième catégorie de sols se situe en général dans les zones basses ou déprimées des paysages. Il est de ce fait étroitement lié à des engorgements permanents ou provisoires contrôlés par les apports pluviométriques et la capacité de ces sols à exporter l'eau au réseau hydrographique. L'altération et la pédogenèse sont alors contrôlées par la dynamique des nappes. Les écoulements d'eau et les exportations de matières sont essentiellement latéraux. Les Gleys et les Podzols sont de bons exemples de sols hydromorphes. Ils peuvent se développer verticalement à partir de matériaux sous-jacents, mais aussi latéralement à partir des formations latéritiques amont (Nascimento *et al.*, 2004). En accord avec Fanning & Fanning (1989), cela suggère que des sols puissent se former dans un premier temps (*soil forming processes*) puis se transformer ou se dégrader dans un second temps (*soil change processes*). Ce concept nouveau permet ainsi d'introduire la notion d'équilibre ou déséquilibre géodynamique pour les formations latéritiques et également de systèmes de transformation (Boulet *et al.*, 1982) ou transformants (Fritsch *et al.*,

1986). Dans les paysages latéritiques des régions humides du bassin amazonien, la pédogenèse semble ainsi favoriser l'exportation des éléments préalablement accumulés lors d'une phase d'intense latéritisation.

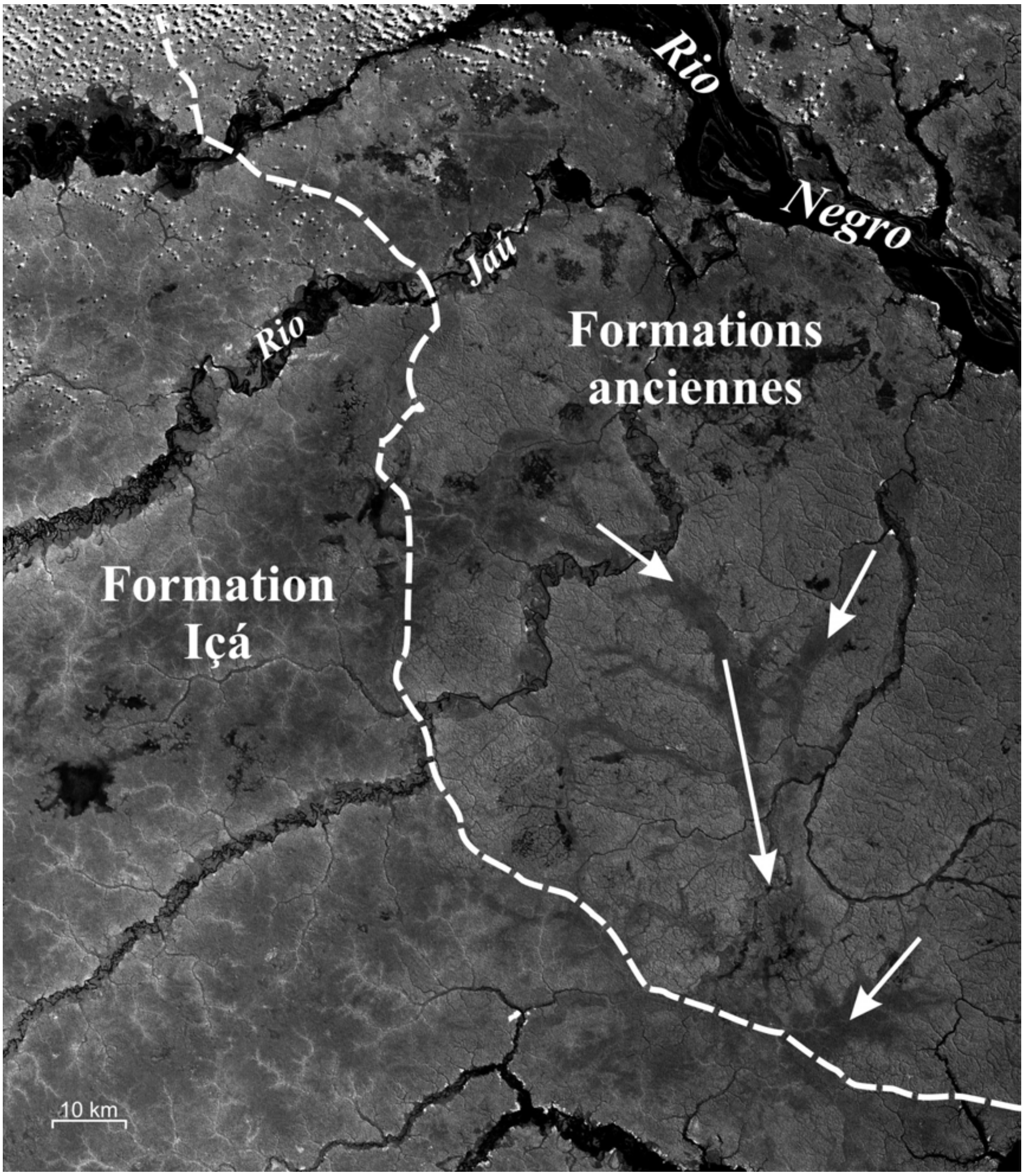


Figure 6*. Image Landsat d'un reseau fluvial fossile (zone foncée sous les fleches) installé sur les formations géologiques anciennes (Prosperança, Trombetas et Alter do Chão). Ce reseau est localement recoupé par le réseau de drainage actuel des bas plateaux de la région du Jaú. Noter des directions opposées pour les écoulements suggérant que les paléo chenals puissent être antérieurs à l'installation du réseau de drainage moderne du fleuve Amazone).*

La distribution de la végétation reflète très généralement cette distinct entre ces deux grandes catégories de sols (Fig. 2a). Par ailleurs, le type de régime climatique et de sol formé en

environnement hydromorphe semble également avoir une incidence notable sur le port du couvert végétal. Ainsi, les sols latéritiques bien-drainés (Ferralsols et Acrisols) soutiennent très généralement la forêt sempervirente (*Floresta de Terra Firme*) (Silva *et al.,* 1977). Sur les sols périodiquement engorgés (e.g. Gleys ou Podzols hydromorphes) se développent des couverts végétaux plus bas et ouverts que la forêt. Dans les podzols hydromorphes de la partie centrale de certains plateaux (cas par exemple du site (3) du Jaú, Nascimento *et al.,* 2004), la forêt laisse place à une végétation arbustive dense à la bordure des dépressions à podzols (*Campinarana*) puis à une savane arbustive ouverte (*Campina*) dans la partie saisonnièrement ennoyée de ces dépressions. Ces couverts arbustifs témoignent ainsi de stress hydriques plus marqués à l'aval de ces dépressions (Anderson, 1982), avec des périodes d'ultra-dessiccation en saisons sèches (faible capacité de rétention en eau du sable) et d'engorgements prolongés en saisons pluvieuses. Dans des régions plus pluvieuses à paysages plus fortement podzolisés mais également incisés par le réseau hydrographique (cas du site (4) de São Gabriel da Cachoeira), une forêt arborée plus haute, mais plus claire que la forêt sempervirente peut alors coloniser les aires podzoliques (*Caatinga*) (Fig. 2a). Ces distributions de végétations (Magnago *et al.,* 1978; Chauvel *et al.,* 1987) semblent ainsi être plus attribuables à des régimes hydriques contrastés entre latérites et podzols, voire même entre podzols hydromorphes et podzols drainés, qu'à des oscillations climatiques Quaternaires comme cela est généralement invoqué dans la littérature (Gouveia *et al.*, 1997).

2.3. Les latérites (Ferralsols) et la latéritisation

La latéritisation correspond à l'altération zonale des régions intertropicales humides ou à saisons contrastées du globe. Les latérites meubles ou indurées (e.g. cuirasses) sont les résidus de cette altération (Melfi & Pedro 1977, Fanning & Fanning 1989). Dans ces régions, les conditions de drainage ouvert à semi-ouvert, les températures élevées et les pHs modérément acides sont propices à une exportation totale des bases, partielle de la silice et une accumulation résiduelle du fer et de l'aluminium dans les minéraux secondaires du sol (essentiellement kaolinite, oxydes de Fe et d'Al) (Robinson 1949; Melfi & Pedro, 1977). Des éléments en trace (e.g. Zr, Ti, Th), présents dans des phases minérales peu altérables (e.g. zircon, oxydes de Ti ou de Th) (Balan *et al.,* 2001; Maurin *et al.*, 2005) ont également tendance à s'accumuler de façon relative dans ces profiles d'altération. Ils sont souvent utilisés comme invariants pour les calculs des bilans de masse (Brimhall & Dietrich 1987; Chadwick *et al.,* 1990). Les latérites meubles présentent des horizons organiques de type

mull. Ils sont fréquemment argileux et présentent verticalement de faibles gradients texturaux. Les oxydes de Fe intimement liés aux argiles forment avec ces derniers des structures polyédriques ou micro-agrégées stables (pseudo-particules, Beaudou & Chatelin, 1972) qui rendent les matrices poreuses et perméables.

Des travaux récemment engagés sur des latérites meubles de la zone intertropicale humide d'Amazonie ont également montré que les accumulations résiduelles de matières étaient aussi reliées à une dissolution ménagée des quartz et à des mécanismes de dissolution/recristallisation affectant les principales phases minérales secondaires de ces sols: la kaolinite (Balan *et al.,* 2005) et les oxydes de fer (Fritsch *et al.,* 2005). Ces transformations minéralogiques sont appréhendées sur le terrain par des variations progressives de texture et de couleur. Les variations texturales sont attribuées à une diminution progressive de la taille des particules de kaolinite de la base vers le sommet des profils latéritiques. Elles sont particulièrement marquées en profondeur à la transition entre les altérites et les sols. La diminution de la taille de ces particules a été reliée à un accroissement du désordre cristallin des kaolinites, lui-même attribué à des fautes d'empilement des feuillets de ce minéral (Balan *et al.,* 1999). Ces variations texturales ne peuvent s'expliquer que par des mécanismes de dissolution/recristallisation propices au remplacement d'anciennes populations de kaolinite de grande taille et dépourvu de fautes d'empilement par de nouvelles populations de kaolinite plus petites et fortement désordonnées. Les variations colorimétriques sont attribuées au jaunissement progressif des latérites rouges, particulièrement marquées dans la partie supérieure des profils d'altération. Ces changements, qui peuvent se faire sans perte des teneurs en fer, ont été attribués à la dissolution d'oxydes de fer faiblement substitués en aluminium (hematite et goethite) suivie par la recristallisation d'oxy-hydroxydes plus fortement substitués (goethite alumineuse) (Fritsch *et al.,* 2005). Lorsque l'accumulation d'aluminium dans les structures des oxyhydroxydes de fer est achevée (maximum de 33%), des hydroxydes d'aluminium (gibbsite) sont alors susceptibles d'être produits. Ces transformations témoignent d'une activité en aluminium et en eau plus élevée et, à l'opposé, d'une activité en silicium plus faible dans la partie supérieure de ces profils. Ces conditions d'altération qui restent propices à la dissolution des kaolinites ne sont par contre plus favorables à la recristallisation de nouvelles générations de phyllosilicates. Elles favorisent à l'opposé le piégeage de l'aluminium dans des phases minérales plus hydroxylées (goethite alumineuse puis gibbsite). Ces dernières témoignent d'un début de mobilité de l'aluminium dans ces profils d'altération.

2.4. Les latérites (Acrisols) et l'appauvrissement

Les latérites, précédemment décrites (Ferralsols), sont susceptibles de s'appauvrir en éléments fins et d'acquérir de ce fait des textures de plus en plus sableuses. L'appauvrissement en éléments fins peut se faire soit directement lors de l'altération de la roche (Wesemael *et al.,* 1995) soit par transformation latérale d'un autre sol (des latérites par exemple). Il donne naissance à des sols qui ont reçu différents qualificatifs: « *sandy bleached brown loam* » (Klinge, 1965), « sols ferrallitiques fortement désaturés, lessivés, intergrades » (Turenne, 1977), « sols intermédiaires ferrallitiques lessivés » (Lucas *et al.,* 1988), Ultisols (Bravard & Righi, 1990) ou Acrisols (Nascimento *et al.,* 2004). Ces sols présentent généralement des horizons organiques de type mull et des gradients texturaux avec ou sans évidence de transport particulaire, en particulier des revêtements argileux (cutanes d'illuviation) dans des horizons Bt plus profonds ou situés plus à l'aval dans les paysages. Deux processus majeurs sont généralement invoqués dans la littérature pour expliquer ces pertes de matières: (i) la lixiviation associée à des dissolutions de minéraux et au transport d'ions en solution (Plaisance & Cailleux, 1958) et (2) le lessivage attribué au transport de particules ou colloïdes en suspension (Aubert, 1954; Bocquier, 1971).

La lixiviation peut être relié au processus de latéritisation tel qu'il a été décrit dans le précédent paragraphe, dans la mesure ou les pertes en éléments dissous peuvent être reliées à une nette prédominance des dissolutions par rapport aux recristallisations de minéraux secondaires. Ces dissolutions seraient sélectives et affecteraient d'abord les oxydes de fer puis les kaolinites. Dans les latérites meubles, les pertes de matières associées à une remobilisation du fer sont souvent minimes. Elles ont néanmoins une répercussion importante sur la structuration et perméabilité du sol. En effet, le rôle agrégeant et stabilisant du fer (surtout hématite) sur la fraction fine du sol est reconnu depuis longtemps (Gombeer & D'Hoore, 1971; Van Ranst & De Coninck, 2002). Son exportation est généralement associée à une dissolution sélective des hématites et à un jaunissement du sol (Fritsch *et al.,* 1989; Peterschmitt *et al.,* 1996). Ce processus conduit à la rupture des liaisons fer-argile, à la destruction des agrégats du sol et à la prise en masse des matrices (Chauvel *et al.,* 1977; Fritsch *et al.,* 1989). La dissolution des kaolinites est un processus beaucoup plus lent qui s'opère vraisemblablement sur des temps géologiques (Balan *et al.,* 2005). Un autre processus est parfois invoqué pour expliquer les pertes importantes de minéraux argileux : La ferrolyse (Brinkman, 1970). Ce processus opère en deux grandes étapes: (i) le Fe^{2+} remplace d'abord des cations échangeables des argiles, qui sont lixiviés (phase réductrice), (ii) ce Fe^{2+} est

ensuite oxydé en Fe^{3+} (phase oxydante avec formation d'hydroxydes), et les protons H^+ occupent leur place dans les argiles. Cet environnement acide favorise la dissolution partielle de ces silicates (Brinkman, 1970; Van Breemen, 1985).

Les pertes en éléments fins entraînent une modification du type d'assemblage (de compact à granulaire) propice au développement d'une porosité grossière (Fritsch *et al.,* 1989) et de ce fait au transport de particules fines lors d'écoulements gravitaires (Fritsch *et al.,* 1989; Bravard & Righi 1990; Lucas *et al.,* 1996). Les pertes de matières semblent ainsi se faire en deux étapes. La première étape est attribuée à l'altération ou lixiviation des matériaux (par dissolutions sélectives et détachement des particules). La seconde étape correspond au soutirage ou lessivage des particules fines d'un horizon ou d'un ensemble d'horizons. Ce lessivage peut être mis en évidence soit par des mesures d'éléments en suspension dans les eaux de percolation soit par la reconnaissance de cutanes d'illuviation dans les profils d'altération. Il peut aboutir à l'individualisation de compartiments éluviés (pertes relatives) et illuviés (accumulations absolues) qui peuvent être soit superposés soit distribués latéralement en accord avec des écoulements hydriques latéraux dominants (Bocquier, 1971; Boulet, 1974; Fritsch *et al.,* 1990a; 1990b; Valentin & Fritsch, 1990). Signalons enfin dans certains paysages de savanes, la contribution non négligeable des remontées biologiques de terre et de l'érosion sélective en surface par ruissellement (Fauck, 1972; Fritsch *et al.,* 2007) dans l'appauvrissement des horizons de surface. Ces horizons sableux ne peuvent plus de ce fait contribuer à la reconstruction des profils latéritiques par la base (Lucas *et al.,* 1996).

La contribution respective des processus de lixiviation et de lessivage dans ces pertes de matière reste toutefois délicate à établir. Des tentatives ont été réalisées en utilisant des éléments considérés comme peu mobiles dans les profils d'altération (e.g. Zr, Ti et Th) et en les comparant aux principaux éléments (Fe et Al) présents dans les principales phases minérales de ces sols : oxydes de fer et kaolinites (Lucas *et al.,* 1987, 1996; Bravard & Righi, 1989, 1990). Ainsi une plus grande perte de Fe par rapport à Al et une bonne corrélation de ce dernier élément avec Ti indiquerait une dissolution sélective des oxydes de fer. Par contre, des pertes des trois éléments (Fe, Al et Ti) dans des rapports qui restent constants pris deux à deux indiquerait plutôt un lessivage (Bravard & Righi, 1990).

Les processus de lixiviation et lessivage, impliqués dans la perte en éléments fins peuvent s'observer dans la partie supérieure ou inférieure des profils d'altération, ou encore les deux à la fois. Ils sont identifiés soit en milieu non saturé (dans la partie supérieure de certains profils latéritiques) soit en milieu saturé (dans la partie inférieure de ces profils) et être associés à des

systèmes de nappe. Cela suggère de ce fait que l'hydromorphie prolongée des latérites (ou forte oxydo-réduction) n'est pas forcement une étape préalable à leur appauvrissement.

Les facteurs environnementaux invoqués pour expliquer ces pertes de matières restent encore incertains et parfois contradictoires. Ainsi en régions tropicales à saisons contrastées, elles ont été attribuées principalement à l'ultra-dissecation des sols (Chauvel *et al.,* 1977; Chauvel & Pedro, 1978). Sous conditions de très faible humidité du sol, les films d'eau deviennent polarisés, les taux de dissociation s'élèvent (Mortland, 1968) et les pH aux interfaces s'abaissent (ordre de 2). Ces conditions permettraient alors la mobilisation du fer des sites d'échange des argiles, même en milieu oxydant (Chauvel & Pedro, 1978). En régions tropicales humides, ces pertes de matières ont, à l'inverse, été attribuées à une plus forte hydratation du sol (climats ou pédoclimats plus humides), à des mécanismes d'auto-développement et au vieillissement des latérites (Fritsch *et al.,* 1989, 2005).

2.5. Les sols hydromorphes (Gleysols) et l'oxydo-réduction

Les sols de ces environnements sont associés à des systèmes de nappe. Ce sont des sols intrazonaux et leur distribution relative dans les paysages est de ce fait commandé par le relief et la capacité des nappes à alimenter en eau mais aussi en matériel dissous et particulaire les rivières. En Amazonie, ils occupent de ce fait systématiquement les bas de versants des rebords des plateaux et les plaines alluviales. On les trouve également dans les dépressions de certains plateaux, plus particulièrement dans les nombreuses dépressions anastomosées de la Formation Içá (Fritsch *et al.*, 2007).

Les sols de ces environnements ont généralement des teneurs en argile assez élevées et l'accumulation d'eau va d'une part altéré les flux du cycle du carbone entre lithosphère, biosphère, atmosphère et hydrosphère, et d'autre part favoriser le développement de conditions réductrices propices à la mobilité de certains éléments (en particulier Fe). En milieu saturé et anoxique, la minéralisation réduite des matières organiques va favoriser leur accumulation dans la partie supérieure des sols, ces accumulations de matières organiques pouvant aboutir à la formation d'Histosols en cas de saturation hydrique permanente jusqu'en surface (Fanning & Fanning, 1989). D'autre part, les saturations hydriques temporaires ou permanentes de ces sols sont propices au développement d'une faune microbienne adaptée aux conditions oxydo-réductices qui règnent dans ces sols (Duchaufour, 1982).

En période d'engorgement, le développement de conditions réductrices est propice sous l'action de bactéries à la consommation de l'oxygène de l'eau, puis à la réduction en chaîne de composés minéraux, les plus connus étant les nitrates, les oxydes de Mn, les oxydes de Fe et les sulfates. En milieu tropical où les oxydes de fer sont largement prédominants, cela conduit progressivement au jaunissement et blanchiment des latérites rouges (Fritsch *et al.,* 1989; Peterschmitt *et al.,* 1996). Ce jaunissement et cet éclaircissement des matrices latéritiques constituent très certainement l'un des processus majeurs de la zone intertropicale. Ils ont été reliés à une dissolution préférentielle des hématites, généralement moins substituées en Al, dans le pool des oxydes de fer souvent dominé par la goethite (Jeanroy et al., 1991; Bousserrhine et al., 1999; Torrent *et al.,* 1987; Peterschmitt *et al.,* 1996). Ces dissolutions sélectives sont majoritairement guidées par la taille et les taux de substitution en Al dans les sites octahédriques de ces minéraux. Ils s'expriment de ce fait différemment suivant qu'on se situe dans les altérites ou dans les sols qui les surmontent au sein des profils d'altération.

En période de rabattement des nappes, l'oxygénation temporaire et parfois localisée de ces sols est propice aux re-précipitations des éléments préalablement dissous. Ces re-précipitations de minéraux mal cristallisés (ferrihydrite) ou mieux cristallisés (lepidocrocite, goethite, hématite…) peut dès lors conduire à l'individualisation de taches, de nodules ou concrétions, de raies ferrugineuses ou d'horizons indurés (e.g. plinthites) (Duchaufour, 1982; Fanning & Fanning, 1989; Fritsch *et al.,* 2002, 2007).

Dans les régions tropicales humides, ces re-mobilisations de matières sous l'action des nappes restent limitées puisqu'elles sont essentiellement attribuées à la dissolution des oxydes de fer pris au sens large, et qu'elles préservent les minéraux argileux (kaolinite) généralement très dominant dans les fractions fines de ces sols (Fritsch *et al.,* 2002). Elles aboutissent généralement à la formation de sols à colouration hétérogène en cas d'engorgements provisoires (horizon diagnostique: pseudogleys) ou à des sols entièrement blanchis en cas d'engorgements permanents (horizon diagnostique: gleys) et lorsque les conditions réductrices sont maintenues dans les sols (Fanning & Fanning, 1989). A l'échelle des paysages et comme dans le cas de l'appauvrissement, la redistribution du fer peut aboutir à l'individualisation de compartiments réduits (pertes relatives) et indurés (accumulations absolues) qui peuvent être soit superposés et déconnectés du réseau hydrographique (Fritsch *et al.,* 2002), soit distribués latéralement et reliés au réseau hydrographique (Fritsch *et al.,* 2007). Dans ce dernier cas, des transitions ou structures en "double langue" ont pu être

identifiées entre les compartiments latéritiques les mieux drainés de l'amont et les systèmes hydromorphes aval. De telles structures témoignent d'écoulements hydriques latéraux dominants en accord avec la fluctuation de systèmes de nappe (Fritsch ***et al.,*** 2007).

2.6. Les podzols hydromorphes et la podzolisation

Comme les Gleysols, les Podzols hydromorphes du bassin amazonien sont associés à des systèmes de nappe. Ils correspondent de ce fait à des sols intrazonaux et leur distribution relative dans les paysages est commandé par le relief et la capacité de ces nappes à exporter les éléments dissous et particulaire aux rivières. Ils occupent sensiblement les mêmes positions topographiques que les Gleysols. Néanmoins et comme nous le soulignons dans cette thèse, la mise place de ces sols nécessite soit des matériaux parentaux à texture sableuse soit des formations latéritiques ayant au préalable perdues une grande partie de leurs constituants fins argileux par appauvrissement. En effet, la migration verticale et latérale des produits de décomposition des matières organiques n'est vraiment efficace que lorsque la porosité du sol devient suffisamment élevée, en dessous d'un seuil de teneur en argile très faible de l'ordre de 2 à 3% (Bravard & Righi, 1989). Dans la mesure où cet appauvrissement des latérites en éléments fins affecte essentiellement les parties déprimées des vastes pénéplaines du bassin amazonien, des podzols d'extension très variable s'observent essentiellement dans les dépressions de ces pénéplaines, qui correspondent de nos jours aux bas plateaux incisés par le réseau hydrographique du fleuve Amazone (Nascimento ***et al.,*** 2004). Toutefois des podzols, sans doute plus récents, s'observent également sur les incisions (Lucas ***et al.,***1988, 1996) et dépôts alluviaux de ce fleuve et de ses tributaires.

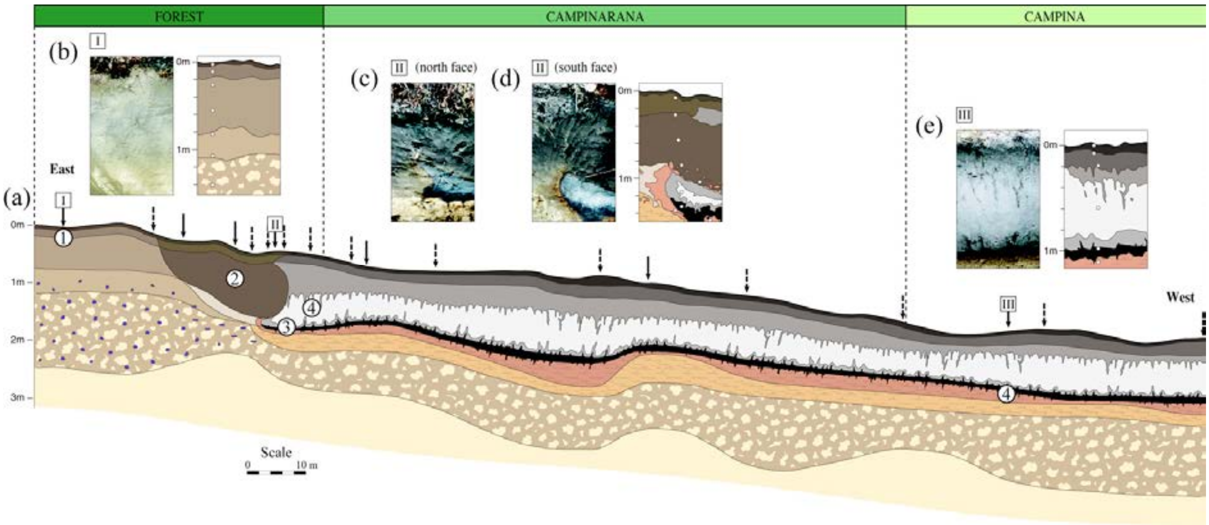


Figure 7*. Séquence de sols étudiée au Jaú (site 3) illustrant la transition latérale entre les latérites (à gauche) et les podzols des dépressions des plateaux (à droite) (d'après Nascimento et al., 2004).*

Dans les dépressions des bas plateaux où les podzols hydromorphes commencent à apparaître (site (3) du Jaú), la caractérisation minéralogique et structurale de séquences ordonnées de sols (Fig. 7) a permis de mieux définir les deux grandes étapes dans la podzolisation des latérites (Nascimento *et al.,* 2004). La première étape marque l'apparition à la bordure de la dépression de podzols faiblement différenciés (ou sols crypto-podzoliques). Ces podzols comprennent des horizons humifères A de type Mor surmontant des horizons spodiques, peu différenciés de type Bhs. La matière organique imprègne de ce fait profondément (sur plus d'1m) les latérites jaunes, appauvries de la bordure de ces dépressions, qui contiennent essentiellement du quartz mais aussi des minéraux argileux résiduels (kaolinite, gibbsite et goethite). Ces substances organiques assurent l'altération de ces minéraux argileux et contribuent à la formation et au transfert vertical de complexes organo-métalliques (principalement à base de Al mais aussi de Fe). La deuxième étape marque la quasi-disparition de ces minéraux argileux dans les horizons AE et E de podzols mieux différenciés et l'accumulation à plus grande profondeur d'une seconde génération de complexes organiques dans les deux horizons spodiques de ces podzols (Bh et Bs). Une étude hydrodynamique et géochimique le long de ces différentiations pédologiques a montré que la seconde étape était étroitement liée au développement de conditions réductrices et acides au sein d'une nappe perchée qui alimente en saisons pluvieuses les ruisseaux à l'aval des dépressions (Nascimento *et al.,* 2008).

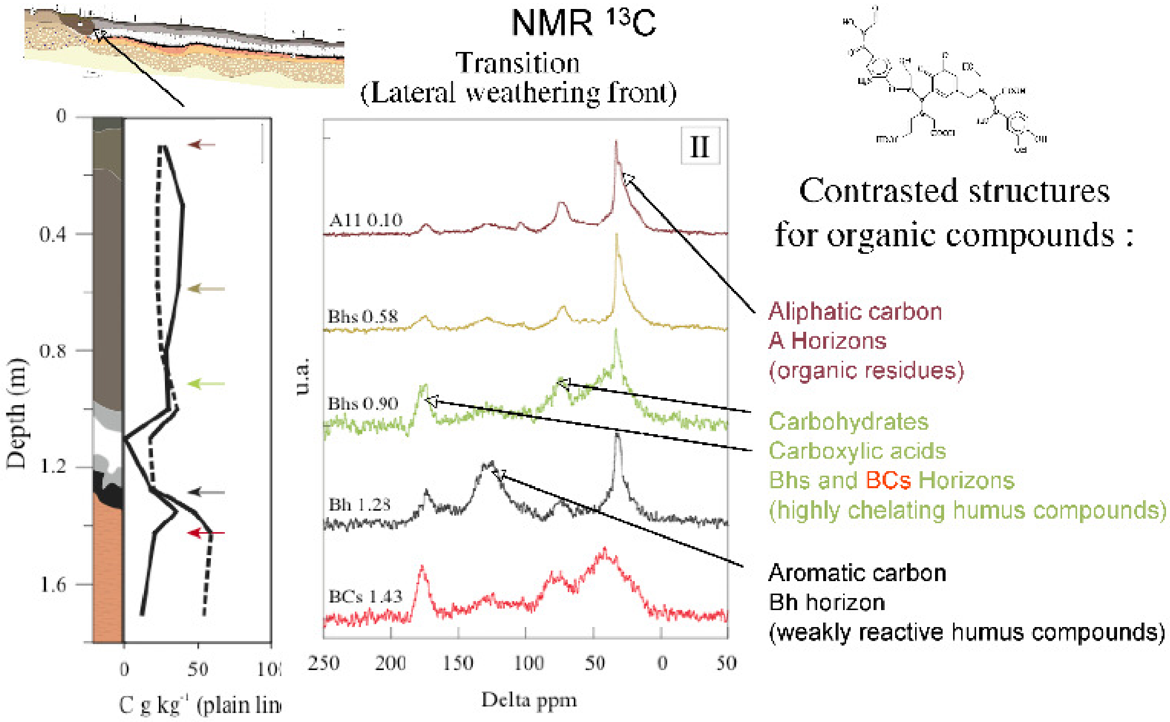


Figure 8*. Spectres RMN des matières organiques dans les horizons éluviés (A) et illuviés (Bhs, BCs et Bh) des podzols à la bordure de la dépression de la séquence du Jaú (d'après Bardy et al., 2008).*

La caractérisation microscopique et spectroscopique (RMN) des matières organiques de ces podzols a par ailleurs révélé des groupements fonctionnels dont l'abondance relative variait de façon significative suivant la nature des principaux composés organiques reconnus dans les horizons identifiés le long d'une séquence de sols (Fig. 8) (Bardy *et al.*, 2008). Ainsi les horizons de surface, éluviés, des podzols (A et AE) à nombreux résidus végétaux présentent essentiellement des groupements aliphatiques sur spectres RMN. Des matières organiques très fines formant des revêtements bruns dans les horizons spodiques Bhs des podzols faiblement différenciés, mais aussi plus en profondeur dans les horizons Bs de podzols mieux différenciés, sont caractérisés essentiellement par des groupements carboxyliques, dont l'aptitude à complexer les métaux est unanimement reconnue. Enfin, les revêtements organiques noirs et plus grossiers qui colmatent la base des horizons sableux de ces podzols et forment des horizons Bh sont essentiellement caractérisés par des groupements aromatiques. Les matières organiques qui alimentent les eaux noires des podzols en colloïdes organiques (Allard *et al.*, 2004, Fritsch *et al.*, 2009) s'observent sous forme de « boulettes », dispersées et peu abondantes dans les horizons de surface et en remplissage entre les quartz ou en

revêtements sur ces derniers dans les horizons Bh (Bardy *et al.,* 2008). Ces différenciations verticales témoignent ainsi d'un fractionnement physique des matières organiques lors de leur migration verticale dans les profiles d'altération. Les éléments les plus fins migrent plus en profondeur ou à la périphérie des aires podzoliques dans des horizons moins poreux (horizons Bhs et Bs) et les plus grossiers tapissent la bordure des réservoirs sableux de ces podzols (horizons Bh) (Duchaufour, 1972). L'aptitude de ces matières à complexer les métaux a été révélée dans un premier temps par des attaques chimiques sélectives (Nascimento *et al.,* 2004). Elle a été ultérieurement confirmée par des approches spectroscopiques à la fois pour l'aluminium qui est abondamment complexé aux matières organiques dans ces environnements (Bardy *et al.,* 2007) et pour le fer qui l'est beaucoup moins du faite des conditions réductrices qui prévalents dans ces podzols hydromorphes (Fritsch *et al.,* 2009). Ces travaux ont également montré qu'au fractionnement physique des substances organiques dans ces podzols pouvait être relié une séparation des formes complexées de l'aluminium et de celles du fer, les complexes alumineux s'accumulant plus en profondeur (Bs) ou plus à la périphérie dans les organisations latéritiques encaissantes (Bhs) que les complexes ferriques qui tapissent la bordure des réservoirs sableux (Bh). L'ensemble de ces travaux montre également que le développement de conditions très acides ($pH < 3.5$) dans les réservoirs sableux de ces podzols est propice à la remobilisation des métaux, principalement de l'aluminium, en accord avec les travaux de Jansen et al. (2003). Ces podzols seraient de ce fait des pièges à métaux dans les fronts latéraux de podzolisation et à l'inverse une source de métaux pour les rivières, à proximité des incisions qui drainent les dépressions de ces podzols (Allard et al., 2004; Benedetti *et al.,* 2003a, 2003b; Nascimento *et al.,* 2004; Bardy *et al.,* 2007; Fritsch *et al.,* 2009).

L'étude de la dynamique et composition chimique des nappes qui drainent ces associations de sols montre par ailleurs que la recharge rapide de la nappe perchée dans les réservoirs sableux de ces podzols est susceptible de créer des gradients de charge inverses à la topographie des dépressions et de contribuer ainsi à la recharge de la nappe phréatique profonde des latérites, à la bordure des aires podzolisées (Nascimento *et al.,* 2008). La mobilisation des éléments chimiques a lieu essentiellement à l'amont, dans le nappe phréatique des latérites (pour Fe), mais aussi dans les fronts de podzolisation lors de la recharge de la nappe perchée (à la fois pour Fe et Al) (Fig. 9). Cette nappe, chargée en matière organique dissoute et colloïdale, est donc susceptible de contribuer à la formation des complexes organiques, puis à leur accumulation dans les organisations périphériques, encaissantes lors du rabattement de cette

nappe. La forte baisse des teneurs en silice dissoute et en métaux (Fe et Al) dans la nappe perchée des horizons sableux des podzols (Fig. 9) témoigne enfin d'un temps de résidence court des eaux noires qui drainent les aires podzoliques (Bravard & Righi, 1989; Lucas *et al.*, 1996; Patel-Sorrentino *et al.*, 2007).

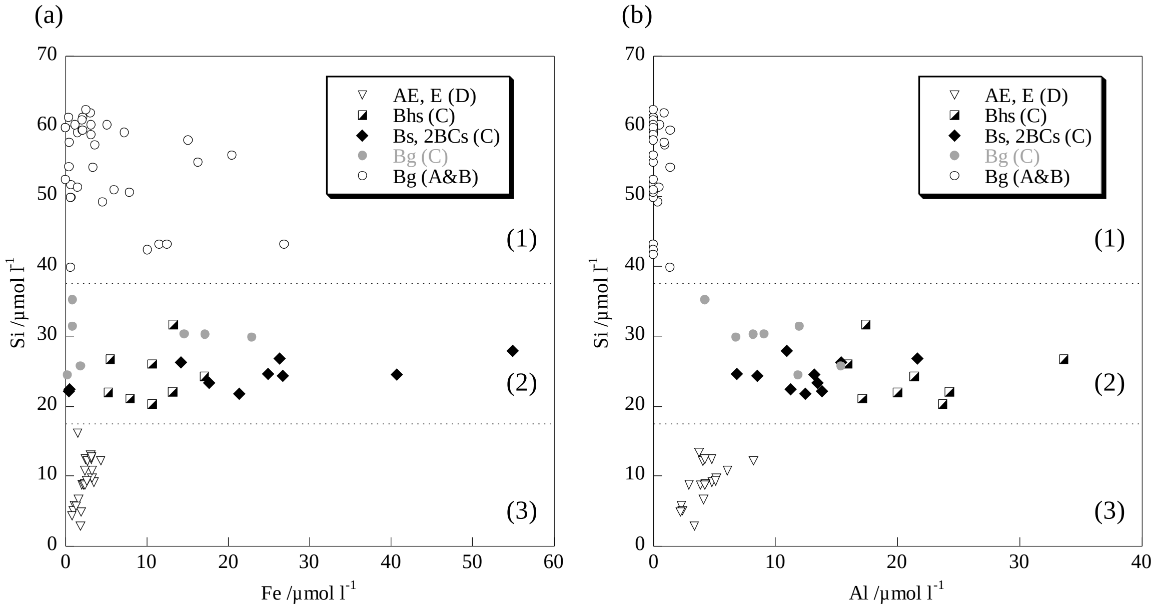


***Figure 9**. Composition géochimique des eaux (Si, Al, Fe) dans les trois compartiments majeurs de la séquence du Jau : (1) à l'amont dans la nappe phréatique des latérites, (2) dans les fronts latéraux de podzolisation et (3) dans la nappe perchée des podzols de l'aval.*

***Figure 10**. Front latéral de podzolisation en forme de double langue dans la séquence du Curicuriari (site 4): Latérites jaunes appauvris (à gauche) et podzols évolués (à droite).*

Les structures pédologiques mise en place dans les dépressions de ces plateaux reflètent dès lors la dynamique évolutive de ces systèmes. Les travaux entrepris par Nascimento et al. (2004) au Jaú et ceux que nous avons entrepris à São Gabriel da Cachoeira montrent que le développement vertical des podzols est arrêté dès qu'une discontinuité texturale ou structurale est rencontrée (une dalle rocheuse ou une altérite). Ces podzols ne peuvent donc plus se développer que latéralement, ce qui aboutit par soutirage à un agrandissement de la taille des dépressions. Latéralement, la transition entre latérite et podzols présente une forme en "double langue" qui a systématiquement été observée dans le haut bassin amazonien (Fig. 10). Cette structure peut être reliée à la dynamique des nappes perchées de ces podzols (Nascimento *et al.,* 2008). La langue inférieure est attribuée aux périodes de rabattement des nappes et plus particulièrement au soutirage généré par les écoulements latéraux de la nappe phréatique amont des latérites dans les systèmes podzoliques. La langue supérieure est associée aux fluctuations de la nappe perchée au voisinage de la surface topographique et à la bordure des aires podzoliques lors d'épisodes particulièrement pluvieux en saisons humides.

2.7. Processus d'altération et d'érosion, relations avec la morphogenèse

Deux grands types de processus peuvent être invoqués pour expliquer l'évolution des modelés sur les surfaces continentales: (i) des processus érosifs associés aux écoulements superficiels et aux transports de matières en surface (ruissellement en nappe ou concentré avec décapage ou incision des versants et dépôts dans les zones planes aval), et (ii) des processus érosifs associés à l'altération, aux écoulements internes et au transport d'éléments en solution (lixiviation) ou au transfert de particules en suspension dans les horizons poreux du sol (lessivage ou éluviation). Les premiers processus (érosion essentiellement physique) ont généralement été privilégiés dans de nombreuses études géomorphologiques au détriment des seconds (érosion principalement chimique) pour expliquer la mise en place des paysages. En particulier des épisodes d'érosion physique intense en climats secs seraient propices à la mise en place de surfaces d'aplanissement ou de pénéplaines (King, 1953). Ces surfaces pourraient être ultérieurement incisées en période plus humides et par abaissement des niveaux de base locaux, aboutissant ainsi à des inversions de relief. En particulier et comme cela semble être le cas pour le bassin amazonien, des plateaux pourraient ainsi résulter de l'incision d'immenses surfaces d'érosion et de sédimentation, marquant ainsi d'anciennes positions basses du bassin.

D’autres travaux ont néanmoins montré que l’érosion chimique des couvertures d’altération par soutirage interne (véritable fonte géochimique) et exportation au réseau hydrographique de matières en solution et ou en suspension pouvaient former des dépressions en surface (dolines en milieu karstique), des décrochements sur les versants et également de vastes zones déprimées ou plaines dans les paysages (Trescases, 1975; Millot, 1983; Lucas *et al*., 1988; Dubroeucq & Volkoff, 1998). Dans les régions arides d’Afrique de l’Ouest, des processus d’éluviation (pertes) et d’illuviation (gains), associés à des systèmes de nappe, se relayent latéralement sur de vastes zones aplanies (Bocquier, 1971; Boulet, 1974). Comme nous le verrons par la suite dans ce mémoire, il sera parfois difficile de déterminer l’origine de certaines facettes des paysages du bassin amazonien (e.g. dépressions et vastes chenaux anastomosés des bas plateaux). Ces facettes pourront soit marquer d’anciennes structures sédimentaires (chenaux fluvio-lacustres) soit résulter d’une véritable fonte géochimique des latérites avec comme stade ultime l’individualisation de podzols dans les zones déprimées des paysages, soit encore résulter d’une combinaison de ces deux types de processus (a “t*wo stage process*”, e.g. Wayland, 1934; Linton, 1955; Budel, 1957; Planchon et al.,1987).

CAPITULO 3. O EMPOBRECIMENTO DOS SOLOS LATERÍTICOS: UMA ETAPA PRÉVIA À PODZOLIZAÇÃO

Résumé

Le chapitre traite de l’appauvrissement des latérites comme étape préalable à la podzolisation. Cette étude a été réalisée dans la région de São Gabriel da Cachoeira à la bordure des aires fortement podzolisées du bassin versant du Curicuriari. Cinq profils latéritiques ont été sélectionnés depuis la bordure d’un plateau disséqué vers la partie centrale d’une dépression à podzols hydromorphes. Sur un transect de 1,6 km de long, les cinq profils (P1 à P5) illustrent les pertes graduelles en minéraux argileux qui s’observent essentiellement dans la partie supérieure des profils d’altération. Le profil P5 est situé 5m en amont de la dépression à podzols. Des caractérisations pétrographiques, minéralogiques (DRX, IRTF et DRS) et géochimiques, elles-mêmes couplées à des calculs des fonctions de transfert (éléments majeurs et en trace), ont permis de révéler les principales étapes dans la perte sélective de matières et la différenciation verticale et latérale des profils latéritiques.

Les profils d’altération, développés sur des granites à corps mafiques de la formation Uaupés, appartiennent à la surface d’aplanissement *Ucayali*. La latéritisation a généré une exportation totale des bases et partielle de la silice à la base de ces profils d’altération, et à une accumulation résiduelle du fer et de l’aluminium dans les principaux minéraux secondaires de

ces sols (kaolinite, gibbsite, hématite et goethite). La gibbsite, généralement présente en faibles quantités au sein de ces profils, est toutefois très abondante dans le profil sommital le plus rouge (P1), probablement due aux excellentes conditions de drainage régnant dans cette partie du paysage. Une altération plus ménagée des minéraux métamorphiques ou corps mafiques (illite, épidote, biotite, titanite, apatite, allanite, magnetite) dans les saprolites permet de différencier le manteau d'altération de l'épaisse couverture de sols (2.3 m) qui le surmonte.

Les différentiations latérales très progressives et l'absence de structures lithologiques d'origine sédimentaire sont en faveur d'une perte de matière par érosion interne des couvertures d'altération (lixiviation et lessivage). Ces différenciations latérales, qui affectent séparément le compartiment sol et le manteau d'altération, se rejoignent à l'aval (P5). Dans les sols, un net jaunissement, associé à des pertes ménagées de matières, est tout d'abord observé de P1 à P2. Cette première étape dans la différenciation latérale de ces sols est attribuée à une dissolution sélective des hématites dans le pool des oxydes de fer. Elle traduit une plus grande hydratation des matériaux et de ce fait un pédoclimat plus humide. Une perte très progressive de minéraux fins argileux, associée au développement d'une porosité d'assemblage inter-quartz, est ensuite constatée entre P2 et P5. L'absence de revêtements argileux et des pertes de matières à rapport Al/Fe sensiblement constant d'un profil à l'autre suggèrent une altération conjointe des kaolinites et oxydes de fer (essentiellement de goethite) lors de la fonte géochimique. Un léger accroissement du rapport Al/Fe de la base vers le sommet de ces sols suggère néanmoins une plus grande dissolution de goethites. Dans le manteau d'altération, des pertes brutales en fer sans variations texturales majeures et ordonnées le long de la séquence (nette accroissement du rapport Al/Fe) sont reliées au blanchiment d'altérites rouges sous l'action d'une nappe phréatique. Ce blanchiment et ces pertes en fer sont localisés à l'amont (P2 et P3) et généralisés à l'aval (P4 et P5). Enfin, la partie supérieure blanchie du réservoir de nappe s'appauvrit brutalement à l'aval de ce transect (P5). Les pertes ultimes d'éléments fines dans ce réservoir affectent également les éléments en trace (Zr), témoignant de ce faite de transport particulaire (zircon) en milieu saturé.

En conclusion, cette étude montre que les pertes de matières s'expriment différemment suivant qu'on se situe au voisinage de la surface dans les sols en milieu non-saturé, mais à hydratation saisonnière croissante vers l'aval, ou plus en profondeur en milieu saturé dans le manteau d'altération. Ainsi, des processus lents de dissolution sélective et de lixiviation prédominent dans les sols. A l'inverse dans le manteau d'altération, les pertes de fer puis de

minéraux argileux sont brutales et nettement dissociées latéralement dans le réservoir de la nappe phréatique. Lorsque le milieu devient suffisamment poreux, les pertes ultimes d'éléments fins lors d'écoulements latéraux de nappe pourraient en grande partie se faire sous forme particulaire. Les pertes de matières en surface et en profondeur aboutissent à l'individualisation en bordure des dépressions d'un compartiment sableux dont la transition latérale présente une forme caractéristique en "double langue". Comme nous le verrons dans le second article, cette nouvelle structure sera exploitée ultérieurement par la podzolisation. L'étude souligne également que les re-mobilisations de matières attribuées à une ultime évolution podzolisante resteront minimes par rapport à celles résultantes d'un appauvrissement préalable des latérites.

3.1. Introduction

The weathering of rocks in tropical regions leads to the intense leaching of base cations and silica. In high elevated and freely drained environments of the landscapes, this kind of weathering, also known as lateritisation (Kronberg & Melfi, 1987; Fanning & Fanning, 1989), leads to the residual accumulation of the less mobile Al and Fe in secondary minerals, predominantly kaolinite, Al- and Fe-oxides (mainly gibbsite, hematite and goethite), and the formation of thick clayey regoliths comprising both soils and saprolites (Ségalen, 1966; Nahon, 1991; Tardy, 1993; Fritsch et al., 2002).

Weathering of granitic rock basements may also lead to the residual accumulation of metallic trace elements (MTE) such as Zr, Ti and Th, which are frequently used as invariants in the assessment of losses or gains of more mobile chemical elements (Brimhall *et al.*, 1991; Braun et al., 1993). The commonly weak mobility of Zr in regoliths derived from granites is mainly due to its incorporation in zircon, a highly resistant primary mineral to chemical weathering with dominant silt and fine sand particle sizes (Braun et al., 1993; 2005; Balan *et al.*, 2001; Maurin, 2005; Taboada et al., 2006). The mobility of Ti and Th is also low in lateritic soils as they are incorporated in stable secondary minerals of smaller particle sizes (mostly anatase and thorianite) (Fritsch et al., 2005). However, the mobility of both MTE may be enhanced at depth in saprolites, depending on the nature of the parent host minerals. In particular, the weathering of titanite, rutile and ilmenite into anatase (Middelburg et al., 1988; Cornu et al., 1999) may contribute to significant losses of Ti.

The upward accumulation of clay minerals in loose laterites has been related to major crystallographic changes in kaolinites and Fe-oxides. In particular, the gradual transition from saprolite to soil is mostly due to decreasing size and increasing disorder of kaolinites (Balan et al., 2005). The upward yellowing of red laterites has been related to increasing proportion of goethite and Al substitution rates in the pool of Fe-oxides (i.e. in both hematite and goethite) (Fritsch et al., 2005). Such crystallographic trends illustrate changing weathering conditions in soil horizons that have been attributed to soil aging and longer wetting periods in the upper part of the soils. They also reveal cyclic dissolution and crystallization reactions that concern both kinds of minerals (i.e. kaolinites and Fe-oxides). These mechanisms increase the specific area and reactivity of the soil minerals and favor the aggregation of the soils. However, the upward yellowing of soils has also been related to clay depletion and soil structure breakdown (Fritsch et al., 1989; 2005).

In the Rio Negro watershed of the upper Amazon Basin, lateritic soils are widely and closely associated with waterlogged Podzols. Red clayey lateritic soils (Ferralsols) are commonly found at the margin of strongly dissected low elevation plateaus that belong to the pan American *Ucayali* peneplain (Campbell et al., 2006). By contrast, podzols are commonly found in poorly drained depressions of the central parts of the plateaus. Podzol formation results from the downward and downslope migration of organic acids (Pedro, 1987) in highly porous sandy materials during the lowering of perched groundwaters (Bravard and Righi, 1990; Nascimento et al., 2004). The accumulation of the organic acids at the periphery of the podzolic areas enables to sustain the perched groundwater. It also promotes the weathering of clay minerals and the formation of organo-metallic complexes (Lundström et al., 2000, Nascimento et al., 2004). Accordingly, the dominant Al and Fe previously incorporated in mineral phases of the lateritic environments become predominantly bound to organic matter in waterlogged podzols (Bardy et al., 2007; Fritsch et al., 2009). The high porosity of the sandy horizons of podzols explains the short residence time of water (Nascimento et al., 2008) and fast lateral fluxes in perched groundwater (Lucas et al., 1996) that enhanced the lixiviation and acidification of the soils. In these highly reduced, acidic and organic-rich environments, the heavy minerals such as Ti-oxides and zircon may be partly dissolved, and the metal cations released in solutions be exported in black surface waters (Colin et al., 1993; Oliva et al., 1999; Braun et al., 2005). The interstices managed by the quartz sands of these podzols may also promote the physical transport in perched groundwater of clay and silt size

particles, comprising therefore kaolinite, thorianite, Ti-oxides and to some extent zircon (Nascimento et al., 2004).

Red clayey laterites (Ferralsols) and waterlogged podzols belong to two end-members of soil catena on the low elevation plateaus of the Rio Negro watershed. A transition zone between these two end-members comprises yellow clay-depleted laterites (Acrisols) that can extend on several hundred meters on the plateaus. Soil catena studies have shown that podzolic areas can increase in size and form at the expenses of their surrounding clay-depleted laterites (Turenne, 1977; Chauvel et al., 1978; Lucas et al., 1987; Bravard and Righi, 1990; Nascimento et al., 2004). This kind of soil dynamics then suggests that yellowish clay-depleted laterites could in the same manner be formed laterally from better-drained laterites exhibiting heavier texture and redder colours. Pre-existing weathering processes associated with drastic colorimeric and textural changes seem therefore necessary to form waterlogged podzols on the plateaus. Such processes that enhance the chemical and physical erosion of laterites still remain poorly understood. Moreover, the hydraulic regime contributing to greater erosion and the compartments of the regoliths where they are acting need to be better defined. On this regards, Bravard and Righi (1990) and Nascimernto et al. (2004) point out that tropical podzols commonly form in poorly drained areas. This suggests that reducing conditions that promote yellowing and bleaching in laterites (Chauvel et al., 1977; Peterschmitt et al., 1996) could be one of the major soil change processes promoting the formation of podzols, the second one being associated to clay depletion. Fe could therefore be mobilized before Al in the transition zone between red clayey laterites and waterlogged podzols. At least, the removal and the transfer of matters that play a major role in the vertical and lateral differentiation of regoliths (Simonson, 1959), may be assigned to two major mechanisms (Fanning & Fanning, 1989): (i) solution transport (lixiviation or chemical erosion) and (ii) particulate or suspension transport (eluviation or mechanical erosion). Solution transport and redistribution of major and trace elements by chemical erosion are mostly controlled by hydrological regimes and weathering conditions (e.g. Eh, pH) (Van der Weijden and Van der Weijden, 1995; Grybos et al., 2007). Particulate transport depends on pore size, dispersion/flocculation properties and the existence of hydraulic gradients (Soil Survey Staff, 1975). This suggests that chemical erosion and solution transport might prevail in the transition zone, whereas particulate transport could be also involved close to the podzolic areas due to greater development in soil matrix of macro-voids between adjacent quartz grains.

Structural, geochemical and mineralogical (XRD, FTIR et DRS) investigations were performed in five profiles (P1 to P5), located along a 1.6km long transect from the margin of a dissected plateau to the border of a huge depression containing waterlogged Podzols. The profiles illustrate vertical and lateral differentiations associated with the formation of reddish clayey laterites (Ferralsols) at the margin of the plateau and their lateral transformation into yellowish clay depleted laterites (Acrisols) towards the depression. Lateral differentiations in the field are mostly assigned to colorimeric and textural changes in both soils and saprolites The aims of this work are to reveal (i) the sequence of major weathering processes that generates losses of clay minerals and therefore promote the podzolisation of lateritic landscapes, (ii) the general hydric regimes that enhanced the chemical and physical erosion of the regoliths and (iii) the places in the landscapes where these weathering processes and hydraulic regimes are acting.

3.2. Environmental setting

The transect with its five profiles is located near São Gabriel da Cachoeira (0^o 15’ 50”S; 67^o 03’ 10”W) in the upper Negro River watershed (see star in Fig. 1). It belongs to the *Ucayali* peneplain, formed during an intense erosion phase of the mid Miocene (Campbell et al., 2006) that corresponds nowadays to the low elevation and dissected plateaus of the upper Amazon basin (about 90m above mean sea level, or 15m above mean river level at São Gabriel da Cachoeira). This transect is also located at the margin of a huge podzolised and inundated peneplain that covers 95% of the Curicuriari subcatchment in the West.

The vegetation of the region is in agreement with the soil distribution. The evergreen Amazonian forest covers the lateritic soils of the plateaus (*Terra Firme*), whereas a lower and more open forest with thin tree trunks (*Caatinga*) is growing on the hydromorphic Podzols of the depressions and peneplains (Silva et al., 1977). The mean annual temperature in that region is 25^oC and the rainfall is about 3000 mm per year with two maxima, on January (289 mm) and April (339 mm), and two minima, on February (282 mm) and August (124 mm) (Costa et al., 1977).

Soils in the region of São Gabriel da Cachoeira are formed on (titanite)-(amphibole)-biotite-granites and gneisses, with similar composition, of the western part of the Guyana Shield. They yielded 1518 +/- 25 Ma age by the ID TIMS U/Pb (zircon) method (Santos et al., 2000)

and younger thermotectonic event, related to Grenville orogeny, has been affect these granites at 1200 +/- 100 Ma (K'Mudku episode).

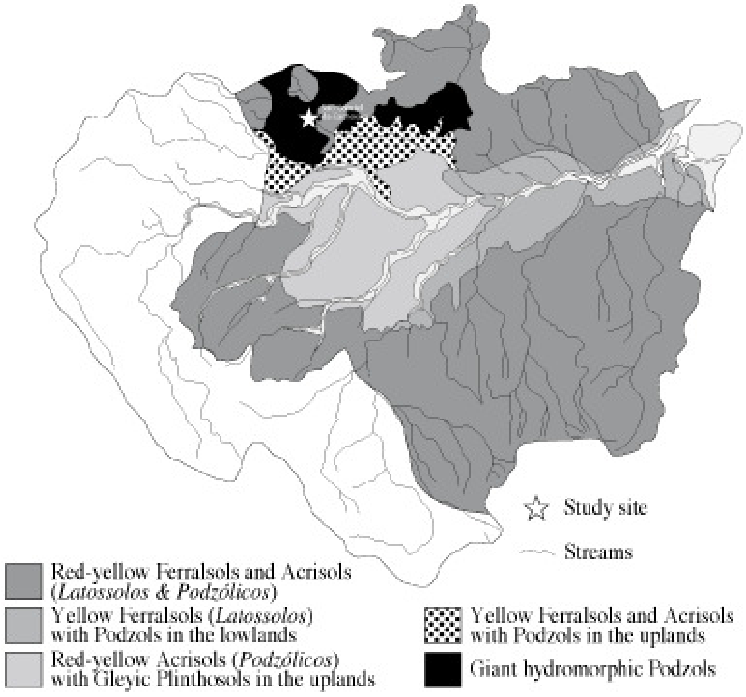


***Figure 1**. Broad scale soil map of the Brazilian Amazon basin (reduced and simplified from RadamBrazil maps at 1:2.500.000) showing the site location (star) at the margin of a highly podzolised region of the Rio Negro watershed.*

Granitoid rocks of the region comprise mafic-bearing granitic bodies locally sheared and mineralized and are crosscut by pegmatite or quartz veins (Fernandes et al., 1977, CPRM, 2006). Two major structural lineaments were recognized in that region: a dominant NE-SW to ENE-WSW lineament and a secondary NW-SE one. In the low course of Curicuriari River, the rock basement belongs to two granitic suites: (i) the syenogranites to alkali-feldspar granites of the Curicuriari Suite and (ii) the monzogranites to quartz-monzonites of the Uaupés Suite (Almeida, 2005, CPRM, 2006). Profiles of the transect have formed on the quartz-monzonite and monzogranite of the Uaupés Suite that contain less quartz (15%) and alkali-feldspar (30%) than that of the Curicuriari Suite (42 and 50%, respectively) and much more plagioclase (44% versus 5%) and mafic minerals (11% versus 3%).

Table 1 : Analytical data from electron microprobe analyses (wt% oxides) of major minerals identified in the granite

Minéral	SiO_2	Al_2O_3	FeO	K_2O	Na_2O	CaO	MgO	MnO	TiO_2	P_2O_5	La_2O_3	Ce_2O_3	ZrO_2	LOI	Total
Microcline	64.62	18.63	0.14	15.99	0.49	-	-	-	-	-	-	-	-		100.4
(σ, n=10)	(0.45)	(0.14)	(0.06)	(0.26)	(0.13)	-	-	-	-	-	-	-	-		
Anorthite	60.83	25.34	0.10	0.10	7.76	6.46	-	-	-	-	-	-	-		100,6
(σ, n=10)	(0.89)	(0.52)	(0.11)	(0.03)	(0.28)	(0.60)	-	-	-	-	-	-	-		
Albite	66.29	21.21	0.27	0.17	9.93	1.82	-	-	-	-	-	-	-		99,7
(σ, n=15)	(2.23)	(1.44)	(0.29)	(0.19)	(0.85)	(0.60)			-	-	-	-	-		
Biotite	39.13	16.52	20.04	9.16	-	-	8.61	0.59	1.61	-	-	-	-		95.7
(σ, n=15)	(2.00)	(0.37)	(1.13)	(0.31)	-	-	(0.81)	(0.08)	(0.20)	-	-	-	-		
Amphibole	41.97	9.98	21.07	1.32	1.17	11.28	7.88	0.93	0.80	-	-	-	-		96.5
(σ, n=15)	(0.41)	(0.05)	(0.26)	(0.02)	(0.03)	(0.16)	(0.28)	(0.05)	(0.09)	-	-	-	-		
Titanite	30.34	2.15	1.73	-	-	26.88	-	0.18	34.80	-	-	-	-		96.1
(σ, n=15)	(0.39)	(0.21)	(0.48)	-	-	(1.19)	-	(0.05)	(0.65)	-	-	-	-		
Apatite	0.47	-	0.10	-	-	54.19	-	0.08	-	40.88	0.18	0.39	-		96.3
(σ, n=15)	(0.20)	-	(0.10)		-	(0.50)	-	(0.03)	-	(1.20)	(0.10)	(0.18)	-		
Allanite	31.13	13.79	14.51	0.07	0.31	11.42	0.25	0.54	1.02	0.10	4.54	8.16	-		86.0
(σ, n=15)	(1.07)	(0.81)	(1.99)	(0.03)	(0.13)	(1.19)	(0.07)	(0.12)	(0.39)	(0.06)	(0.73)	(0.65)	-		
Garnet	38.05	23.32	11.95	0.09	-	22.33	0.11	0.48	0.10	-	0.03	0.08	-		96.7
(σ, n=15)	0.65)	(0.28)	(0.29)	(0.12)	-	(0.43)	(0.14)	(0.02)	(0.01)	-	(0.01)	(0.04)	-		

In the bedrock of the profiles, the alkali-feldspar corresponds to perthitic microcline with Tartan type twinning, which locally encloses quartz and plagioclases inclusions. The plagioclase show two generations and common polysynthetic twinning. Indeed, phenocrystals of plagioclase (2nd generation), highly saussuritized, exhibit sericite, epidote and smaller plagioclase inclusions (1st generation). The centrimetric mafic clots, which give to the rock its characteristic speckled aspect, mostly consist of biotite and amphibole (8%) and accessory minerals, such as apatite, allanite, zircon and opaque minerals (mostly magnetite and also locally pyrite) commonly surrounded by titanite. Allanite crystals are locally surrounding epidote and often aggregated with titanites. When apatite and allanite crystals appear as inclusions within biotite crystals, they often display a thin fringe of radiation-induced defects in the phyllosilicate (pleocroic haloes). The crystal chemistry of most of the major and accessory minerals on thin sections is given in table 1. It has permitted to identify the main mineral carriers for trace elements in rocks, saprolites and soils (e.g. mostly titanite and rutile for Ti, apatite for P and Ca, allanite for light rare earth element (La, Ce) and zircon for Zr).

3.3. Materials and methods

Soil survey, soil description and sampling

We used 2005 Ikonos satellite images to map the main geomorphologic and pedological units at the transition between the huge podzolized and waterlogged peneplain of the Curicuriari watershed and their lateritic counterpart at the border of the Guianense shield, in the western part of the watershed (Fig. 2a). Field surveys under forest were carried out in selected areas to

control map unit demarcations and to obtain precise topographic data using Topcon Hiper GPSs with a pair of Paulin Altimeters. Satellite images together with topographic GPS and altimeter data allowed building up a block-diagram for the investigation region using 3D design softwares (black insert in Fig. 2a and Fig. 2b). The site selected for this study belongs to the *Ucayali* Peneplain (Campbell et al., 2006) at the margin of the low elevated lateritic plateaus, just before reaching the huge podzolic and inundated peneplain of the region. It corresponds to a 1.6 km long transect on the edge of an incised plateau. The transect starts on the right bank of the Curicuriari river with red clayey laterites and ends up 5m before reaching the margin of a large podzolized depression (white dashed line in Fig. 2a,b). Along the transect, topographic survey was made at 7 m intervals and 27 soil augerings allowed the selection of 5 pits (from P1 to P5 in Fig. 2c) for soil sampling and investigations. Soil pits are located on hill-top positions at a water divide in the dissected plateau to minimize the contribution of colluvial deposits. Soil description was done according to ISRIC-FAO (1994). 121 samples from the 5 pits and 4 samples from rock outcrops were collected for chemical, physical and mineralogical investigation. 32 undisturbed samples of rocks, saprolites and soil horizons were also collected in cardboard boxes. They were impregnated with resin, cut and grounded for the elaboration of thin sections. The latter were observed under plain-polarized light (PPL) and cross-polarized light (CPL) using a microscope.

Chemical and physical analyses

Air-dried soil samples were sieved through a 2-mm screen. Particle-size distribution was determined by sieving (sand fractions) and pipetting (clay and silt fractions) after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. pH was measured both in water and in 1 M KCL (soil:solution; 1:2.5). Organic C and N contents were determined using a Carmograph LECO CHN analyser. Total chemical composition was performed on pulverized samples (150 mesh) at Actlabs Ltd (Canada); major elements by inductively coupled plasma atomic emission spectrometry, and trace elements by inductively coupled plasma atomic mass spectrometry.

Electron Punctual Microprobe Analyses (EPMA) were carried out on thin sections to determine the chemical composition of parent material minerals using a CAMECA SX50 equipped with four Wavelength Dispersive Spectrometers (WDS) and operating at 15 kV and 30 nA at the Centre d’Analyse des Minéraux de PARIS (CAMPARIS, Université Pierre et Marie Curie, Paris, France).

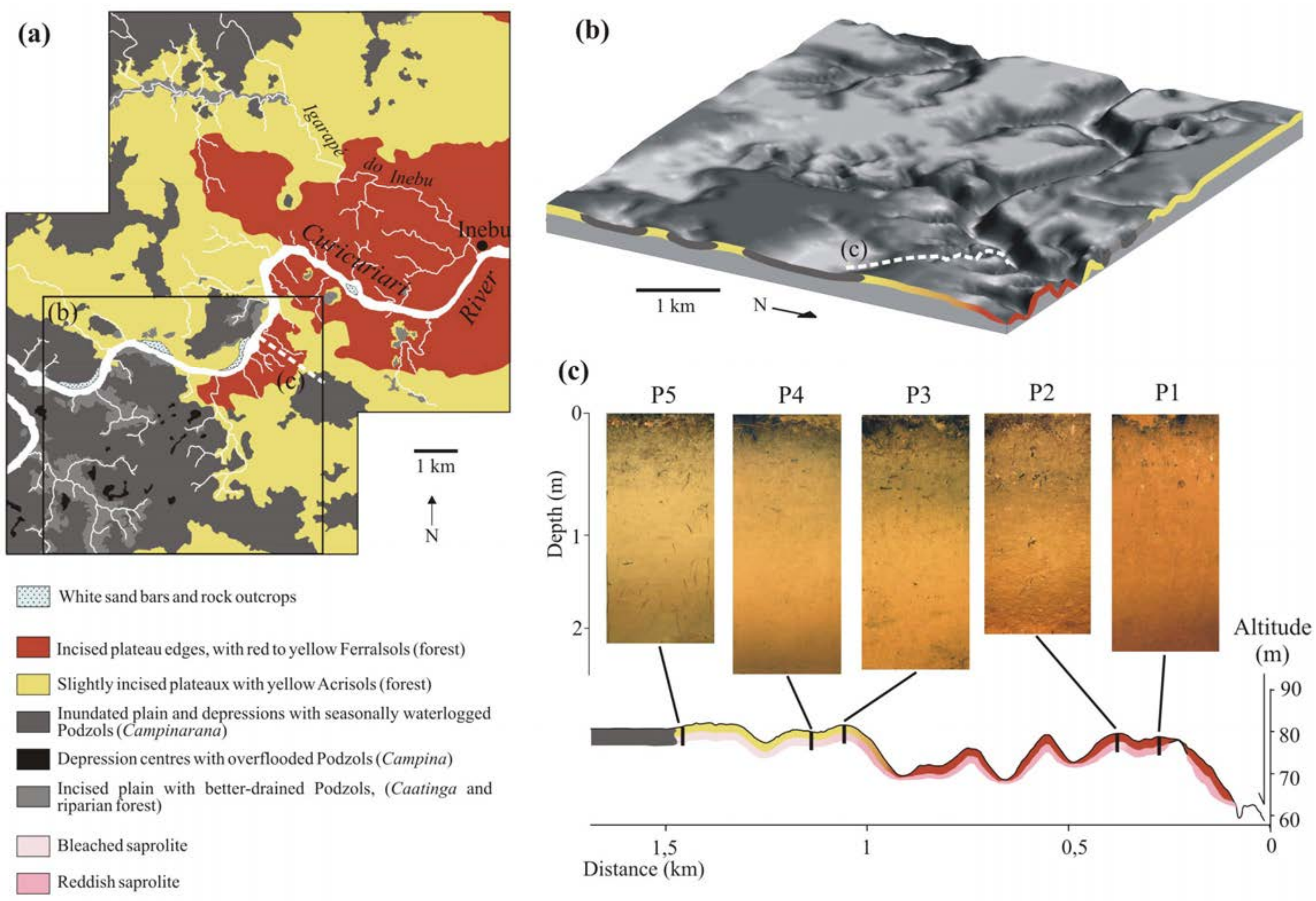


***Figure 2**: (a) Regional map of major soil landform units with their vegetation in the lower course of the Curicuriari watershed at the transition between podzols and laterites, which also shows the localisation of the transect (white dashed line), (b) 3D representation of the same area (see black rectangle insert in (a) for location of the selected zone), (c) soil transect with the position of the five selected profiles (from P1 to P5) and photographs of their upper parts (soils).*

Total chemical analyses and the mass-balance approach (Brimhall et al., 1991, Chadwick et al., 1990) were used to assess the relative losses or gains of chemical elements in the 5 profiles as compared to their underlying bedrock. This approach requires the selection of a chemical element, considered as immobile during weathering processes. In our investigation site, the element used as an invariant (suffix *i*) to assess the mobility of other elements (suffix *j*) in saprolites and soils is Zr. Indeed, Zr is present in zircon in the granitic rocks and their overlying weathered products, i.e. in an accessory mineral known for its high resistance to chemical weathering. The iso-element approach of Brimhall et al. (1991) requires the selection of a protore (suffix *p*), considered as chemically homogeneous and representative of the parent material for the overlying weathered (suffix *w*) saprolite and soil layers (average of the four rock samples). The relative loss or gain of a chemical element (*j*) in the investigated profiles were then determined from the mass balance factor (${}_{j,w}$) according to the following equation (Chadwick et al., 1990):

$${}_{j,w} = \frac{C_{j,w}/C_{i,w}}{C_{j,p}/C_{i,p}} - 1$$

In this equation, the mass balance factor is expressed independently of the volumetric strain (ε), related either to soil swelling or expansion (positive ε values) or soil shrinkage or collapse (negative ε values) during weathering processes. This mass balance factor corresponds to concentration ratios between a chemical element (*j*) and the chemical invariant (*i*) in a considered weathered material (*w*), as compared to its corresponding parent material (*p*), minus 1. The ratio of both elements in the protore (*p*) is a reference and thus assimilated to a constant. A mass balance factor smaller than 1 will then refers to a loss of chemical element (*j*), which is completed at ${}_{j,w}$ = O, whereas a mass balance factor greater than 1 will reveal a gain of the same element.

X-Ray diffraction and spectroscopic analyses

The mineralogical composition of clay and bulk samples was assessed by powder X Ray Diffraction (XRD) with a PHILLIPS PW 1730 using Co K radiation and operating at 40 kV and 30 mA at the Institut de Minéralogie et Physique des Milieux Condensés (IMPMC, Paris, France). XRD traces were collected for 2 angles ranging from 5 to 120° with a 0.02° steps and a counting time of 400s per step. Grounded powder samples (± 30 m) were prepared according to the technique of the "back pack-mounted slide” (Bish and Reynolds, 1989).

Identification of the mineral phases was carried out by comparing the experimental XRD traces with those from the mineral references of the ICDD data set.

FTIR spectroscopy was performed in the transmission mode using a Nicolet Magna 560 IR Spectrometer. One mg of oven-dried sample was mixed with 300 mg KBr and pressed at 10 $t.cm^{-2}$ to form a KBr disc. KBr discs were heated at 105°C overnight to remove absorbed water. Spectra were run in the 250 to 4000 cm^{-1} range with a 2 cm^{-1} resolution and normalized with sample exact weight.

Diffuse reflectance spectroscopy (DRS) was performed on bulk samples using a Cary 5G (US-VIS-NIR) spectrophotometer with a 100 mm-diameter integrating sphere coated with Halon (Labsphere, Inc., USA). Samples were gently ground (breakdown of the aggregates), overnight oven dried at 60° and filled into a 27 mm diameter and 2 mm thick hole of an Al holder without packing to minimize preferential orientation and specular reflection. An optically treated silica slide was used to cover the sample holder. Reflectance R was measured relative to a Halon standard. The spectra were run in the 200 to 2500 nm range with a 1 nm increment. The wavelength-dependent reflectance function was transformed into Kubelka-Munk remission functions by $f(R) = (1 - R)^2 / 2R$, which is proportional to the absorber concentration. The curves were smoothed using a cubic spline fitting procedure then the second derivatives were calculated (Malengreau et al., 1996). The nature and relative proportion of Fe-oxides (mostly goethite and hematite) were determined from the position and intensity of the optical transitions on the second-derivative curves calculated from f(R) (Kosmas et al., 1984).

Soil colour was quantified from the reflectance curves in the visible range (from 360 to 830 nm). The CIE tristimulus values (X, Y, Z) were computed from the spectral reflectance and energy of the light source for each wavelength using the colour matching functions of the CIE standard illuminant C (Wyszecki & Stiles, 1982). Tristimulus values were converted into colour units (x, y and Y%) of the CIE System (1931) and in those of the Helmholtz coordinates (L_d and P_e). They were ultimately plotted in the colour diagram of the visible range. In this diagram, the dominant wavelength (L_d) is the slope between the white light source and a given dot, and is related to the tint of the sample. The excitation purity (P_e) is equivalent to the chroma of the Munsell colour chart. It is scaled between 0 % for a colourless sample and 100 % for a pure colour monitored at the output of a monochromator (Bedidi et al., 1992).

3.4. Results

3.4.1. Vertical and lateral soil differentiation along the transect

Two sets of horizons are distinguished in the 5 soil profiles: (i) an approximately 2.3m thick soil cover (solum), strongly weathered and relatively homogeneous showing gradual changes of colour, texture and structure towards the depression and (ii) an underlying saprolite, slightly heterogeneous, less weathered and massive, which display abrupt changes of colour and then of texture towards the depression.

In the freely drained environment of the margin of the dissected plateau (P1), the regolith is clayey and intensively coloured by Fe-oxides. The thick massive saprolite (BC and C horizons) inherited from the weathering of granites of the Uaupés Suite (reached at 5m deep in P1) is clay loam to sandy clay loam and dominantly red. It exhibits slightly darker colours at the bottom of the saprolite due to the weathering of centrimetric mafic bodies of the granites. The transition with the overlying soil cover is progressive and mainly associated with (i) heavier sandy clay textures (decrease of the silt size fraction, predominantly made of clay minerals, and increase of the fine sand fraction with dominant quartz), (ii) more yellowish colours (yellowish red soils) likely due to greater amounts of goethite, and (iii) the development soil aggregates in B-horizons (mostly medium to fine blocky aggregates, with micropeds of biological origin). Towards the soil surface, the soil impregnated by the organic matter turns yellowish brown and becomes clay-depleted. Such changes thus mark at about 0.4m deep the second major transition between topsoil A-horizons and subsoil B-horizons. From the edge of the plateau (P1) to the margin of the podzolic area (5m upslope of latter in P5), the following morphological changes are reported (Fig. 2c).

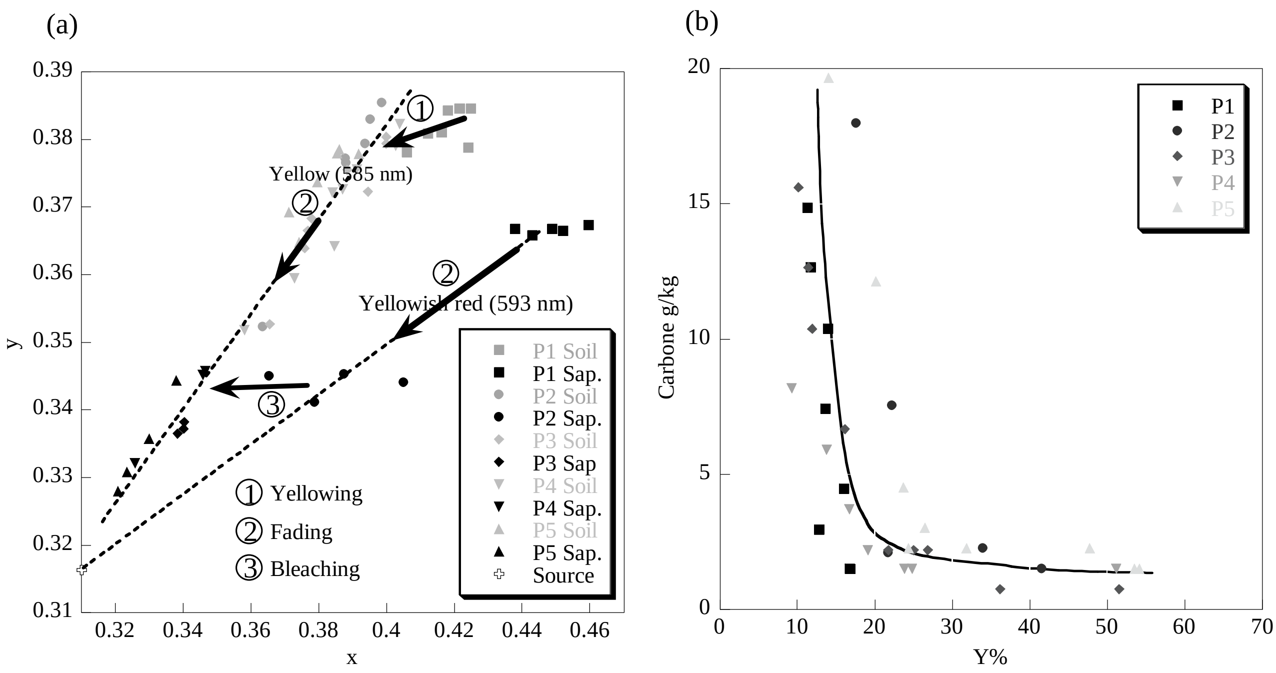


Figure 3*. (a) x and y values of the CIE System (1931) for soil (grey symbols) and saprolitic (black symbols) samples of the five profiles (P1 to P5) plotted in the visible colorimeric diagram, slope and distance from the CIE standard illuminant C (source: white cross) are used to calculate the dominant wavelength (L_d) and the excitation purity (P_e), respectively for each sample (Helmholtz coordinates), (b) Y% value of the CIE System (1931) versus total carbon content.*

In the upper soil cover, lateral changes are progressive but also slightly dissociated in space for colour and texture. From P1 to P2 and within the 2m thick B-horizons, soil colour grades from reddish-yellow to yellow whereas the soil texture remains almost unchanged (sandy clay). Such a soil yellowing is revealed on a colour diagram by a slight decrease of the dominant wavelength (L_d) that reaches an average value of 585nm in P2 (arrow 1 in Fig. 3a). Change of texture occurs later on and range from sandy clay in P1 and P2, to sandy clay loam in P3, sandy loam in P4 and loamy sand in P5 (Fig. 4a). This regular decrease of clay particles from P2 to P5 occurs without significant change of tint in B-horizons, but is closely associated with fader soil colours. On the colour diagram, this second colorimeric trend is related to equivalent dominant wavelength (average L_d of 585 nm) but to smaller values for excitation purity (P_e) (arrow 2 in Fig. 3a).

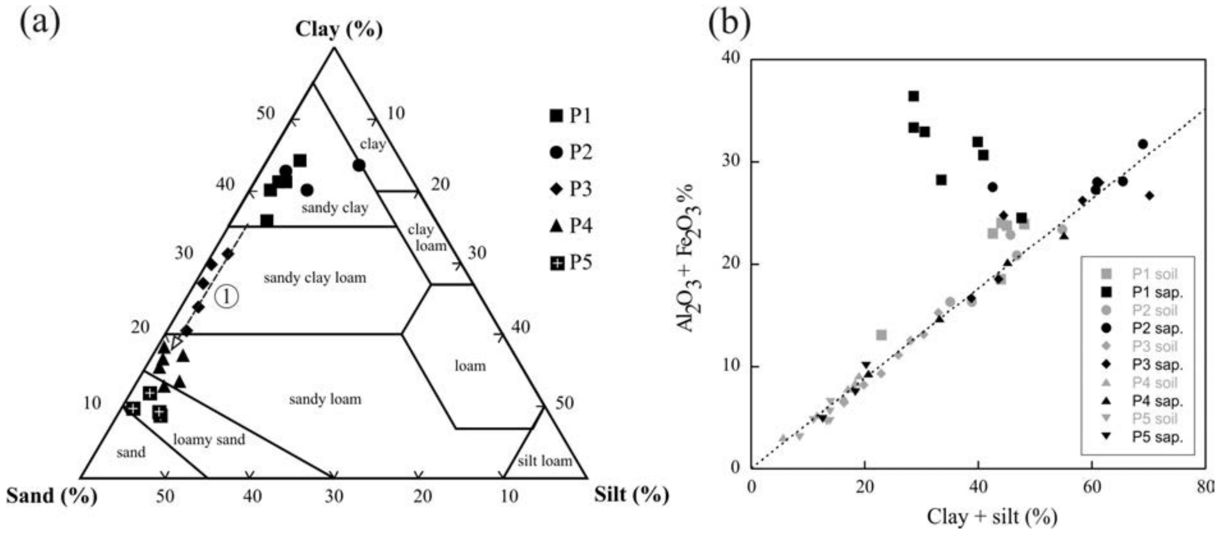


Figure 4*. (a) Ternary representation of the percentage of clay, silt and sand in soil samples of the B-horizons from the five profiles (P1 to P5) with corresponding soil texture classification, showing the gradual loss of fine clay minerals towards the depression (arrow 1), (b) positive correlation between the amount of clay + silt (< 50µm) weight % determined from particle-size extractions and the amount of clay minerals assessed from the Al_2O_3 + Fe_2O_3 % in bulk samples (negative correlation for P1).*

Losses of fine particles is also linked laterally in the soil cover to soil structure breakdown and to changes in mineral assemblage on thin sections between coarse primary minerals (mostly quartz) and finer secondary clay minerals (mainly kaolinite and goethite), as already discussed in Fritsch et al. (1989) for a soil catena of western Africa at the transition between forest and savannah. Indeed, soil structure tends to exhibit a greater range of aggregate size in P3 and P4 than in P1 and P2 and to become massive in P5. Concomitantly on thin sections (not shown), the assemblage between primary and secondary minerals (Brewer, 1964) is (i) dense with numerous, well-defined, thin cracks (porphyrosquelic) in P1 and P2 (Clay% > 35), (ii) less dense with larger and ramified macro-voids delineating soil matrix aggregates of various sizes (agglomerplasmic) in P3 and P4 (15 < Clay% < 35), and (iii) more open and porous with almost adjacent quartz grains and clay bridges between some of them (intertextic) in P5 (5 < Clay% < 15). The more macro-porous and compact assemblage of quartz sands (granular), linked to an almost total loss of clay particles (Clay% < 5), was not reached as it mostly characterizes the eluviated E horizons of podzols (out of the selected zone for this study). Accordingly, the selective but continuous loss of matter leads in a first stage to soil structure breakdown that most likely should reduce soil permeability and in a second step to a gradual increase in macro-voids between quartz grains, that become closer and closer, thus increasing in return water fluxes in soils (Fritsch et al., 1989; Bruand et al., 1990).

In the underlying clay loam to sandy clay loam saprolite, lateral changes of colour and texture are more abrupt and neatly dissociated along the transect. Redder colours as compared to the overlying soils are at first noted in the freely drained saprolite of the plateau edge, as illustrated on figure 3a by higher wavelengths (L_d), with an average value of 593nm in both P1 and P2. However, the saprolites also exhibit fainter reddish colours in P2 than in P1 (decrease of the excitation purity P_e, arrow 2 in Fig. 3a). They also display bleached mottles or layers at different depths that become more and more abundant from P2 to P4 (see also arrow 3 in Fig. 3a). Veins of kaolin were also found at depth in bleached saprolites of P4. In P5 and close to the downslope podzolic area of the depression, the saprolite is completely bleached and its upper part is also strongly depleted in fine particles. The groundwater table reached the clay-depleted area of the saprolite during the dry season (e.g. at 2.4m the 15th of November 2006).

3.4.2. Geochemistry of major and trace elements

Major elements (Si, Al, Fe, Na, K, Ca and Mg) and Zr

All five profiles are strongly depleted in base cations (Na, Ca, K and Mg) as the mass balance factor ($_{j,w}$) calculated in the whole regolith, using Zr as an invariant, is almost nil for each of these highly mobile chemical element (not shown), with the exception of the bottom part of the saprolite only reached in P1. This suggests the almost total weathering of the feldspars (albite, anorthite and microcline) and ferromagnesiens (biotite and amphibole) inherited from the bedrock (see also the average chemical composition of these primary minerals and that of the granite in Tab. 1). Petrographic observations confirm the disappearance of these primary minerals in the regolith. Moreover, the extremely low CEC (< 10 cmolc/dm^3) and base cation saturation of the exchangeable sites (<4%), predominantly occupied by Al^{3+} and H^+, thus pertains to low activity clay soils specific to laterites and confirm the strong leaching conditions, which have prevailed in both soils and saprolites.

The amounts of total Al and Fe also vary vertically and laterally according to major morphological patterns. Firstly, the total amounts of clay plus silt in both soils and saprolites is positively correlated to the Al_2O_3 + Fe_2O_3 content (Fig. 4b) and negatively correlated to the SiO_2 content, excepted in P1 due to the occurrence in the sand fractions of small nodules of gibbsite. This indicates that most of the clay minerals (i.e. kaolinite and Fe-oxides) is in particle-size fractions smaller than 50µm. As we previously reported greater amounts of silt in

saprolites than in soils, we then conclude to the occurrence kaolinite populations of larger particle size at depth than close to the surface. At the margin of the plateau in P1, the total amounts of Al_2O_3 (Fig. 5a) but also of Fe_2O_3 (Fig. 5b) tend to decrease vertically upwards from saprolites to soils. The reverse trend is reported for Zr (Fig. 5c), the less mobile chemical element of these regoliths. Accordingly decreasing size of clay minerals from saprolites to soils seems also to be link to loss of these secondary minerals, and consequently to a residual accumulation of the more resistant primary minerals to chemical weathering, i.e. predominantly quartz but also accessory minerals, such as zircon.

From the plateau edge to the margin of the depression, the amounts of clay minerals assessed predominantly by the Al_2O_3 content remain almost unchanged in the soils from P1 to P2, and then decrease gradually from P2 to P5 (arrow 1 in Fig. 5a). These amounts are much higher in saprolites than in soils from P1 to P4 and then decrease abruptly in P5 (arrow 2 in Fig. 5a). As already reported from textural data, two clay-depleted zones are reported downslope close to the podzolic area (arrows 1 and 2 for P5 in Fig. 5a). In the deeper clay depleted one of P5 (arrow 2 in Fig. 5a), loss of clay minerals is also linked to an important loss of Zr (arrow 2 in Fig. 5c, note that the Zr values are there lower than that in the bedrock, materialized by a vertical dashed line on the figure). This likely indicates physical transfer and loss of zircon, of mostly silt particle size, due to the development of macro-voids in clay-depleted saprolite and abundant lateral fluxes in groundwater. As a matter of fact, Zr can no longer be used as a chemical invariant in such a place. The amounts of Fe-oxides, assessed by the Fe_2O_3 content, decrease laterally in soils, from P1 to P5 (arrow 1 in Fig. 5b). In the underlying saprolite, it decreases significantly from P1 to P2 that exhibits faint reddish yellow colours and reaches smallest values further downslope in bleached saprolites (from P3 to P5) (arrow 2 in Fig. 5b). Mass balance factor calculation ($_{j,w}$) confirms the vertical losses of Al and Fe from saprolites to soils on the plateau edge (Fig. 5d and e). Losses increase laterally towards the depression (from P1 to P5). Mass balance factors also show that 60% of the initial stock of Si from the bedrock is lost in saprolites following the dissolution of primary minerals (mostly feldspars and ferromagnesians) and the neoformation of clay minerals (Fig. 5f). In the overlying soils, Si losses slightly increase (arrow in Fig. 5f), likely due to greater dissolution rates of secondary minerals.

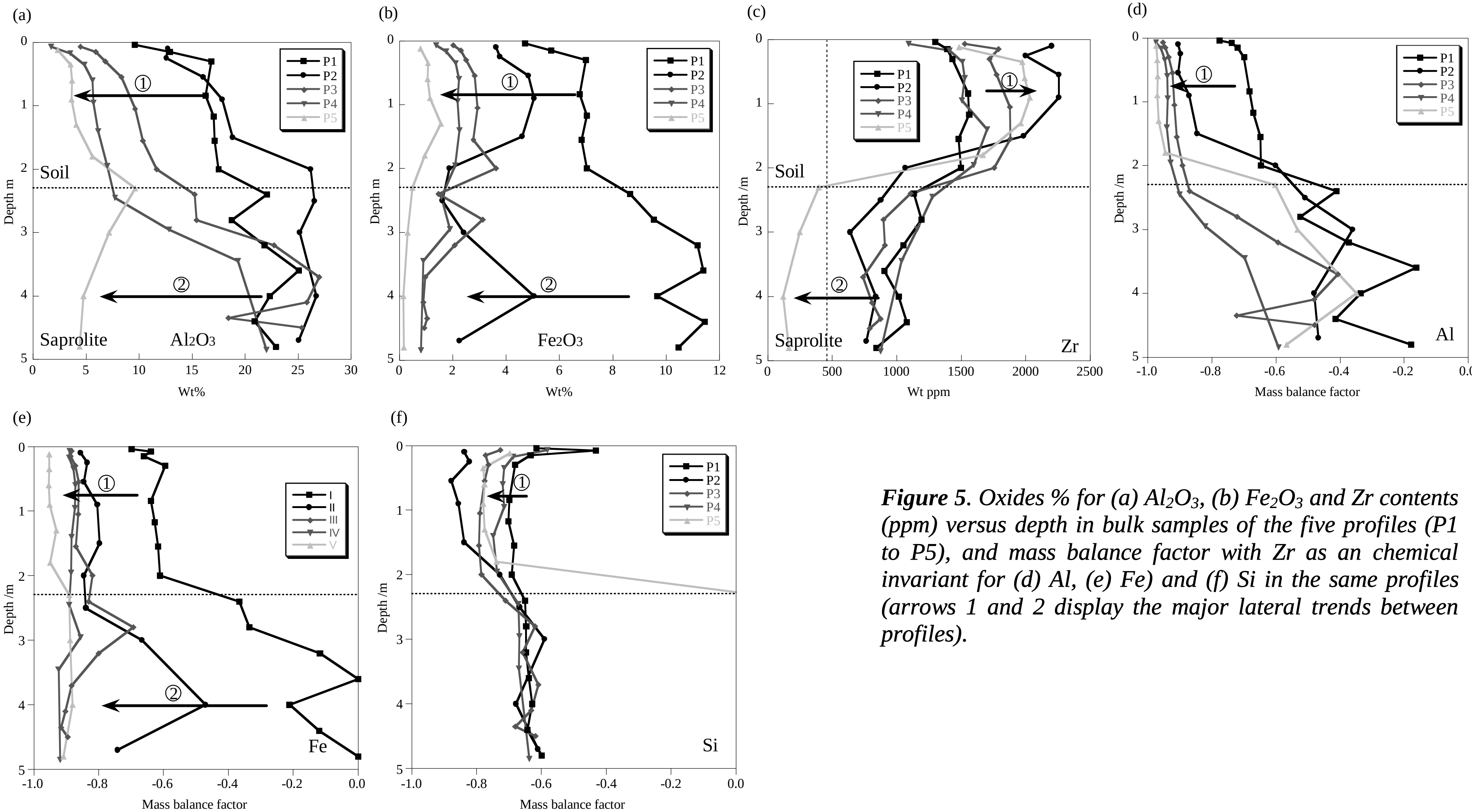


***Figure 5**. Oxides % for (a) Al_2O_3, (b) Fe_2O_3 and Zr contents (ppm) versus depth in bulk samples of the five profiles (P1 to P5), and mass balance factor with Zr as an chemical invariant for (d) Al, (e) Fe) and (f) Si in the same profiles (arrows 1 and 2 display the major lateral trends between profiles).*

The relative loss of Fe as compared to Al appears quite different in soils and saprolites, as illustrated by the Al_2O_3/Fe_2O_3 ratio as a function of the Zr content for all samples (Fig. 6). On the plateau edge in P1, the Al_2O_3/Fe_2O_3 ratio is equivalent in both saprolites and soils, indicating therefore an upward residual accumulation of both Al and Fe. Towards the depression from P2 to P5, this ratio also remains almost unchanged in soils. Al and Fe are thus exported simultaneously either by chemical erosion or physical transport. However the ratio increases slightly from the bottom to the top of each profile suggesting a greater dissolution of Fe-oxides than kaolinites. This trend is strongly amplified in bleached areas of the underlying saprolites thus indicating a massive dissolution of Fe-oxides.

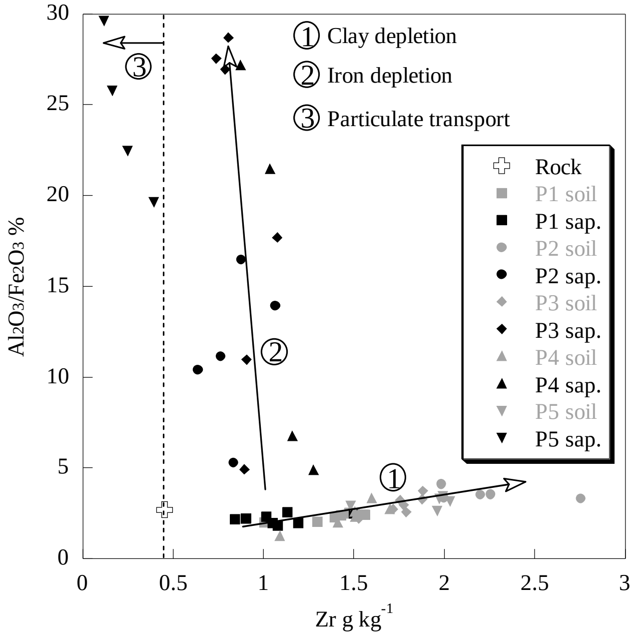


***Figure 6**. Al_2O_3/Fe_2O_3 ratios of bulk samples in the five profiles (P1 to P5), showing the pathways for clay depletion, selective iron depletion and particle transport (1, 2 and 3 respectively in the figure) in soils (grey symbols) and saprolites (black symbols).*

Accessory elements (Ti, P, La, Ce, Yb, Th, U and Pb)

Accessory elements enable to distinguished saprolites from soils, as well as freely drained environment (P1 and P2), from more hydrated or waterlogged ones (from P3 to P5). The more abundant accessory element, Ti (up to 2.5% of TiO_2), is about half lost in saprolite according to mass-balance calculations (Fig. 7a). Petrographic observations (not shown) and electron punctual microprobe analyses (EPMA) (Tab. 1) relate Ti losses to the weathering of titanite crystals that surround opaque minerals (mostly poorly weathered magnetite) from rich-mafic

clots in the mafic-bearing granites. Such losses increase upwards and become stabilized in soils following the complete weathering of titanite. The remaining Ti in soils belongs to primary rutile and secondary anatase from XRD (not shown), and represents about 40% of the initial stock of Ti in P1 and 20% in the other profiles (Fig. 7a).

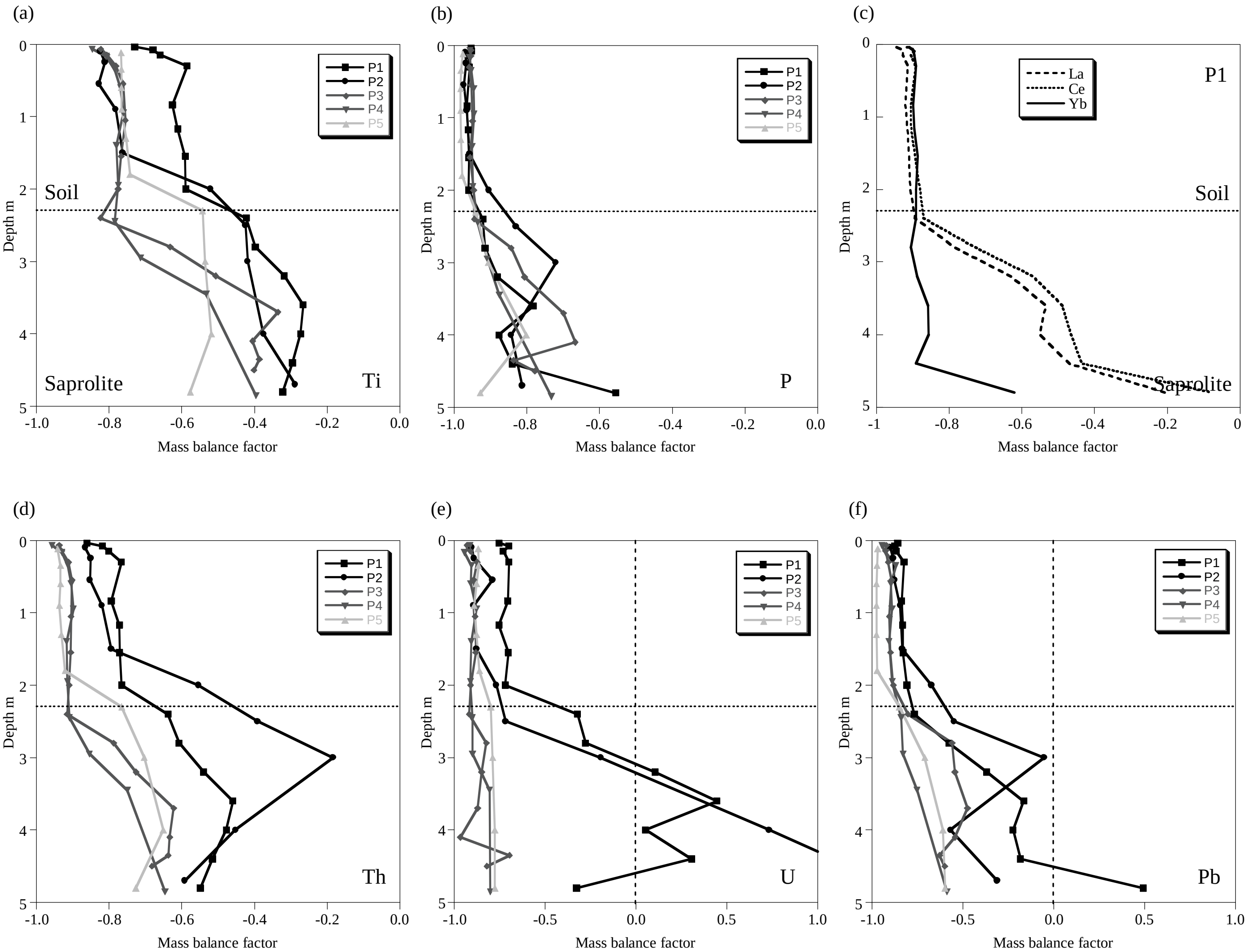


Figure 7*. Mass balance factors versus depth for (a) Ti, (b) P in the five profiles (P1 to P5), for LEE (La and Ce) and HEE (Yb) in P1, and for (d) Th, (e) U, and (f) Pb in the five profiles (horizontal dashed line demarcates the saprolite from the overlying soil and the vertical dashed line relates to no loss or gain of chemical elements).*

Although present in much less quantities in the bedrock (Tab. 1), the phosphorous (P) and light earth elements (LEE) exhibit similar trends upward in saprolites and soils. Losses of P (Fig. 7b) and LEE (see La and Ce in Fig. 7c) are mainly attributed to the weathering of apatite and allanite crystals, respectively according to EPMA (Tab. 1). Phosphorous is almost completely lost in soils following the complete disappearance of apatite crystals. By contrast,

about 10% of the initial stock of LEE in preserved in soils. Heavy earth elements (HEE) behave differently than LEE in saprolites. They are more rapidly lost likely due to their incorporation in more easily weatherable minerals (see Yb in Fig. 7c).

Three other trace elements (Th, U and Pb) also display similar trends that however differ significantly from the plateau edge to the margin of the depression (i.e. from P1 to P5). Actinides in these lateritic regoliths are most likely incorporated in zircon (Balan et al., 2005) but also in apatite and allanite (occurrence of fission tracks in the surrounding primary minerals of the granite). The upward losses of Th (Fig. 7d), U (Fig. 7e) but also of Pb (Fig. 7f) is likely due to the opening of the decay chains of Th and U during the weathering of apatite and allanite. However, U and Pb behave differently between freely drained (P1 and P2) and poorly drained environments (P3 to P5). In P1 and P2, losses of both elements in soils are linked to gains of the same elements at depth (positive values are locally obtained for mass balance factors in saprolites). By contrast, this kind of vertical transfer does not occur from P3 to P5. Indeed, greater losses of both elements are reported in bleached saprolites and consequently smaller losses upward in soils. This confirms the downward accumulation of actinides in freely drained, red lateritic profiles and the contribution of Fe-oxides in the storage of these elements at depth (P1 and P2). The quite specific chemical behavior assigned to these accessory chemical elements during the vertical development of the lateritic regoliths must be linked to the occurrence of mafic bodies in the granitic rock basement of the transect.

3.4.3. Mineralogy of clay minerals

DRX (not shown) and spectroscopic data in the infra red (FTIR) and visible (DRS) ranges reveal a quite monotonous mineral composition for clay minerals (mostly kaolinite, gibbsite, hematite and goethite as secondary minerals and residual magnetite as primary mineral) but a high variability in the proportions of these minerals from bottom to top of the regolith and from the plateau edge to the margin of the depression in bulk samples of both soils and saprolites (Figs. 8 and 9). The changes in the proportion of the Al-bearing minerals (kaolinite and gibbsite) are assessed from FTIR (Fig. 8), whereas those of the Fe-oxides (hematite, goethite and magnetite) are deduced from second-derivative spectra - SDS (Fig. 9).

Al-bearing minerals (kaolinite and gibbsite)

The redder lateritic profile from the edge of the dissected plateau (P1) is easily differentiated from the other profiles (P2 to P5) by the much larger quantities of gibbsite in the pool of Al-bearing minerals. In this profile (Fig. 8a), the largest contents of gibbsite are reported in the saprolite, more specifically in the lower section of this layer and at different depths. In particular, Al hydroxides are almost exclusive at 3.6 and 4.8m deep. In the overlying soils, the relative proportion of kaolinite increases significantly and becomes nearly as abundant as gibbsite.

The reverse trend is observed towards the depression with dominant kaolinite in more yellowish soils and in the underlying faint red to bleached saprolites (i.e. from P2 to P5). Gibbsite is mainly observed in the soils, more specifically in their lower sections and is barely detectable in the underlying bleached and waterlogged saprolites (depths > 2.5m in Figs. 8b, c and d). According to such trends, the longer periods of episodic (soils) or more permanent (saprolites) water saturation in regoliths seem to restrict the formation of gibbsite. The vertical trends in profiles also suggest the downward accumulated of gibbsite following the dissolution of kaolinite in overlying regolith compartments. This vertical transfer of Al and precipitation of Al hydroxides is likely limited (hardly detected by mass balance factors) but slightly enhanced by textural discontinuities, in particular just above the rock/saprolite transition in freely drained environments (P1), and closer from the soil surface at the soil/saprolite transition in poorly drained environments (from P2 to P5). The upward depletion of clay minerals in soils and towards the depression is linked to simultaneous collapse of the OH vibration bands for both kaolinite and gibbsite (Figs. 8b, c and d).

In the dominant kaolinitic and poorly drained area of the transect (e.g. from P3 to P5 in Figs 8b, c and d), the high resolution of the two internal bands (3668 and 3652 cm^{-1}) for the out-of-phase motion modes of inner-surface OH groups reveal low defect kaolinites (Balan et al., 2001). Defect in kaolinites are better observed in normalised spectra, as larger crystallographic disorder are mainly linked to significant changes in the two internal bands, with a decrease of the magnitude of the band at 3668 cm^{-1} and a broader and intense band centred at 3650 cm-1 (Balan et al., 2005). Normalised spectra (not shown) reveal weak crystallographic changes both vertically and laterally along the transect. The well-ordered kaolinites always occur in saprolites, more specifically at different depths in P3 and P4 (kaolins, see for instance 3.9m deep for P4 in Fig. 8c). Disorder in kaolinites can increase slightly in the overlying soils (for example in P3 and P4), but always remains limited. This

strongly differs from other lateritic profiles of the Manaus region, where lateritic soils mostly consist of high defect kaolinites (Balan et al., 2005).

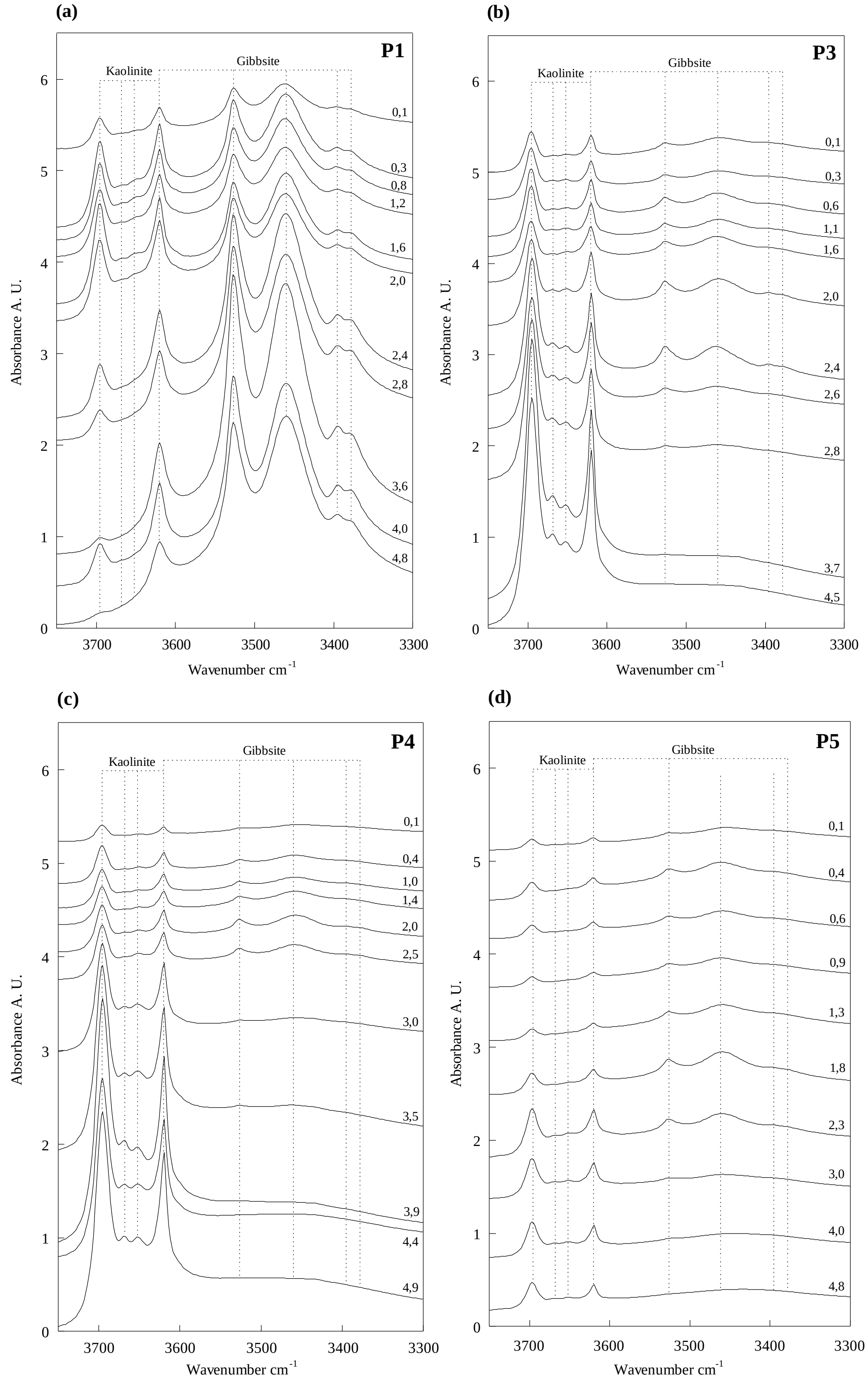


Figure 8*. FTIR spectra in the OH stretching region showing the four characteristic bands of kaolinite (3695, 3668, 3652 and 3620 cm^{-1}) and the five bands for gibbsite at lower*

wavenumbers (3620, 3527, 3460, 3395 and 3378 cm^{-1}), as well as changes in the intensity of the bands (or proportion of these Al-bearing minerals) in bulk samples of profiles (a) P1, (b) P3, (c) P4, and (d) P5 (P2 is not presented as it displays similar FTIR spectra than P3).

Fe-oxides (hematite, goethite and residual magnetite)

Major colorimeric changes observed both vertically and laterally at the border of the dissected plateau (from P1 to P2), are related to contrasted changes in the contents of hematite (Hm) and goethite (Gt) (Fig. 9). The proportion of hematite is much larger in saprolites than in the overlying soils, but also decreases significantly in saprolites from P1 to P2 (Figs. 9a and b). On this regards, the assignment of the three major bands for Hm and Gt are related to minima on the second derivative of the remission functions. In the saprolites, the low contents of Hm and Gt assessed by DRS, as compared to the amount of total Fe determined by chemical analyses, indicate large proportions of magnetite, which are easily recognized on thin sections. Upward in profiles P1 and P2, the amount of hematite decreases slightly and that of goethite increase strongly (Figs. 9d and e). Simultaneously the content of magnetite decreases drastically, more specifically in P1 (Fig. 9d). Accordingly, the intense weathering of magnetite in soils contributes largely to the formation of goethite. However, hematite to some extend seems also to contribute to the formation of goethite through dissolution/cristallisation cycles, as already proposed by Fritsch et al. (2005) in other lateritic profiles.

From the margin to the center of the plateau, yellowing in soils is at frist related to significant losses of Hm (from P1 to P2, Figs. 9a and b) and fading to losses of the remaining Gt (from P2 to P5, Figs. 9b and c, see also Figs 9e, f, g and h). Bleaching in saprolites is mostly assigned to the disappearance of both hematite and goethite (Fig. 9c, see also Figs 9f, g and h).

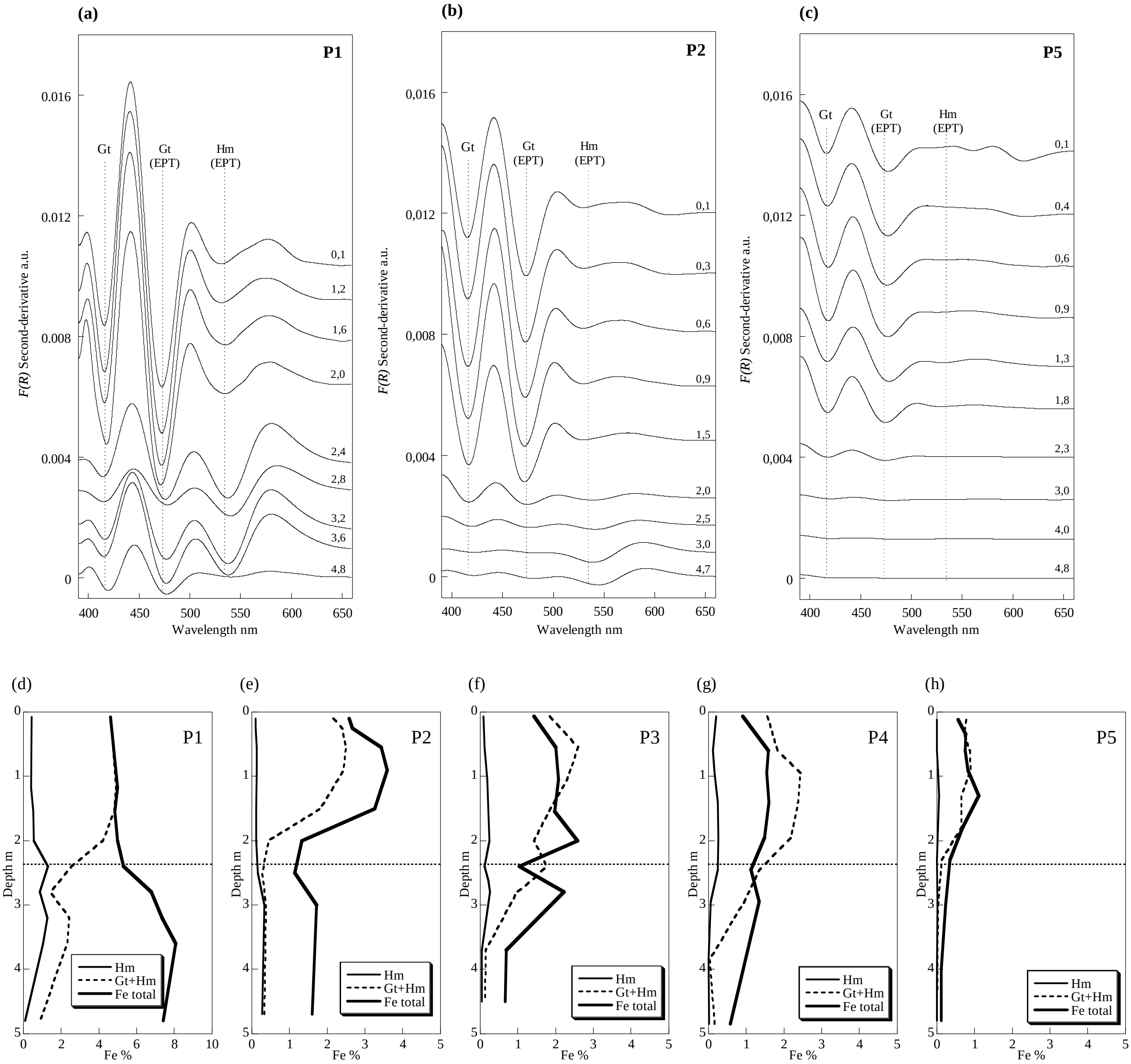


Figure 9. *Second-derivative spectra of the remission function f(R) (DRS) showing the absorption bands (minima) for goethite (Gt) and hematite (Hm) in selected bulk samples from (a) P1, (b) P2 and (c) P5 and assessment of the relative proportion of hematite (Hm,), goethite and magnetite (determined indirectly) from DRS and total chemical analyses in (d) P1, (e) P2, (f) P3, (g) P4, and (h) P5 (horizontal dashed line demarcates the saprolite from the overlying soil).*

3.5. Discussion and conclusions

The study enables to establish major geochemical and mineralogical changes in the vertical differentiation of lateritic profiles from (titanite)-(amphibole)-biotite granites of the margin of the Guyana Shield. It also enables to establish selective geochemical and physical erosion trends in their lateral transformation following the incision of *Ucayali* peneplain surface by the modern Amazon drainage system. River incision formed the low elevation plateaus of the upper Amazon Basin. In this kind of humid tropical landscape, the freely drained conditions favourable to the vertical development of red clayey laterites are preserved on the edges of the plateaus. They mainly result from the incision of the plateau edges by numerous tributaries of river systems. By contrast, poorly drained conditions have settled in the central parts of the plateaus and have likely increased in space and time. They have enhanced the lateral and internal erosion of laterites, generated depressions and prepared their ultimate transformation into highly degraded and waterlogged podzols. In the study site, the lack of sedimentary structures in regoliths from the edge to the centre of the plateaus then assigns the geochemical and physical erosion of laterites to yellowing in soils, bleaching in saprolites, as well as to an ultimate depletion of clay minerals in both kinds of compartments.

On the edges of the plateaus, lateritisation has led to complete depletion of base cations and partial loss of silica at the bottom of deeply weathered profiles and therefore to residual accumulation of Al and Fe in secondary minerals (kaolinite, gibbsite, goethite and hematite) following the complete dissolution of major primary minerals of the granites of the Uaupés Suite (mostly feldspars, biotites and amphiboles). The occurrence in these granites of pegmatites and mineralised zones have also generated differential chemical weathering processes and led to specific geochemical signatures in regoliths. Accessory minerals of the mafic-bearing granites, more resistant to chemical weathering, are indeed partly preserved in the overlying regoliths. They mostly consist of titanite, apatite, allanite, and magnetite, which are particularly rich in Fe, Ti, Ca, P, LEE and actinides.

As commonly reported in the tropics, lateritisation is a two-step process that first leads to the vertical development of thick saprolites and ultimately to the accumulation of more intensively weathered, bioturbated and aggregated products in soils (Gombeer and D'Hoore, 1971; Nahon, 1991; Tardy, 1993; Fritsch et al., 2002; Balan et al. 2005). The second weathering step frequently marks greater losses of chemical elements as well as relevant changes in the proportion and nature of primary and secondary minerals. In other deeply weathered lateritic profiles of the Amazon basin, these changes were mostly assigned to

decreasing size and increasing crystal disorder in populations of kaolinites, suggesting alternate dissolution - recrystallisation steps leading to residual accumulation of small and poorly ordered soil kaolinites (Balan et al., 2005). Changes in the nature and Al substitution rates of Fe-oxides were also reported upwards in these soils (Fritsch et al., 2005). In our study site, the upward transition between saprolites and soils also marks a decrease in the particle size of kaolinites, but is not linked to relevant changes in the crystal order of kaolinites. Indeed, low defect kaolinites in saprolites remains weakly altered upward in soils. By contrast, the transition also results in an intense weathering of the accessory mineral remnants inherited from the mafic bodies. In particular, it marks the complete disappearance of titanite, apatite and allanite, as well as the ultimate dissolution of magnetite that feeds the pool of secondary Fe-oxides (i.e. hematite and goethite) in soils.

The freely drained conditions prevailing at the margin of the plateaus also favour the crystallisation of hematite over goethite, as well as that of gibbsite over kaolinite, more specifically at depth in the highly porous saprolite. The larger amount of gibbsite at depth could also result from the downward accumulation of Al following the dissolution of kaolinite in the overlying soil compartment with however a global loss of this element to the rivers as pointed by mass balance factor calculations. This downward transfer of matter in oxic environments also affects actinides, which accumulate significantly at depth in iron-rich saprolites. The larger amounts of kaolinite and goethite in the overlying soil likely result from denser and less permeable materials, which are finely divided and more frequently and durably hydrated by rainfalls. This trend is enhanced laterally, illustrating therefore longer periods of hydration in soils or waterlogging in saprolites from the margin to the centre of plateaus. However, small quantities of gibbsite may still be produced and accumulated downward at the transition between soils and saprolite.

We also recognised two distinct compartments (soils and saprolites) subject to significant losses of matter from the plateau edge to the margin of depression. The first one corresponds to unsaturated soils that average 2.3m of thickness in our investigated site. In this upper compartment, losses of matter are progressive in space and probably slow in time. They are most likely linked to selective dissolution of clay minerals and soil leaching, which could result from increasing periods of soil wetting towards the depression of the plateau, particularly during the rainy season. In this soil compartment, losses of matter are at first limited. They are mostly assigned to selective dissolution of Fe-oxides, particularly hematite, and therefore related in the field to soil yellowing (e.g. Peterschmitt et al., 1996). This

chemical erosion is closely followed by the weathering of the remaining clay minerals (i.e. goethite and kaolinite) and thus to clay depletion and soil fading (Fritsch et al., 1989; Chauvel et al., 1977, Chauvel & Pedro, 1978). By contrast, losses of matter are more abrupt at two distinct places in the underlying saprolitic compartment. They are first related to the complete removal of secondary Fe-oxides (i.e. hematite and goethite) and therefore to bleaching under the action of the groundwater. They enable to differentiate in saprolites the saturated zone from the unsaturated one at higher elevations. Further downslope and at the margin of the depression, groundwater dynamics may also lead to depletion of fine clay particles in the upper part of the bleached saprolite, likely due to greater lateral water fluxes.

Losses of matter change the type of assemblage (from compact to granular) between coarse primary minerals (mostly quartz) and finer secondary clay minerals. These textural changes induce the development of macro-voids between quartz grains (Fritsch et al., 1989), which favour the transfer of fine particles (mostly clay but also silt) during gravity flows (Bruand et al., 1990). This leads us to suggest that chemical erosion (lixiviation) with preferential dissolution of F-oxides could at first prevailed in sandy clay to sandy clay loam soil horizons and favour particle dispersion and soil structure breakdown. Later on, the development of interconnected macro-voids in sandy loam to loamy sand horizons would also favours the transfer of suspended fine particles (first clay then silt) during lateral water flows and the formation of eluviated compartments and close to major groundwater reservoirs (Bocquier, 1971; Boulet, 1974; Fritsch et al.,1990a, 1990b; Bravard and Righi, 1990; Lucas et al., 1996).

Losses of matter in the unsaturated topsoils and at greater depth in the waterlogged saprolites lead to the formation of a highly porous eluvial compartment that clearly displays a double tongue-like shape transition towards upslope positions. The abundant and interconnected macro-voids produced in this compartment enable the downward migration of humic substances in soils, their accumulation at depth and at the margin of the depression in clay-depleted laterites. This accumulation of organic matter in less permeable materials tends to waterproof the periphery of the eluvial compartment thus favouring the implementation of a perched groundwater in newly formed podzols, which are widely spread in the region. The study thus reveals that yellowing, bleaching and losses of clay minerals in soils and saprolites are preliminary steps to podzolisation. It also points out that the characteristic and spectacular double tongue-like shape transition, which demarcates the upslope clay-depleted laterites from the downslope podzols, has been acquired before the transfer of organic substances, by chemical and physical erosion and according to major hydraulic fluxes in regoliths.

Acknowledgements

The research was funded by CAPES-COFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l'Univers du CNRS), through the "Ecosphère continentale" programme: "Podzolisation des latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)".

CAPITULO 4. PODZOLIZAÇÃO DOS SOLOS LATERÍTICOS E INCISÃO DOS PODZÓIS HIDROMÓRFICOS NO ALTO RIO NEGRO

Résumé

Le chapitre présente les résultats d'une étude minéralogique et structurale d'une séquence de sols développés sur les granites de la formation Uaupés de la région de São Gabriel da Cachoeira, à la bordure des aires fortement podzolisées du bassin versant du Curicuriari (site 4). Ce bassin versant, podzolisé sur prêt de 95% de sa superficie, présente des eaux noires et des sables blancs dans les lits de ses principaux tributaires, attribués à l'érosion physique des podzols. Appartenant aux vastes pénéplaines podzolisées et inondées d'une surface d'érosion, la séquence débute sur une colline résiduelle à latérite et se termine dans un bas de versant convexe résultant d'une incision d'un tributaire du Curicuriari. Le long de cette séquence de 80m de long, six tranchées de sols et d'altérites ont été ouvertes, décrites et échantillonnées. L'étude intègre des caractérisations pétrographiques, minéralogiques (DRX, IRTF et DRS), géochimiques et des calculs des fonctions de transfert (éléments majeurs et en trace). Dans un premier temps, l'étude vise à établir les analogies minéralogiques et structurales par rapport à ce qui a déjà été révélé dans les environnements podzoliques peu incisés de la région du Jaú (site 3). Les principales différences entre sites (3) et (4) sont abordées dans un second temps. Elles nous conduisent à traiter des effets des incisions du réseau hydrographique sur la morphologie et géochimie des podzols et donc des interactions entre podzolisation et incisions en relation avec la dynamique des nappes dans les paysages.

De grandes analogies sont révélées entre les deux sites d'étude ce qui laisse présager d'une grande similitude de processus et de fonctionnement dans la mise en place de ces podzols. La plus importante est la reconnaissance des mêmes ensembles structuraux, avec les sols jaunes appauvris surmontant les ensembles hydromorphes, essentiellement saprolitiques, des laterites de l'amont et les aires podzoliques de l'aval. L'autre analogie de grande importance, qui a toujours été reconnue lors d'étude de séquence de sols en Amazonie, est la transition latérale en forme de "double langue" entre laterites et podzols. La langue supérieure témoigne d'un développement de podzols faiblement différenciés sur les latérites (horizons éluviés surmontant un horizon spodique Bhs). Plus à l'aval, la base de podzols mieux différenciés repose en profondeur sur les saprolites hydromorphes des latérites. Elle se prolonge à l'amont dans la partie supérieure hydromorphe des latérites formant ainsi la seconde langue inférieure de la transition (cette dernière peut correspondre en 3D à des chenaux remontant le versant sur plus de 15m). Cette connexion témoigne de ce fait d'interactions entre deux systèmes de nappe : (i) une nappe phréatique à eaux claires pour les latérites amonts et (ii) une nappe perchée à eaux noires dans les horizons sableux des podzols. Ces distributions relatives montrent également le contrôle des discontinuités structurales (dans le cas de l'étude entre sol et saprolite) dans le développement vertical des podzols et sa contribution dans la différentiation des horizons spodiques. En effet, la discontinuité sol-saprolite limite le développement vertical des podzols et favorise à l'inverse son expansion latérale dans les paysages. Par ailleurs, l'horizon Bh s'individualise à la base ou périphérie des réservoirs sableux des podzols et l'horizon BCs dans la partie supérieure des saprolites hydromorphes sous jacentes. Les accumulations absolues de matières organiques dans les horizons spodiques des podzols réduisent la porosité de ces matériaux et assurent de ce fait la mise en charge de la nappe perchée. Des reliques de matériaux latéritiques imprégnées par la matière organique dans les aires podzoliques aval montrent également que le précèdent équilibre entre structures et fonctionnement de nappe est précaire et que ces systèmes podzoliques peuvent se développer assez brutalement vers l'amont.

De grandes analogies minérales et géochimiques sont également établies entre les deux sites. Les latérites jaunes appauvries de l'amont sont dominées par le quartz mais aussi par des phases minérales résiduelles, essentiellement de la kaolinite mais aussi de la gibbsite et goethite. L'étude montre aussi, et d'une façon plus claire que dans celle du Jaú, que l'enrichissement en gibbsite dans le niveau saprolitique sous-jacent (essentiellement dans sa partie supérieure) est relié à une baisse des teneurs en kaolinite et que cette gibbsitisation bien

marquée à l'amont de la séquence tend à s'estomper vers l'aval. Ces évolutions minéralogiques ne vont pas sans rappeler notre précédente étude sur la pré-podzolisation et confirment de ce fait qu'elles soient bien antérieures à la podzolisation. Le calcul des fonctions de transfert révèle pour les éléments majeurs et en trace une altération latéritique dominante couplée à une perte considérable de matières (essentiellement en Al, Si et Fe) qui est attribuée en grande majorité à un appauvrissement de ces sols en minéraux argileux. Ces calculs montrent également que cet appauvrissement a affecté la partie supérieure et la plus altérée du niveau saprolitique. Ce dernier a de ce fait été scindé en une saprolite fine très altérée et appauvrie, surmontant une saprolite plus grossière, moins altérée (grains de microcline, anorthite, amphibolite) et non appauvrie. Si les pertes attribuées à la podzolisation restent minimes (moins de 12% de l'Al total et 5% du Fe total de la roche), elles n'en demeurent pas moins significatives. L'étude montre aussi l'importance non négligeable du transport particulaire dans ces pertes de matières en environnement podzolique ou pré-podzolique. Dans les horizons sableux blanchis, les plus poreux des podzols, nous révélons ainsi une perte significative en éléments traces (surtout Ti et Th, mais aussi Zr à l'aval de la séquence), présents dans des phases minérales réputés stables et difficilement altérables (rutile, anatase, thorianite, zircon…). Ces éléments se retrouvent accumulés dans les horizons spodiques sous-jacents (Ti plutôt dans Bh et Th plus en profondeur dans BCs). Ces accumulations absolues pourraient résulter de la formation et du transfert vertical de complexes organo-métalliques (comme pour Al et Fe). Toutefois, elles ont pu être reliées pour l'un d'entre eux (Ti) à un accroissement très important des phases minérales porteuses de l'élément considéré (anatase), confirmant de ce faite le transfert de particules de la taille des argiles (<2 µm) dans les podzols. Ce transfert d'éléments fins est confirmé plus à l'amont par la présence de revêtements argileux (cutanes) dans les horizons blanchis et appauvris (Bg) du sommet du réservoir de la nappe phréatique des latérites. Enfin et comme dans la séquence du Jaú, l'accumulation de substances organiques dans les horizons spodiques des podzols peu différenciés (Bhs), ou plus en profondeur de ceux de podzols mieux différenciés (Bh et BCs), est couplée à une accumulation de métaux, qui s'observe aussi à plus grande profondeur pour Al (dans Bhs et BCs) que pour Fe (essentiellement dans Bh).

Les podzols incisés de cette site (4) présentent des différences notoires par rapport à ceux étudiés antérieurement au Jaú (Site 3) dans des dépressions. Ces différences s'observent à deux niveaux : (i) à l'amont au niveau des fronts latéraux de podzolisation, soulignés en surface par un léger affaissement topographique, et (ii) à l'aval des versants qui acquiert alors

une forme convexe du faite d'une érosion régressive par les rivières. A l'amont, les accumulations de matières organiques sont nettement moins abondantes dans les fronts de podzolisation, plus particulièrement dans les horizons spodiques des podzols peu différenciés (moindre épaisseur des horizons Bhs), mais aussi dans les horizons Bh (fins et discontinus) de la bordure des réservoirs sableux. D'autre part, la plus grande abondance de ségrégations ferrugineuses dans les saprolites hydromorphes jouxtant les aires podzoliques de l'amont témoigne de périodes d'oxydation plus prolongées. A l'aval, l'érosion du bas de versant semble propice à une nette réactivation du processus de podzolisation. Cette réactivation se traduit par la descente du front de podzolisation dans les saprolites fines puis grossières des latérites et la formation d'une seconde génération d'horizons spodiques très fortement imprégnés par les substances organiques. De l'amont vers l'aval des aires podzolisées, l'accroissement en profondeur des imprégnations organiques dans les horizons illuviés ou spodiques est étroitement couplé à un épaississement des horizons éluviés de surface où prédominent les résidus organiques. Ce gradient latéral affectant à la fois les horizons éluviés et illuviés des podzols peut dans un premier temps être attribué à une augmentation des apports organiques, avec le développement d'une forêt plus ouverte à l'amont en milieu mieux drainé et d'une forêt dense ripariènne dans la zone d'affleurement de la nappe à l'aval. Il est aussi le reflet de conditions de drainage contrastées. Le rabattement des nappes à l'amont des aires podzoliques améliore les conditions de drainage, réactivant de ce fait la minéralisation des substances organiques des horizons spodiques des podzols et libérant de ce fait les métaux préalablement associés à ces composés organiques. A l'inverse, le maintien de conditions anoxiques en bas de versant favorise l'accumulation de substances organiques sans doute plus récentes. La faible acidification de ces nouveaux environnements podzoliques riches en minéraux altérables favorise la production de grandes quantités de complexes organo-métalliques (principalement Al).

4.1. Introduction

We present in this study results of geochemical, mineralogical and structural investigations performed along a 80m long soil catena, which illustrated the lateral transition between clay-depleted laterites and podzols, and the consequences of the downslope incisions of waterlogged podzols by river incisions. Soils of the catena are formed on granites of the Uaupés Suite and are localised 30km West of the town of de São Gabriel da Cachoeira, at the

border of the widely podzoliszed region of the Curicuriari subcatchment (Radam Brasil, 1974). This subcatchment is located in the high rainfall region of the upper Negro River watershed and covered by waterlogged podzols on 95% of its surfaces. It is then dominantly drained by black waters and presents in major riverbeds white sands from the physical erosion of podzols. Belonging the huge podzolised and waterlogged peneplains of the *Ucayali* surface (Campbell et al., 2006), the soil catena extends from yellowish clay-depleted laterites on a residual hill-top of the peneplain to waterlogged podzols eroded by a tributary of the Curicuriari river. Results of this study are compared to those obtained previously on less podzolized landscapes and drier climates of the Jaú region, 600km South East of São Gabriel da Cachoeira in the middle Negro River Watershed (Nascimento et al., 2004). In the Jaú region, small areas of poorly drained waterlogged podzols are found in the central parts of low elevation plateaus. The main objectives of this study is to establish the structural and mineralogical analogies between both types of soil catena and to reveal the major differences, which mostly result from the incision and drainage of waterlogged podzols of the upper Amazon Basin.

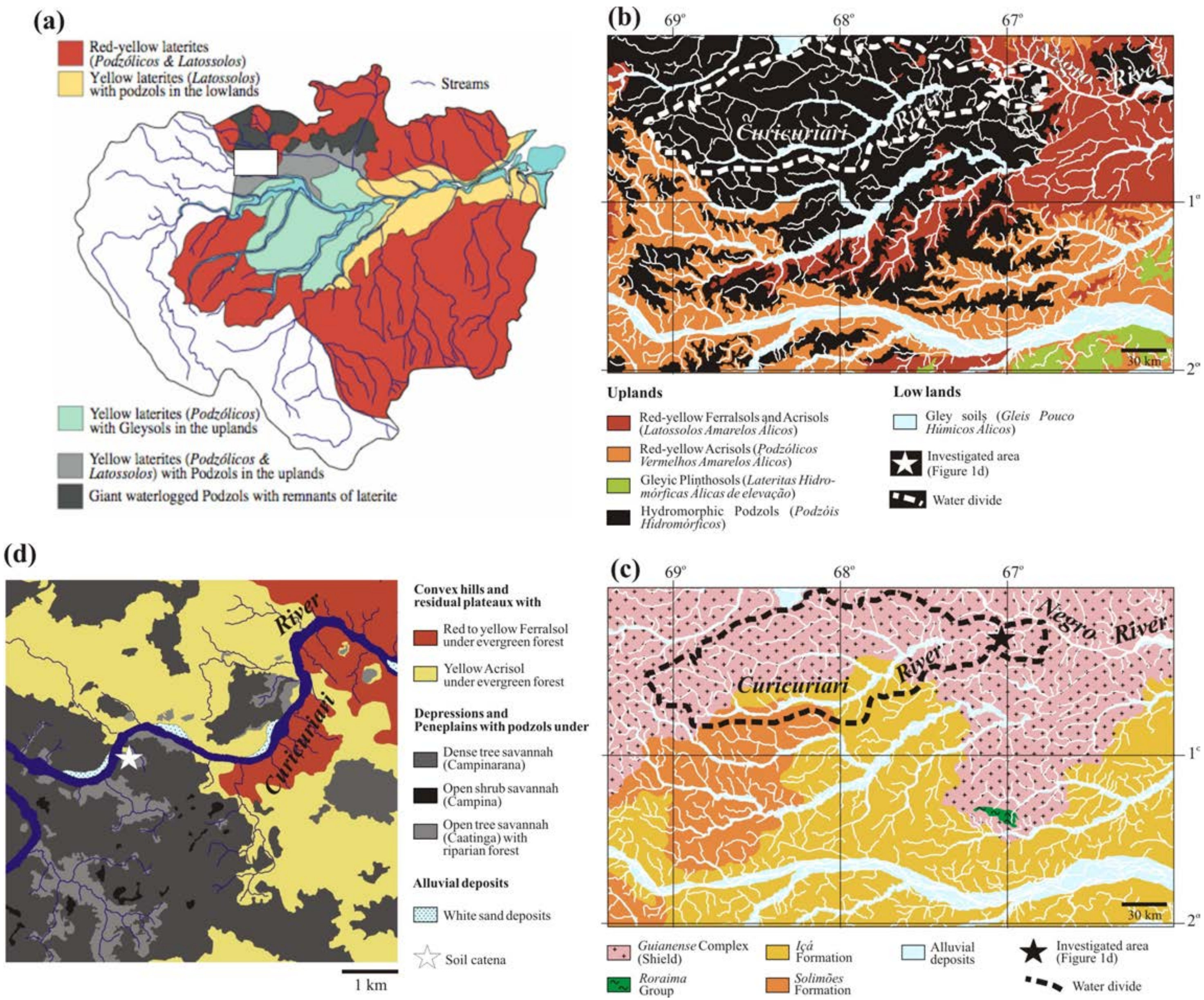


Figure 1. *(a) Broad scale soil map of the Brazilian Amazon Basin (reduced and simplified from Radam Brasil maps at 1:2 500 000) showing the extent of podzols in the upper Basin (white rectangle insert refers to Figure 1b,c). (b) Regional soil and (c) geological maps (extracts from the Radam Brasil maps at 1 :1 000 000) showing the distribution of Gleyic Plinthosols and Hydromorphic Podzols in relation to better drained lateritic soils (Ferralsols and Acrisols) of the low elevation peneplain formed on both rock and sedimentary formations (stars insert refers to Figure 1d). Note that the Curicuriari watershed (water divide in dashed line) is almost completely podzolised. (d) Local geomorphological and vegetation map at the lateral weathering front between laterites and podzols (white star insert refers to the soil catena).*

4.2. Materials and methods

Soil description and sampling

Soil profiles were photographed on clean cuts trenches and pits and described according to the ISRIC-FAO (1994) vocabulary along a 80m long soil catena. Photographs (Figure 2a) and soil description allowed the construction of a bi-dimensional representation of the soil organization along the catena using graphic softwares (Figure 2b) (Rinder et al., 1994). The soil catena illustrates the transition between well-drained Acrisols and waterlogged Podzols of the low elevation peneplain of the upper Rio Negro watershed (Figure 1d). A small brook of the Curicuriari River incises the downslope podzols of the catena. This brook is 5m below the hill-top level with Acrisols. The soil catena presents a convex sloping side and extends from a forest on the hill-top to a *Caatinga* in the midslope position and an inundated riparian forest near the brook.

Soil profiles were described in detail and sampled at 8 key sites along the catena (I to VIII in Figure 2b). A total of 89 bulk samples were collected vertically in soil and saprolite of the investigated profiles for chemical, physical and mineralogical investigation. We also sample in cardboard boxes 32 undisturbed fragments of soil horizons, saprolites and rocks from pits or nearby riverbed outcrops. Air-dried undisturbed samples were oven dried at $35^{o}C$ during 1 week, impregnated with resin, cut and ground for thin section elaboration according to Fitzpatrick (1970). Thin sections were observed with a Zeiss Axioskop 40-Hall 100 microscope, under plain-polarized light (PPL) and cross-polarized light (CPL).

Chemical and physical analyses

Air-dried soil samples were sieved through a 2-mm screen prior to chemical and physical analyses. Particle-size distribution was determined by sieving (sand fractions) and pipetting (clay and silt fractions), after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. pH was measured both in water and M KCL (soil:solution; 1:2.5). Organic C and N were determined on air-dried samples using a Carmograph LECO CHN analyser. Total chemical analyses were performed at Actlabs Ltd (Canada) on crushed and pulverised samples passing a 150-mesh (106 µm) sieve. Chemical composition of the samples was determined by inductively coupled plasma atomic emission spectrometry for major elements and inductively coupled plasma atomic mass spectrometry for trace elements. Mass balance factors (j,w) were calculated vertically at the 8 sampling sites (Figure 2b) according

to the iso-element approach of Brimhall et al. (1991) to assess the relative losses or gains of major and trace elements. Calculations were done as follow (Chadwick et al., 1990):

$$_{j,w} = \frac{C_{j,w}/C_{i,w}}{C_{j,p}/C_{i,p}} - 1$$

where C*j*,*w* and C*i*,*w* is the concentrations of the element (*j*) and the invariant (*i*) in the weathered material (*w*), respectively; and C*j*,*p* and C*i*,*p* is the concentrations of the same elements (*j* and *i*) in the protore or parent rock (*p*) .

X-Ray diffraction and spectroscopic analyses

Mineralogical composition of the samples was assessed on fine earths (<2mm) and clay size fractions (<2µm) by powder X Ray Diffraction (XRD) with a PHILLIPS PW 1730 using Cu K radiation and operating at 40 kV and 30 mA. XRD patterns were collected for 2 angles ranging from 3 to 90° with a 0.03° steps and a counting time of 15s per. Fine earth samples were manually ground to powders (± 30 m) in an agate mortar and prepared according to the technique of the "back pack-mounted slide" (Bish and Reynolds, 1989). Identification of the mineral phases was carried out by comparing the experimental XRD patterns with those from the mineral references of the ICDD data set.

Fourier-transform Infra-Red spectroscopy (FTIR) was performed in the transmission mode using a Nicolet Magna 560 IR Spectrometer. One mg of oven-dried and dispersed clay was mixed with 300 mg KBr and pressed twice at 10 ts.cm^{-2} to form a KBr disc. The KBr discs were heated at 105°C overnight to remove absorbed water. The spectra were run in the 400 to 4000 cm^{-1} range with a 2cm^{-1} resolution.

Diffuse reflectance spectra were obtained from gently ground bulk samples, oven dried at 60°C overnight. Samples were put into a 27 mm diameter hole in an Al disk (3 mm thick) then gently pressed against a quartz glass. Spectra were taken from 200 to 2500 nm at 0.1 nm increments using a Cary 5G US/VIS/NIR spectrophotometer with a 150 nm integrating sphere (Labsphere, Inc., USA). Reflectance measurements were made relative to a teflon standard covered with a quartz glass. The wavelength-dependent reflectance functions were transformed into remission functions, which were smoothed using a cubic spline fitting procedure then the second derivatives were calculated (Malengreau et al., 1996). The same smoothing and derivative parameters were applied for all the spectra.

Colours were determined from the reflectance curves in the visible range (from 360 to 830nm) as follows: the CIE tristimulus values (X, Y, Z) were computed from the spectral reflectance and energy of the light source for each wavelength using the colour matching functions of the CIE standard illuminant C (Wyszecki & Stiles, 1982). Tristimulus values were converted into colour units (x, y and Y%) of the CIE System (1931) and in those of the Helmholtz coordinates (L_d and P_e). They were ultimately plotted in the colour diagram of the visible range. In this diagram, the dominant wavelength (L_d) is the slope between the white light source and a given dot, and is related to the tint of the sample. The excitation purity (P_e) is equivalent to the chroma of the Munsell colour chart. It is scaled between 0 % for a colourless sample and 100 % for a pure colour monitored at the output of a monochromator (Bedidi et al., 1992).

4.3. Results and discussion

Vertical and lateral soil differentiation along the catena

According to structure and consistency, two superimposed and unconsolidated sets of horizons can be distinguished over the fresh granitic basement (R) of the catena (Figure 2): (1) a dense and compact saprolitic layer (C, CB and BC horizons), and (2) a loose soil mantle (A, AE, B and E horizons) less than 2.5m thick. The saprolite lacks soil structure, and presents a continuous groundmass. At the base of the saprolite, the porphyric texture and heterogeneous colours of the granite are preserved (C and CB horizons). Coarse sands (200 – 2000µm) are abundant (Figure 3a) and primary minerals are partly weathered (Figure 3b). More strongly weathered materials with finer sands are observed in the upper section of the saprolite, mostly in midslope positions (BC horizons), but also in the overlying soil mantle (A, AE, B and E horizons) (Figure 3a,b). However in the downslope position, the lower part of the soil mantle (E/C horizon) exhibits coarse sands and partly weathered primary minerals, as in the underlying coarse saprolite (C and CB horizons) (Figure 3a,b).

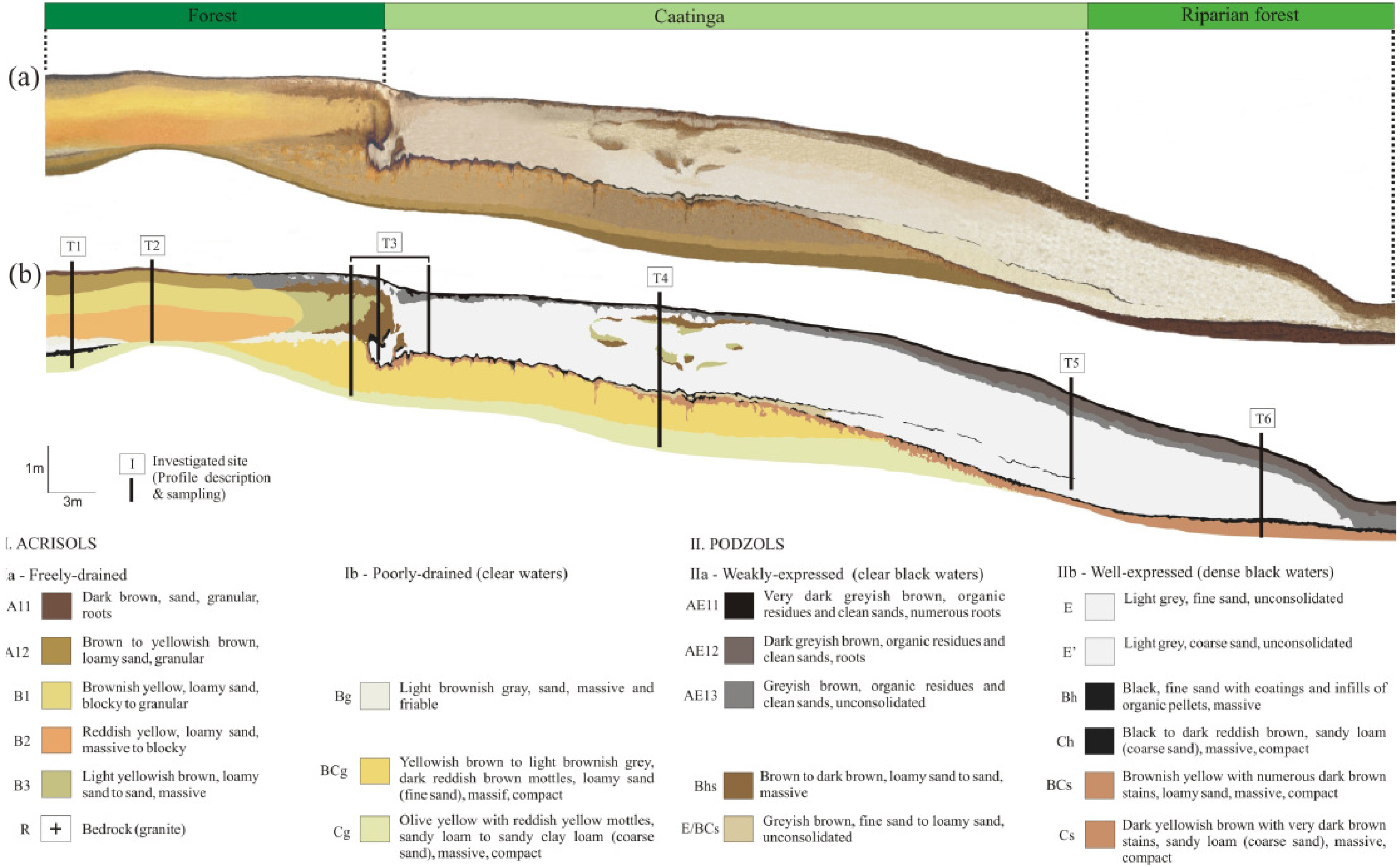


Figure 2*. Soil catena and type of vegetation from a hill-top to a major incision of a tributary of the Curicuriari River: (a) photo composition of pits and trenches used with detailed field descriptions to delineate (b) the major horizons at the weathering front between Acrisols and Podzols. Horizons are grouped in three major compartments of contrasted hydro-geochemical properties (I, II and III).*

The saprolite and soil mantle can further be dissociated in three main compartments according to texture and colour (I, II and III in Figure 2). The three compartments correspond to: (1) the freely drained topsoil A and B horizons of Acrisols on the hill-top, (2) the hydromorphic subsoil Bg, BCg and Cg horizons of Acrisols in upslope and midslope positions and (3) the eluviated topsoil (AE & E) and illuviated subsoil (Bhs, Bh, BCh & BCs) horizons of podzols in midslope and downslope positions. Similar types of compartments were already recognised in the podzolised soil landscapes of the upper Amazon Basin (Dubroeucq et al., 1999; Nascimento et al., 2004). They were assigned to contrasted hydrological regimes and geochemical environments, with clear waters in permanent deep groundwater for the upslope and hydromorphic subsoil, and black waters in perched groundwater for the downslope podzolic area (Nascimento et al., 2008). Moreover, the drastic hydro-geochemical change reported in the topsoil between the upslope Acrisols (freely drained) and the downslope podzols (acidic and periodically waterlogged) has significant impacts on the vegetation. It explains that the structure of the vegetation match those of the soils (Figure 1d, 2a).

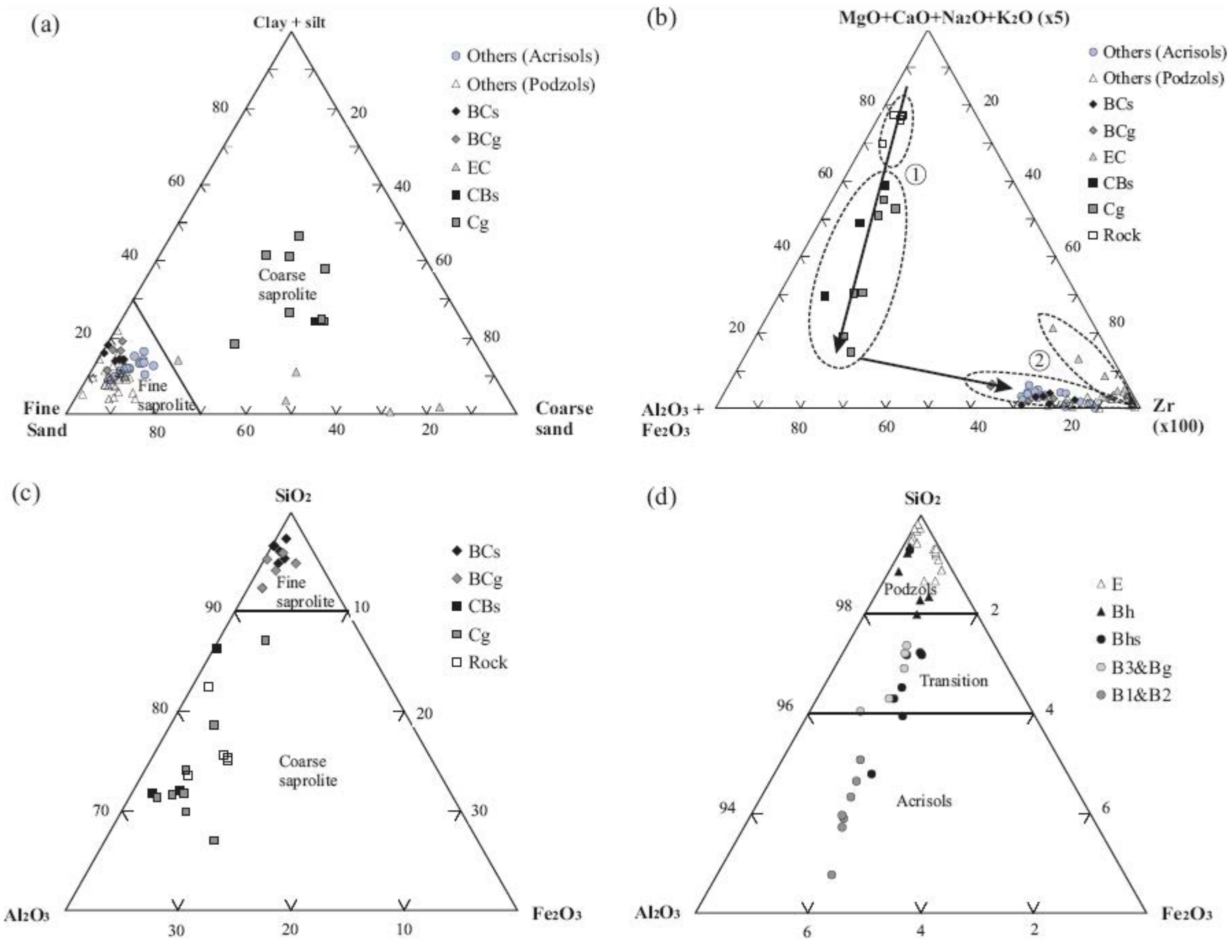


Figure 3*. (a) Textural and (b) chemical plots of major horizons in ternary diagrams showing (a) large proportion of coarse sands and (b) less weathered materials at the base and downslope part of the soil catena (C, BC and E/C). Proportion of SiO_2, Al_2O_3 and Fe_2O_3 in*

ternary diagrams of (c) saprolite and (d) soil horizons of the soil catena, illustrating (c) the drastic loss of Al- and Fe-bearing minerals from the coarse to the fine saprolite and (d) the minor but ultimate loss of such minerals from the upslope Acrisols to the downslope podzols.

The 1st compartment on the hill-top of the catena is covered by forest. The relative homogeneity of its A and B horizons, and their light textures and blocky to granular structures are indicators of a freely drained environment with dominant vertical water flows. The mineral B-horizons are loamy-sand and present the largest clay contents of the soil mantle (8 - 12%). They grade progressively upwards from reddish yellow (7.5YR6/8) in B2 to brownish yellow (10YR6/6) in B1. Under microscope, the iron coloured clay domains are scattered, around or between close packed quartz sands (Figure 4d). Towards the surface, the slight decrease in clay contents and net increase in organic matter leads to the differentiation of the yellowish brown to dark brown (10YR4/3 - 5/6) A12 and A11 horizons. Laterally, the mineral B1 and B2 horizons give progressively place to a light yellowish brown (2.Y6/4) B3 horizon, which marks the transition with the downslope podzols. This last horizon reveals a slight decrease of the clay content and a complete soil structure breakdown.

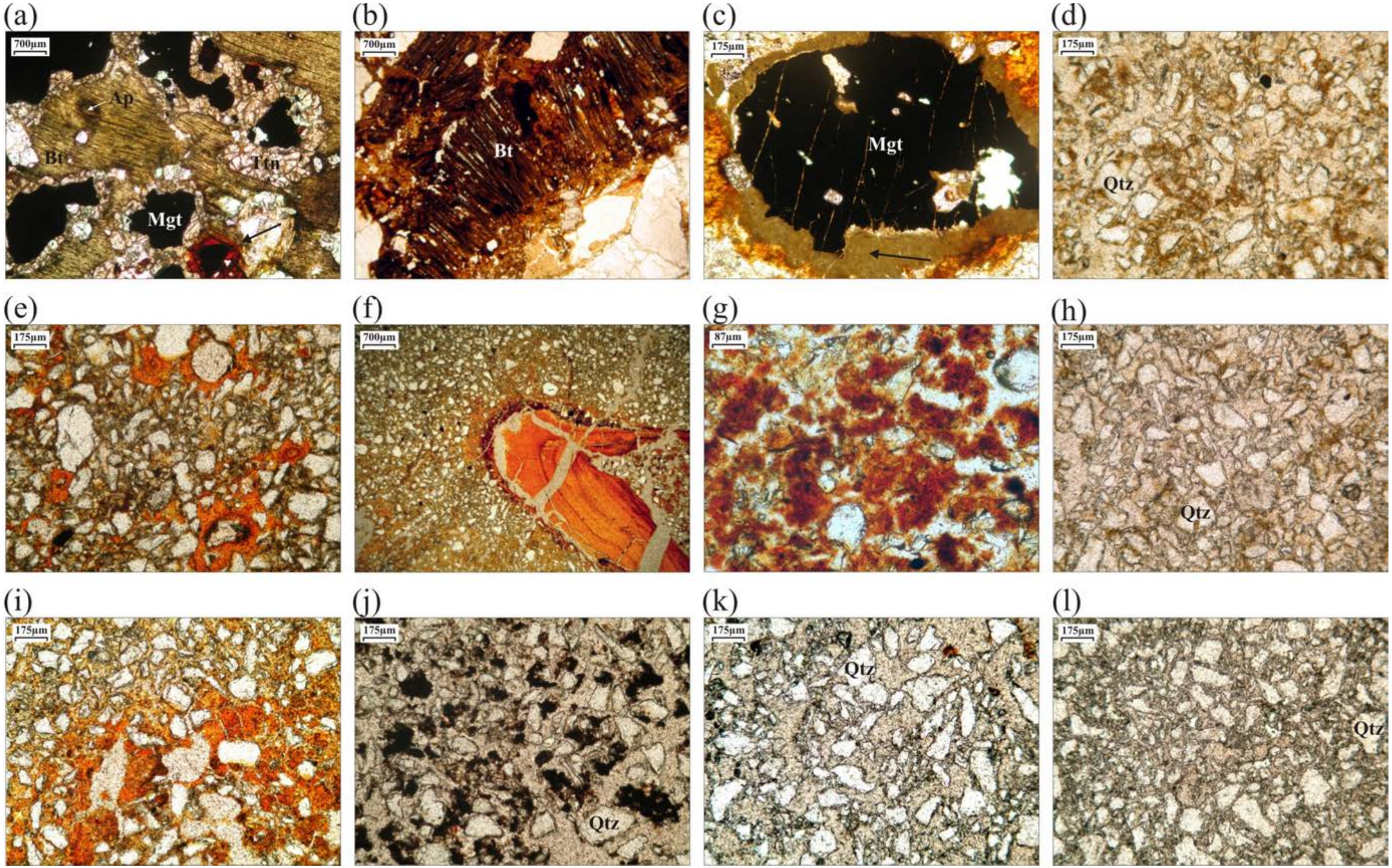


***Figure 4**. Petrographic fabrics of rocks and soil horizons under unpolarized light: (a) detailed view of a mafic body in the granite showing large crystals of biotite (Bt) with smaller inclusions of magnetite (Mgt) surrounded by grains of titanite (Ttn), note red weathered products at the*

margin of a magnetite (black arrow) and an apatite crystal (Ap) with surrounding fission tracks in biotite, (b) weathered biotite (Bt) residues strongly impregnated by Fe-oxides in coarse saprolite (BC2g), (c) yellowish brown weathered products (arrow) of titanite at the margin of a magnetite grain in coarse saprolite (BC2g), (d) dispersed iron coloured clays around or between close packed quartz sands (Qtz) in B-horizon of Acrisols, (e) reddish iron stains around quartz grains or on pore walls in fine saprolite (BC1g), (f) dark reddish iron stains on the wall of a macrovoid and cracked clay cutan infill variously coloured by Fe-oxides in fine saprolite (BC1g), (g) Dark brown organic compounds coating clay minerals in Bhs horizons of podzols, (h) low proportion of clay minerals between close packed assemblage of quartz (Qtz) in Bg horizon, (i) Dark brown, fine-grained and cracked organic coatings on clay minerals in the upper part of the fine saprolite, (j) Black organic decays aggregated in pellets that infill incompletely the interstices between quartz grains in Bh horizon, (k) sandy and porous AE horizons of podzols with dispersed fresh organic residues and black organic pellets, (i) close packed assemblage of quartz (Qtz) in E horizons of Podzols.

The 2nd compartment of the catena is observed at greater depth in upslope and midslope positions and related to Bg, BCg and Cg horizons (Figure 2), which clearly exhibit redoximorphic features. It thus corresponds to the aquifer of the deep groundwater. At the base of this compartment, the coarse saprolite (Cg) is sandy loam to sandy clay loam and is highly heterogeneous, with a dominant olive yellow colour (2.5Y6/6). The coarse saprolite may contain up to 35 wt% of clay, which are mostly inherited from the weathering of the predominant feldspars of the granite (albite, anorthite and microcline). The reddish yellow (5YR5/5) mottles of this saprolite are, on the opposite, mostly assigned to the weathering of mafic minerals (biotite, amphibolite and magnetite), which are grouped in scattered millimetric to centimetric bodies in the granite (Figure 4a). Biotites and amphibolites are strongly weathered in the coarse saprolite. Iron segregations are either observed as coatings on primary mineral remnants (Figure 4b) or as stains on secondary clay minerals. By contrast, the more resistant magnetite to chemical weathering are locally preserved as small grains in the saprolite and overlying soil mantle (Figure 4c,d). Small crystals of titanite are commonly surrounding the gains of magnetite in granite (Figure 4a). They are rapidly dissolved and replaced by yellowish brown weathering rings in the coarse saprolite (Figure 4c). The overlying fine saprolite (BCg) is laterally discontinuous along the catena and particularly thick in midslope positions (Figure 2b). It is clay depleted and deeply weathered (Figure 3a,b). Mafic minerals and feldspars are much less abundant than in Cg, and the quartz grains have predominantly a fine sand particle size. This saprolite is loamy sand and presents similar clay contents than the above Acrisol B-horizons (8 - 12%). It exhibits a yellowish brown (10YR5/4) to light brownish grey (2.5Y6/2) groundmass with dark reddish brown (2.5YR3/4) iron segregations. The latter surround remnants of mafic minerals (mostly magnetite) or more commonly impregnate clay minerals as diffuse stains on pore walls or within the groundmass (Figure 4e). Crescent clay cutans, variously impregnated by Fe-oxides, are also observed in macrovoids of the saprolite (Figure 4f). Both iron stains and clay cutans are more abundant in the upper part of the fine saprolite than in its lower part, particularly close to the podzolic area. At this location, a thin and discontinuous Bg horizon can dissociate the fine saprolite from the overlying B-horizons of Acrisols (Figure 2b). This horizon is light brownish grey (2.5Y6/2), almost devoid of iron stains, and is lacking soil structure and consistency. It has less clay contents (4 - 8%) and also displays under the microscope less clay minerals (Figure 4h) than its overlying B (Figure 4d) or underlying BC (Figure 4e) horizons.

The 3rd compartment of the catena corresponds to the podzolic area that expands from midslope to downslope positions on a convex sloping side (Figure 2). It comprises eluviated horizons over illuviated ones (also named spodic horizons) and corresponds to the aquifer of a perched groundwater drained by the river network. An open forest (*Caatinga*), with smaller trees than those growing on the upslope Acrisols, covers the podzols in midslope positions. It gradually gives place to a riparian forest close to major river incisions, and thus reveals wetter lands in downslope positions. Podzol development differs on both types of topographic location and vegetation cover. In midslope positions, the vertical development of podzols is impeded, at about 1.5m deep, by the fine saprolite. Podzols thus mostly expand laterally at the expense of the upslope A, B and Bg horizons of Acrisols. Both types of soils display laterally a characteristic double tongue-like shape transition (Figure 2), which has been systematically observed at the margin of the podzolised areas of the upper Amazon Basin (Dubroeucq & Volkof, 1998; Dubroeucq et al., 1999; Nascimento et al., 2004). This kind of transition has recently been assigned to the dynamics of the groundwater (Nascimento et al., 2008).

At high water levels, the perched groundwater seeps at the surface at the margin of the podzolic area. Weakly developed podzols can then form at the expense of the A and B3 horizons of the upslope Acrisols and gives place to the AE and Bhs horizons, respectively, with the local individualisation in between of bleached E materials (upper section of pits III and IV). In the AE horizons, the clay content is less than 4%. The mineral phases consist of clean sands and the organic ones of fresh plant remains (leaves and roots) as well as coarse dark brown to black organic decays. These organic substances and the fine roots of the open forest decrease downwards from the very dark greyish brown (10YR3/2) AE11 horizon at the surface to the greyish brown (10YR6/2) AE13 horizon in the subsurface. They nearly disappear in the underlying and downslope light grey (10YR7/1) E horizon. The latter is bleached and unconsolidated. It is almost free of clay minerals and consists of close packed quartz grains of a dominant fine sand particle size in midslope positions (Figure 4i). Fine grained organic matter accumulates at the margin of podzolic area into the B3 and forms the brown (10YR5/3) to dark brown (10YR3/3) Bhs horizon. It impregnates the clay minerals between the quartz grains and demarcate at micro-scale diffuse, dark brown organic stains on pore walls and within the groundmass (Figure 4g).

At low water levels, the deep groundwater of the upslope Acrisols can seeps into the lower part of the podzolic area and thus feeds the perched groundwater. Greater trough flow and loss of matter in perched groundwater explain the lateral expansion of the E horizon into the

hydromorphic subsoil horizons of the upslope Acrisols (Nascimento et al., 2008). The lower tongue then forms at the base and margin of the podzolic area (lower section of pit IV). Moreover, podzolic horizons can expand upslope on longer distances (up to 15m) at the favour of twisting channels, more specifically within the clay-depleted and light brownish grey Bg horizon of Acrisols (one of these channels is cut perpendicularly in the lower section of pit II). This reveals that eluviation and illuviation of clay in the upper part of the groundwater aquifer might be pre-existing mechanisms to podzolisation. Due to larger losses of clay particles, a small topographic slope break marks the connection of the upper and lower tongues (between pits IV and V). Downslope, remnants of B3 and Bhs within the bleached E horizon of well-expressed podzols (upper section of Pit VI) suggest that the upslope expansion of the latter is not a continuous process. This lateral expansion has likely acted abruptly in successive steps, most likely during periods of exceptional high rainfalls. At least, spodic Bh and BCs horizons are also formed at the base and margin of the podzolic area. They result from the vertical transfer of organic substances in the perched groundwater of podzols and their physical fractionation and accumulation in texture contrasted subsoil horizons during the recede of that groundwater (Duchaufour, 1972; Fritsch et al., 2009). Organic colloids or particles, accumulated at the margin and base of the eluviated E horizon, form the black (10YR2/1) Bh horizon. The latter is thin and discontinuous at the margin of the podzolic area. Under the microscope, it exhibits black organic pellets that fill incompletely the interstices managed by the quartz grains (Figure 4j). Finest organic substances accumulate at greater depths, mainly in the upper part of the saprolite. They form dark brown and cracked organic stains or coatings (Figure 4i) in brownish yellow (10YR6/6) to dark brown (7.5YR3.5/3) BCs horizon, as in Bhs (Figure 4g).

Towards downslope positions, the convexity of the slope increase, the podzols deepen and the granite outcrop in the brook. Physical denudation of the downslope podzols, which has fed in white sand deposits the Curicuriari river, has thus also favoured its downward expansion into the saprolites (Figure 2). This soil dynamics starts at the nicking point of the convex sloping side and is initiated by the formation, under the thin Bh horizon, of a greyish brown (10YR5/2) sandy E/BC horizon (lower section of pit VI). This horizon gradually turns light grey downslope (E horizon) and a second generation of spodic horizons are formed at greater depths. In low-lying positions and under the riparian forest, podzols expand ultimately into the coarse saprolite forming the light grey (10YR7/1) E/C horizon above the black (5YR3/1) and dark yellowish brown (10YR4/4) spodic horizons (CBh and CBs, respectively).

Observation of the whole catena (Figure 2) also shows that organic compounds weakly accumulate at the margin of the podzolic area and, on the opposite, deeply impregnate the eroded soil landforms in lowlying positions. In particular, the thicknesses of the eluviated organic topsoil (AE) and spodic subsoil horizons (Bh and BCs, and ultimately CBh and CBs) of podzols increase gradually towards the brook likely due to longer periods of waterlogging and change of vegetation (from *Caatinga* to riparian forest).

Geochemistry of trace elements (Zr, Ti and Th)

Deep weathering of rocks in tropical regions commonly leads to complete removal of alkali and alkali hearth elements (Na, K, Mg and Ca), partial depletion of Si and therefore to residual accumulation in soils of less mobile elements such as major metal cations (mostly Al and Fe) and trace elements. Trace elements such as Zr, Ti and Th generally accumulate from bottom to top of autochtonous tropical soils (e.g. Ferrasols) and the positive correlations established between each other testimonies of their weak mobility during weathering processes (Fritsch et al., 2002). This is commonly attributed to their incorporation in accessory minerals, which are very resistant to chemical weathering (e.g. zircon for Zr). They are thus commonly used as invariants for mass balance modelling and assessment of losses and gains of more soluble elements in weathered profiles (e.g. Braun et al., 1993). However, chemical analyses of water systems have established that organic acids could initiate the chemical weathering of these accessory minerals in waterlogged environments and contribute to the transfer of trace elements to river systems (Viers et al., 1997). Chemical investigations along soil catena has also emphasised that losses and gains of such elements could also be related to biological uptakes, runoff and selective translocation of their parent minerals according to particle size (Fritsch et al., 2007).

Zirconium behaves differently than Ti and Th in the study site. As expected for most tropical soils, the Zr content increases from rock to saprolite and ultimately to the overlying soil horizons (Figure 3b). The reverse trend is reported for both Ti and Th (Figure 5a). This is consistent with the incorporation of Zr in zircon, an accessory mineral highly resistant to chemical weathering (Balan et al., 2001; Taboada et al., 2006). Zircon in granites and regoliths of the study site has also an average particle size of about 150µm that prevents its translocation in most soil horizons. It was then used as a chemical invariant to calculate mass balance factors and assess relative losses or gains of other chemical elements. Results obtained for trace elements indicate that 80% of the initial stock of Ti and 90% of the Th are

lost in the fine saprolite and overlying soil horizons of the upslope Acrisols (Figure 5b). This is attributed for Ti to the weathering of titanite crystals in coarse saprolite (Figure 4c) and the formation in soils of small grains (< 2µm) of anatase, according to petrographic and XRD investigations. Similar mechanisms have likely happened for thorium with the dissolution at depth of Th-bearing minerals (e.g. apatite and allanite) and the formation in soils of thorianite crystals. However, the tiny size and the small concentration of the latter have prevented its identification.

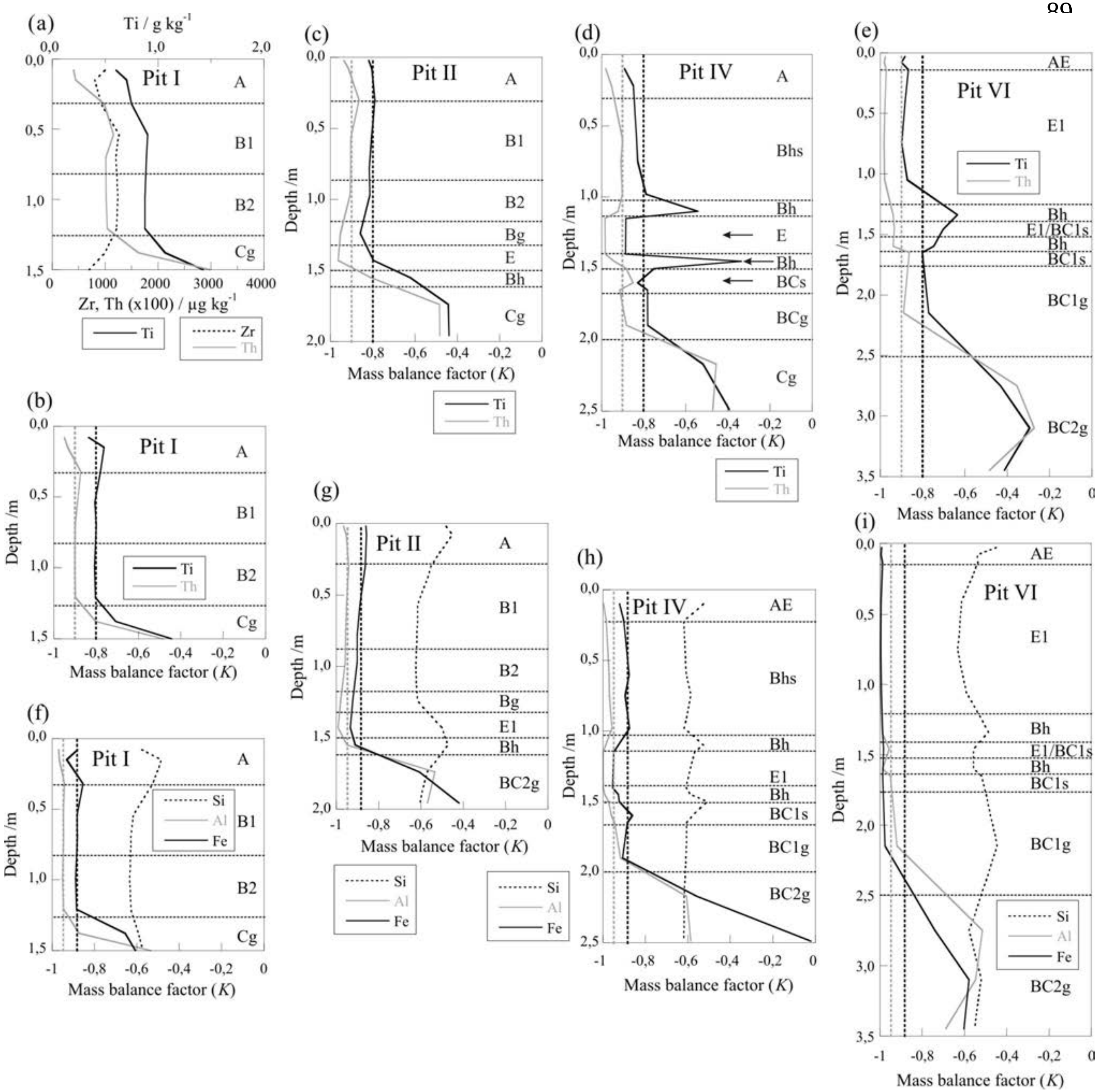


Figure 5*. (a) Vertical distribution of Zr, Ti and Th in the upslope Acrisol (Pit I) and mass balance factors calculated vertically for (b, c, d and e) Ti and Th, and (f, g, h and i) Si, Al and Fe in four profiles of the soil catena (I, II, IV and VI, respectively).*

As the eluviated and illuviated horizons of podzols mainly form laterally at the expense of the upslope Acrisol soil horizons, the remaining fractions of Ti (20%) and Th (10%) stored in the latter will be used as new threshold values for assessing losses and gains of both elements in the downslope podzols (see vertical dashed lines in Figure 5). Figure 5c,d,e shows that the development of podzols into Acrisols leads to drastic losses of Ti and Th in their eluviated horizons and, on the opposite, gains of the same elements in their illuviated or spodic B-horizons. Losses of Ti and Th are initiated at depth in the Bg and E horizons of the twisted channels that enter into the upslope Acrisol, on top of the saprolite (bottom section of pit II in Figure 5c). In the transition zone (pit IV in Figure 5d), losses of both elements are also initiated near the surface in the AE and Bhs horizons of weakly expressed podzols (upper tongue). These losses become more relevant at the same topographic location, but at greater depth, in the bleached E horizon of better differentiated podzols (lower tongue). They are optimal and remains almost unchanged in the eluviated AE and E horizons of the well-developed podzols in midslope and downslope positions (pit VI, in Figure 5e). Thorium has almost been completely removed from these horizons whereas half of the initial stock of Ti stored in Acrisols has been lost. Both elements are on the opposite accumulated in the illuviated or spodic horizons of well-expressed podzols (Figure 5d,e). These gains are more important for Ti than Th and the former accumulate at shallower depth in Bh horizons than the latter in the underlying BCs horizons. This dissociation with depth of both types of trace elements in two superimposed spodic horizons suggests that they could be bound to distinct organic carriers, and translocated vertically according to their particle size. Dissolved organic carbon and their chelated Th would then accumulate at greater depth in BCs than higher molecular weight organic fractions and associated Ti. However, Ti and Th could also be incorporated in crystals of anatase and thorianite, whose particle sizes ($< 2\mu m$) allow their vertical transfer in the macro-voids of AE and E horizons of podzols. As thorianite crystals are much smaller than that of anatase, they can accumulate at greater depth in less porous horizons. XRD investigations on clay size fractions ($< 2\mu m$) confirm the physical translocation of anatase, as the main diffraction peak for the latter appear much more important in Bh horizons than in their overlying E or underlying BCs horizons (not shown). Physical transfer of organic and mineral phases is thus an important mechanism in podzol development and consistent with the concept of eluviation and illuviation commonly attributed to the formation of these soils. Obviously, this does not exclude the contribution organic acids in the weathering of clay and accessory minerals and the formation and transfer of organo-metallic complexes. The greater loss of Th than Ti in eluviated horizons of Podzols

and their smaller accumulation in their underlying spodic horizons also indicate that this element is massively exported in the black waters and rivers of podzolic environments.

Geochemistry of major elements (Na, K, Ca, Mg, Si, Al and Fe)

The contents of alkali and alkali earth elements (Na, K, Mg and Ca) stored in the bedrock decreases rapidly upwards in the weathered mantle, first in the coarse saprolite and ultimately in both the fine saprolite and overlying soil horizons (Figure 3b). The extremely low contents measured in the latter attest of the strong weathering conditions, which led to the almost complete weathering of feldspars, biotites and amphiboles from granites and the formation of Al- and Fe-bearing secondary minerals (predominantly kaolinite and gibbsite, and at lesser extent Fe-oxides). The contents of Al_2O_3 and Fe_2O_3 do not change significantly between granites and coarse saprolites but drop abruptly between latter and both fine saprolites and soil horizons (Figure 5c,d). These geochemical trends reveal that fine saprolites are clay-depleted whereas the underlying coarser ones are not. As already discussed, a third category of materials can be distinguished. They correspond to the base of the eluviated horizons of the downslope Podzols (E/C in Figures 2b and 3b), which is clay depleted but still contains alkali and alkali earth elements. This last trend confirms that podzols have ultimately expanded downwards in less weathered materials close to major river incisions.

According to mass balance factor calculations, about 60% of the Si, 90% of the Fe and 95% of the Al stored in granites have been lost by chemical weathering in the A and B horizons of the upslope Acrisols (Figure 5g). Losses seem to be less in A horizons than in B-horizons (particularly for Si), which is likely not the case as clay depleted topsoils appear also depleted in Zr (Figure 5a). As for trace elements, the remaining fractions of Al (5%) and Fe (10%) stored in the upslope B-horizons of Acrisols (see the vertical dashed lines in Figure 5) were used as new threshold values for assessing losses and gains of both metal cations in podzols (Figure 5h,i). Only losses are reported for Al and Fe, and both elements seem to be exported simultaneously (Figure 3d). Such losses, initiated in B3 and Bg horizons of Acrisols, become almost total in eluviated horizons of podzols (AE and E). For spodic horizons of podzols, their chemical compositions approach those of the surrounding horizons in which they have formed: BCg and Cg for BCs and Cs (Figure 3c), B3 and Bg for Bhs and E for Bh (Figure 3c,d).

Al-bearing secondary minerals (kaolinite and gibbsite)

DRX (not shown) and spectroscopic data in the infra red (FTIR) range reveal a monotonous mineral composition for secondary Al-bearing minerals (kaolinite and gibbsite) but a high variability in their relative proportions and total contents in bulk samples from bottom to top and upslope to downslope positions of the catena (Fig. 6). In the A and B-horizons of the upslope yellowish clay-depleted laterites (Acrisols), the contents of gibbsite are larger than that of kaolinite (Figure 6a). It slightly increases downwards in these horizons, and more abruptly in the upper part of the underlying coarse and clayey saprolite (Cg). This vertical trend in laterites likely results from the weathering of the Al-bearing minerals in the upper section of the soil profiles and the downward accumulation of Al, which precipitate as gibbsite and in larger proportion at the textural transition. It then indicates that both clay depletion and soil gibbsitisation are prior to soil podzolisation.

At the margin of the podzolic area, similar variations are observed (Figure 6b), with however lower amounts of gibbsite and kaolinite in the upper A and B horizons (AE, Bhs, B3 and Bg), but also in the underlying fine saprolite (BCg). Strong textural contrasts then exist between the fine (BCg) and coarse (Cg) saprolites, the latter still exhibiting larger amounts of Al-bearing secondary minerals and greater proportions of gibbsite in its upper section. Towards the downslope podzols, this trend is maintained. The textural contrast between the clay-depleted and upper section of the soil and the lower clay-rich saprolite in enhanced, mainly due to greater losses of Al-bearing minerals in the former (Figure 6c,d). In the midslope position (Figure 6c), the spodic horizons (Bh and BCs) do not form at this textural transition but just above at the structural transition between soil horizon and saprolite. It then confirms that clay depletion is prior to soil podzolisation but also reveals the structural control of the upper saprolitic limit in the downward expansion of podzols at the margin of the podzolic area. It also explains that podzolisation can locally pass through this transition, more specifically towards low-lying positions following deep river incisions in the landscapes. At least, gibbsite seems to be inexistent in the eluviated compartment of the downslope podzols whereas traces of kaolinite are still observed (Figure 6c,d). This new trend suggests greater dissolution rates for gibbsite than kaolinite in podzolic environments (Nascimento et al., 2004). However in the remnants of the Bhs horizons, which are preserved in the midslope position and contains greater amount of clay minerals, gibbsite is also weakly present (Figure 6c). We thus rather suggest that podzols have expanded in poorly drained laterites, restricting therefore the formation of gibbsite in their upper section.

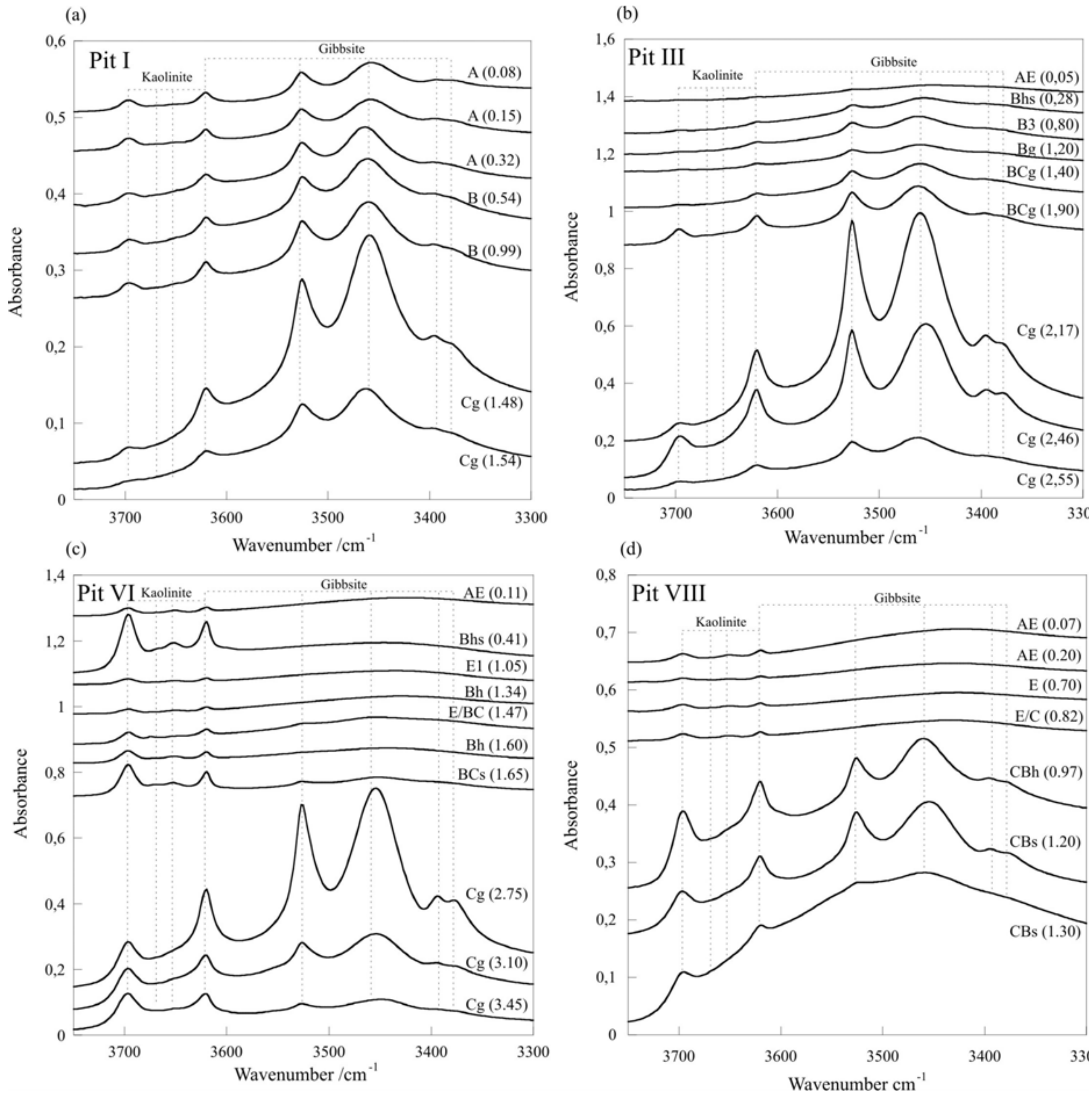


***Figure 6**. Infra Red spectra in the OH stretching band region of kaolinite and gibbsite of bulk samples from (a) the upslope Acrisol (Pit I), (b) the transition zone (Pit III) and (c,d) the downslope podzols (Pits VI and VIII, respectively) (sampling depth in meter of each sample is given in brackets).*

Fe-oxides and organically bound Fe

Diffuse reflectance spectroscopy reveals the nature and proportion of secondary Fe-oxides as well as the relative abundance of organically bound Fe (Figure 7). Soil profiles of the catena mainly contain goethite as Fe-oxides, whose proportion decreases significantly from the iron coloured topsoil A and B horizons of the upslope Acrisols to their underlying hydromorphic and downslope podzolic areas. Such global trend is illustrated with samples exhibiting on a

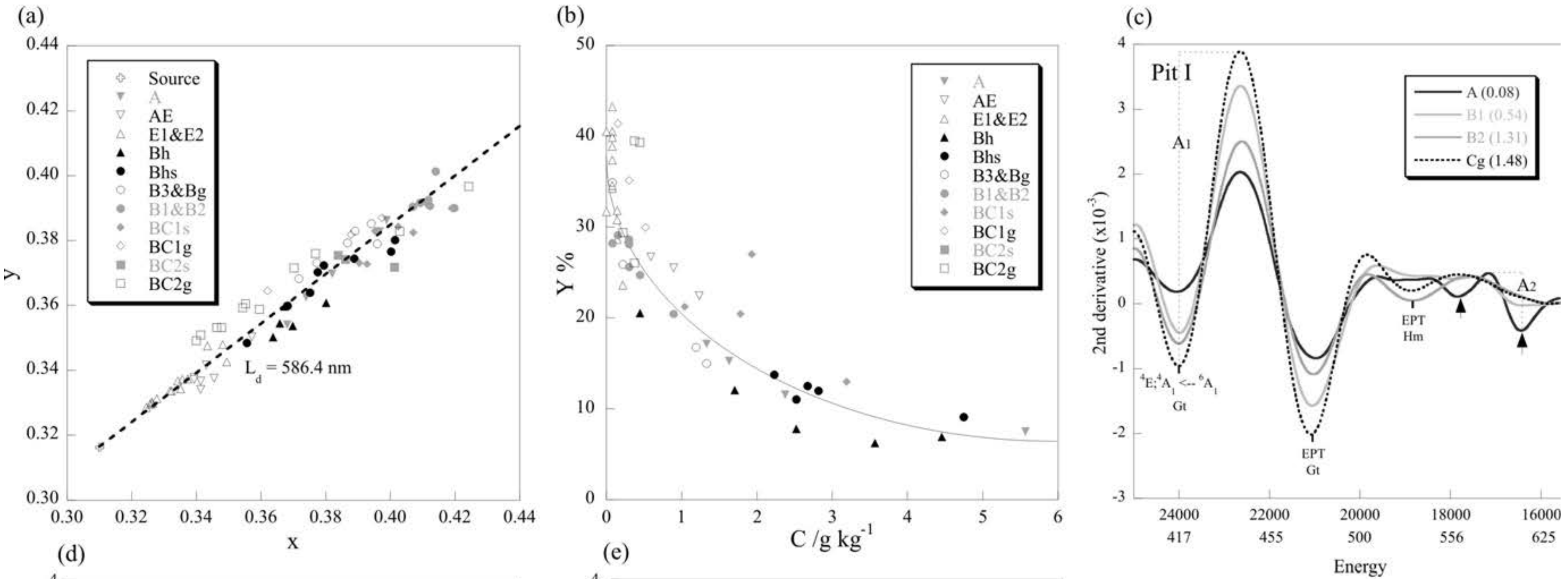
colorimeric diagram similar L_d (dominant wavelength) but contrasting P_e (excitation purity) (Figure 7a). The average L_d of 586nm is characteristic of goethite. The iron-rich samples (largest P_e values) correspond to the topsoil A and B horizons of Acrisols and the iron depleted ones (lowest P_e values) to the greyish samples of their underlying hydromorphic area (Bg, BC1g, BC2g) and all the topsoil bleached horizons of the downslope podzols (AE, E, E/C). Spodic horizons of podzols (Bhs, Bh, BC1s, BC2s) present intermediate values.

Second derivative of the remission function from reflectance curve in the visible range also exhibits two major bands (minima) for goethite (Gt) but also a minor band for hematite (Hm) at lower wavenumbers for the topsoil A and B horizons of the upslope Acrisols (Figure 7c). The relative proportion of hematite in the pool of Fe-oxides (i.e. both hematite and goethite) is optimal at the base of the B horizon and almost nil in its upper part, which is consistent with a gradual change of colour from reddish yellow (7.5YR6/8) in B2 to brownish yellow (10YR6/6) in the overlying B1. A significant decrease of the two minima for goethite (Gt) in the topsoil A horizon of Acrisols can also be linked to the appearance of two additional bands, at 16350 cm^{-1} (610 nm) and 17500 cm^{-1} (565 nm) (arrows in Figure 7c), which were assigned to organically bound Fe^{III} (Nascimento et al., 2004, Fritsch et al., 2009). At the transition between clay-depleted laterites and podzols, loss of goethite increases and the organically bound Fe is also reported in weakly expressed podzols, in topsoil AE horizons but also and mainly in their underlying Bhs horizons, as shown by the amplitudes of the two additional bands at 16350 and 17500 cm^{-1} (Figure 7d). This is further enhanced laterally in better-expressed podzols, where the organically bound Fe is also abundantly found in Bh horizons. By contrast, it is less abundant or absent in the underlying spodic BCs horizon. This is consistent with the formation of organically bound Fe following the dissolution of goethite in topsoil horizons of the margin of the podzolic area and the downward and downslope accumulation of organic colloids and Fe in Bh horizons of better-expressed Podzols (Fritsch et al., 2009).

Organic matter, organically bound Al and soil acidity

Carbon contents decrease regularly with increasing depth in the upslope clay-depleted laterites from up to 24 g kg^{-1} in A horizons to less than 3 g kg^{-1} in B horizons and the C:N ratio ranges from 10 to 27. In the podzolic area the carbon content increases (Figure 8a), more specifically in spodic horizons (up to 48 g kg^{-1}). The C:N ratio increase slightly near the surface in Bhs horizons of weakly expressed podzols, and more significantly at greater depths in Bh and BCs horizons (up to 67). The contents of Al extracted by the pyrophosphate

treatment (Al_p), which permit to assess the amounts of organically bound Al (Figure 8b), gave similar values than that obtained by Nascimento et al. (2004) on another catena associating on short distances clay-depleted laterites and waterlogged podzols. The Al_p contents in bulk samples of B-horizons average 1 g kg^{-1} in the upslope clay-depleted Acrisols. It remains almost unchanged or decreases significantly in organic-rich AE and Bh horizons of podzols and, on the opposite, increases in spodic Bhs and BCs horizons of podzols. This general trend is thus consistent with previous results of Bardy et al. (2007).



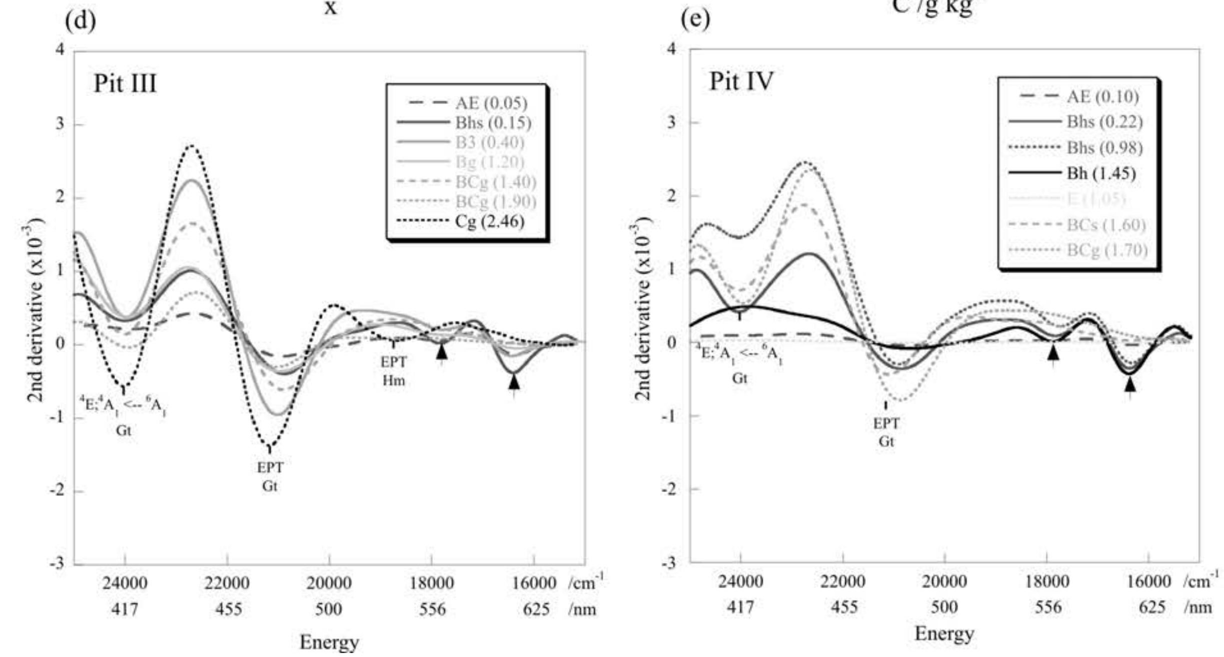


Figure 7*. (a) x and y values of tristimulus coordinates (CIE system, 1931) in a colorimeric diagram showing similar dominant wavelength (L_d) for all samples but distinct excitation purity (P_e) (tristimulus values were converted in Helmholtz coordinates: L_d and P_e), (b) Y% coordinate (CIE system, 1931) versus carbon content (C), Second-derivative spectra of the remission function f(R) in the visible range of Fe-oxides (Gt: Goethite, Hm: Hematite) in bulk samples of (c) the upslope Acrisol (Pit I) and (d,e) the midslope podzols (Pits III and IV, respectively) (sampling depth in meter of each sample is given in brackets).*

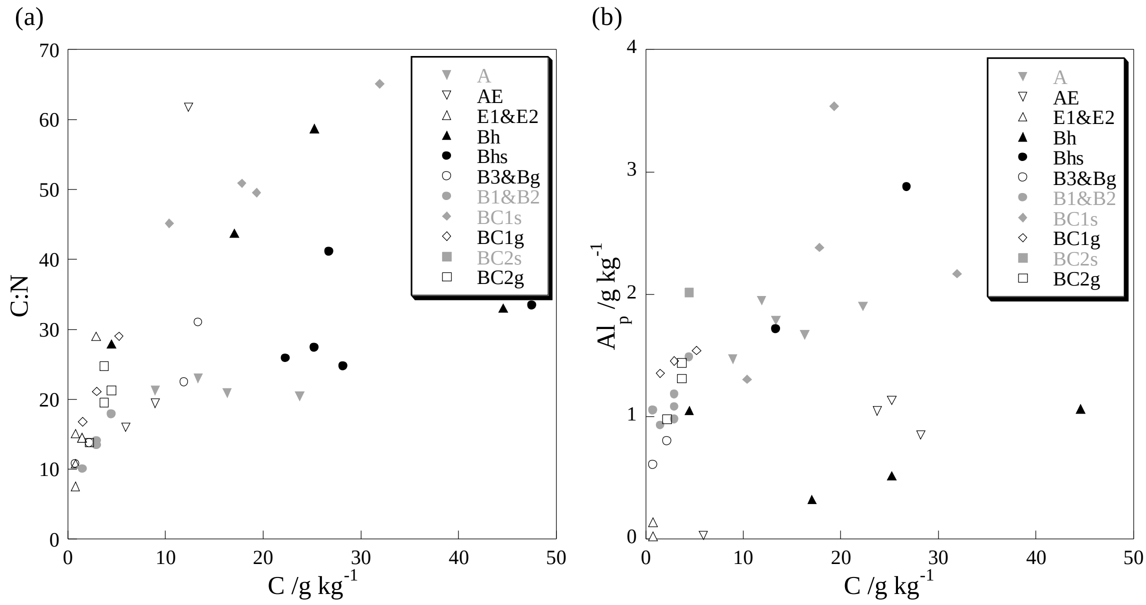


Figure 8. *(a) carbon content (C) versus C/N ratio, (b) carbon content (C) versus amount of extractable Al by the pyrophosphate treatment (Al$_d$).*

The pH of soils and saprolites ranges between 5.5 and 4.0 along the catena (Figure 9). Highest pH values are reported in the topsoil A and B horizons of the upslope Acrisols. pH decreases slightly in the underlying hydromorphic horizons of these soils. It also decreases laterally in podzols. It reaches the lowest values (pH = 4) at the base of the bleached E horizons at the margin of the podzolic area in midslope positions. By contrast, pH increases downslope in eroded and less weathered waterlogged podzols.

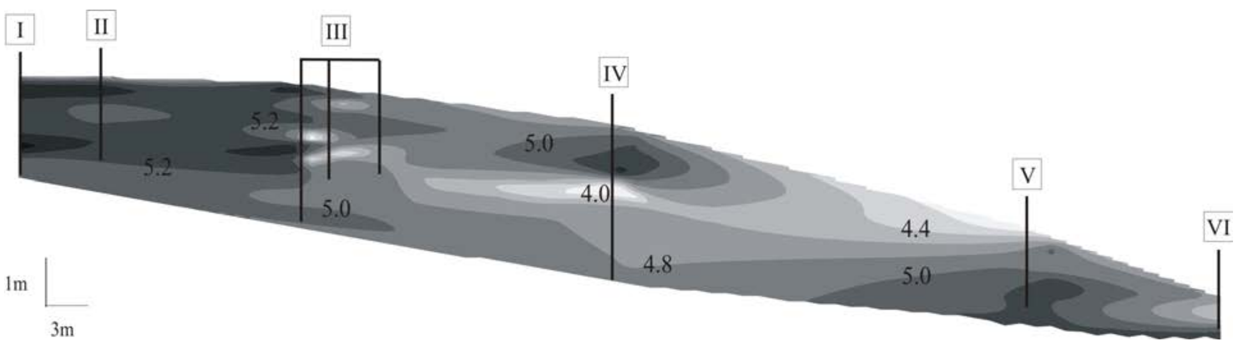


Figure 9. *Range of pH along the soil catena.*

4.4. Discussion and conclusions

The soil catena investigated in this paper presents major structural and mineralogical analogies with that studied by Nascimento et al. (2004) in less podzolised soil landscapes of the Negro River watershed. The main analogy is the identification of the same type of structures along the catena with (i) the clay-depleted and freely drained upper part of laterites (Acrisols), (ii) their hydromorphic lower part, predominantly formed in saprolites, with their corresponding deep groundwater and (iii) the upper and downslope podzolic area, which sustains a perched groundwater. The second major analogy, which has systematically been observed along soil catena of the Amazon Basin, is the “double tongue-like” transition between the upslope laterites and the downslope podzols (Turenne, 1975; Bravard & Righi, 1989, 1990; Dubroeucq & Volkof, 1998; Lucas et al., 1987, 1996; Nascimento et al., 2004). The upper tongue results from the upslope and downward development of weakly expressed podzols on the clay-depleted laterites, thus forming thin eluviated AE and E horizons over weakly differentiated Bhs horizons. Further downslope and at greater depths, the bottom part of better-differentiated podzols is lying on the hydromorphic saprolite of laterites. It expands laterally into the upslope bleached and clay-depleted Bg horizons of the upper part of the groundwater aquifer, forming the second tongue or, in 3 dimensions, twisted channels on more than 15m long. These structures result from the interactions and dynamics of two groundwaters: (i) a permanent deep groundwater with clear waters fluctuating in the hydromorphic part of the laterites, and (ii) a more seasonal perched groundwater with black waters fluctuating in the eluviated horizons of podzols (Nascimento et al., 2008).

Soil organisations and groundwater dynamics also reveal the contribution of major structural discontinuities (in both study sites: the transition between soil and saprolite) in the vertical development of podzols and their consequences in the individualisation of well-differentiated spodic Bh and Bs (or BCs) horizons. The vertical development of podzols is impeded as soon as they reach this discontinuity, initiating therefore the lateral expansion of podzols in the landscape. In both study sites, the downward accumulation at the base of the eluviated E horizon of black organic colloids during the recede of the perched groundwater built up the Bh horizon in podzols. The accumulation just below of dissolved organic carbon in the less permeable hydromorphic saprolite of the laterites forms the BCs horizon. These accumulations of organic matter, at depth but also at the margin of the podzolic areas, reduce the porosity of their spodic horizons and favour the implementation of a perched groundwater in their overlying eluviated and bleached horizons. Remnants of lateritic horizons

impregnated by organic compounds are observed in the latter. They indicate that podzols may expend abruptly upslope at the expense of freely drained and clay-depleted laterites in response to major rainfall events and subsequent expansion of perched groundwater aquifers.

Soils and saprolites in both study sites also exhibit strong geochemical and mineralogical analogies. Better than that of the Jaú site, this study reveals that massive gibbsitisation of the upper clayey saprolite is likely linked do the downward accumulation of Al following the dissolution of Al-bearing minerals (mainly kaolinite and gibbsite) in the upper clay depleted horizons of laterites. This hypothesis suggests that gibbsitisation has occurred before the podzolisation of laterites. The greater proportion of kaolinite in the pool of the remaining Al-bearing minerals within the overlying soil horizons and towards the podzolic area also suggests higher dissolution rates for gibbsite than kaolinite in more acidic environments (Nascimento et al., 2004). However, such a trend could also result from the development of poorly drained conditions in laterites, before their ultimate podzolisation, which should restrict the formation of gibbsite.

In both study site, podzols are formed laterally at the expense of yellowish clay depleted laterites with mainly contains quartz grains but also residual clay minerals (kaolinite, gibbsite and goethite). Massive iron and clay depletion, confirmed by mass balance calculations, are preliminary weathering steps to soil podzolisation. Such preliminary weathering steps may even affect the upper part of the saprolite in hydromorphic environments. Losses of clay minerals develop interconnected macrovoids between quartz grains that promote the migration of fine particles. Chemical erosion of laterites then generates particulate transfer in clay-depleted horizons. Clay transfer mostly occurs in the deep groundwater of the upslope laterite and is consistent with the individualisation in their upper bleached and clay depleted Bg horizon or BCg saprolite of clay cutans in macrovoids. Transfer of clay and silt particles is strongly enhanced in the sandy and bleached horizons of podzols and is also associated with the downward accumulation of Th-, Ti-bearing minerals in spodic horizons. Simultaneously, the accumulation of organic substances in spodic horizons of weakly expressed Podzols (Bhs horizons of the margin of the podzolic areas), or at a greater depth in those of better differentiated podzols (Bh and BCs horizons) is associated with the accumulation of metals bound to organic ligands, which occur at greater depth for Al (Bhs and BCs) than for Fe (Bhs and Bh).

Podzols in the incised inundated peneplain of the study site also display relevant differences with the waterloged podzols studied elsewhere by Nascimento et al. (2004) in poorly drained

plateau depressions. Major morphological differences in podzols result from the incision of the podzolic areas by river systems. They are observed at two distinct places within the soil catena: (i) at the lateral weathering front between the upslope clay-depleted laterites and the midslope podzols, and (ii) in the downslope eroded podzols developing convex sloping sides with the river network. The accumulation of organic matter at the lateral weathering front is less abundant, in particular in the thinner spodic Bhs of weakly expressed podzols but also at greater depth in the thin and discontinuous Bh horizon of better differentiated podzols. Besides, the hydromorphic saprolite, directly in contact with the upslope podzolic area, locally displays numerous iron segregations. These major morphological changes likely result from shorter periods of anoxia due to river incisions and the recede of the perched groundwater from the upslope podzolic area. Indeed, shorter periods of anoxia at the lateral weathering front speed up the mineralization of organic mater, release the organically bound metals, and favour the precipitation of Fe-oxides. Downslope on the convex sloping side, the podzolic weathering front has expanded downwards into the fine and clay-depleted saprolite and ultimately in low-lying positions into the coarse saprolite. Consequently, this weathering front has initiated the formation of a second generation of eluviated and illuviated or spodic horizons in strongly and ultimately in less weathered saprolitic materials. The deeper impregnation of organic matter in spodic horizons from the upslope to the downslope position of the podzolic area is closely linked to a simultaneous increase of the thickness of the organic-rich and eluviated topsoil horizons of podzols. This lateral trend results from drastic structural changes in the vegetation cover and therefore in the organic inputs to soils, with a more open forest (*Caatinga*) in the upslope podzols and a dense riparian forest in the downslope podzols. It also assigned to contrasted hydrological regime, with higher turnovers of organic matter in better-drained podzols of the *Caatinga* and slower ones in the waterlogged podzols of the riparian forest. Moreover, the weak acidification of the downslope podzols mainly formed on weakly weathered saprolites prevents the release of metals bound to organic ligands.

Acknowledgments

The research was funded by CAPES-COFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l’Univers du CNRS), through the “Ecosphère continentale” programme: “Podzolisation des

latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)”.

CAPITULO 5. ALTERAÇÃO E EROSÃO DAS SUPERFÍCIES CENOZÓICAS E GÊNESE DOS PODZÓIS HIDROMÓRFICOS NA BACIA DO RIO NEGRO

Résumé

Ce chapitre est un essai de reconstitution de la dynamique d'expansion des podzols à nappes dans le bassin du Rio Negro à partir d'études ponctuelles réalisées sur des séquences de sols, de documents cartographiques obtenus à des échelles régionales et des connaissances actuelles sur l'histoire géodynamique et géologique du bassin amazonien. Les études minéralogiques et structurales réalisées le long de séquences de sols situées dans des points clés des paysages faiblement ou fortement podzolisés du bassin versant du Rio Negro (sites (3) et (4)) ont permis d'élaborer un modèle d'évolution de ces paysages qui intègre : (i) processus majeurs associés aux re-mobilisations et exportations de matières, et (ii) fonctionnements hydriques associés. La reconnaissance des principales surfaces géomorphologiques (surfaces d'aplanissement, dépôts sédimentaires, chenaux fluvio-lacustres…) de ce bassin nous a amené à extrapoler ce modèle à plus petites échelles, révélant alors les principaux facteurs associés à l'expansion des podzols à nappe dans les paysages latéritiques d'Amazonie.

Le modèle proposé oppose des processus d'altération propices à une fonte géochimique des formations continentales à des processus érosifs associés à l'incision de ces formations par le réseau hydrographique et à l'accumulation des produits de cette érosion dans les lits des rivières. Dans le bassin du Rio Negro, les surfaces continentales appartiennent essentiellement aux vastes pénéplaines du Tertiaire, qui ont été incisées au Quaternaire par les tributaires du

Rio Negro et ont de ce fait formé les plateaux surbaissés de ce bassin. Dans les parties hautes et bien drainées de ces plateaux, l'érosion chimique des formations continentales a conduit à la formation de latérites plus ou moins épaisses par accumulation résiduelle d'Al et Fe dans les minéraux argileux du sol. Dans les parties centrales et moins bien drainées de ces plateaux, l'érosion chimique accrue de ces latérites est associée à une plus grande mobilité d'Al et Fe. Les pertes de ces éléments sont reliées à un appauvrissement des latérites en milieu faiblement (au voisinage de la surface) ou fortement (en profondeur) anoxique puis, lorsque le milieu devient suffisamment perméable, à une podzolisation de ces latérites. Cette étape ultime dans l'érosion des latérites est liée à la dissolution des quelques minéraux argileux qui subsistent dans ces sols par des substances organiques qui migrent et s'accumulent dans les fronts latéraux de podzolisation sous forme de complexes organo-métalliques. Ce processus marque de ce fait un changement de spéciation majeur pour les métaux (du minéral vers l'organique). Il est étroitement lié à l'individualisation et fluctuation d'une nappe perchée dans le réservoir sableux des podzols et au développement de conditions réductrices et acides au sein de cette nappe. Les deux grands processus (appauvrissement puis podzolisation) transformant les latérites en un résidu sableux progressent de façon centrifuge, depuis le centre vers le rebord des plateaux. A cette fonte chimique des latérites s'oppose une érosion physique progressant dans une direction complètement opposée. Cette érosion régressive des bords des plateaux par les incisions des ruisseaux alimentent en sédiments les lits des rivières. Dans les plateaux faiblement podzolisés du bassin moyen du Rio Negro (site (3)), les dépressions à podzols sont faiblement incisées par les ruisseaux et l'érosion régressive des rebords des plateaux latéritiques fourni d'abondants sédiments argileux aux eaux brunes des rivières. Dans les vastes pénéplaines à podzols du haut bassin du Rio Negro (site (4)), les incisions du réseau hydrographique drainent les nappes de ces podzols et fournissent d'abondants sables blancs aux eaux noires des rivières.

Dans le bassin du Rio Negro, les surfaces continentales appartiennent (i) à la surface d'aplanissement pan-américaine *Ucayali* du Miocène Moyen, (ii) au dernier épisode sédimentaire du Tertiaire attribué à la Formation Içá, épisode qui s'est achevé fin Pliocène lors de la naissance du réseau hydrographique actuel du fleuve Amazone, et (iii) aux surfaces d'érosion et de sédimentation du Quaternaire. Les sédiments Quaternaires se sont essentiellement accumulés à deux endroits dans le lit majeur du Rio Negro formant les archipels de: (i) Mariuá (bassin moyen) et (ii) Anavilhanas (bas bassin). L'épaisseur des formations latéritiques du bassin du Rio Negro dépend étroitement de l'age de ces surfaces.

Ces formations sont généralement épaisses, parfois faillées, sur la surface d'aplanissement pan-américaine *Ucayali* et, à l'inverse beaucoup moins développées sur la Formation Içá (<1m). Cette dernière présente de nombreux chenaux et dépressions qui pourraient correspondre à d'anciens chenaux fluvio-lacustres.

La répartition des podzols dans le bassin du Rio Negro montre un contrôle lithologique et pluviométrique majeur dans l'expansion de ces formations dans les principales surfaces géomorphologiques du bassin. L'expansion des podzols est réduite dans les couvertures latéritiques peu épaisses de la Formation Içá. Elle est limitée aux chenaux ou dépressions de cette formation, ce qui laisse présager d'un contrôle de structures fluvio-lacustres dans la mise en place de ces podzols. L'expansion des podzols dans les paysages devient beaucoup plus importante au Nord et au Nord Ouest, dans les régions les plus pluvieuses du bassin. Dans ces régions, les vastes étendues à podzols se sont également développées sur des couvertures latéritiques plus anciennes et plus épaisses de la surface d'aplanissement *Ucayali*. Les plus grandes étendues de podzols au Nord Ouest sont drainées et incisées par les principaux tributaires du haut Rio Negro. Ils ont alimenté en sables blancs les lits des rivières et construit l'archipel de Mariuá dans le bassin moyen du Rio Negro, le plus grand piège à sédiments de podzols du bassin amazonien.

L'étude montre ainsi que les podzols à nappes du bassin versant du Rio Negro se sont essentiellement développés sur les surfaces d'aplanissement et sédimentaires les plus anciennes du Tertiaire ce qui laisse présager d'un grand âge pour ces sols. Leur plus grande expansion dans les paysages est contrôlée à la fois par les apports pluviométriques (propices aux engorgements par leur abondance) et la nature du support sur laquelle elles se forment (accrue sur latérites très altérées et anciennes de la surface d'aplanissement *Ucayali*). L'incision linéaire des surfaces Tertiaires, il y a environ 2.5 Ma lors de la mise en place du réseau hydrographique moderne du fleuve Amazone, a permis de drainer les aires les plus podzolisées à l'amont et au Nord du bassin du Rio Negro. Ce drainage associé à une érosion des bords de berges a permis de restreindre l'expansion de ces vastes étendues à podzols dans les paysages et d'alimenter en sables blancs les bords de berges et le principal piège à sédiments situé juste à l'aval de ces grandes étendues à podzols (archipels de Mariuá). Une seconde génération de podzols s'est ultérieurement développée sur les surfaces incisées des rebords de plateaux et les dépôts Quaternaires soulignant ainsi la grande continuité dans le temps du processus de podzolisation. En effet, ce processus continue de nos jours à alimenter en substances organiques et métaux les eaux noires des rivières du bassin versant du Rio

Negro, contribuant ainsi à entretenir un environnement extrême peu propice au développement de la vie.

5.1. Introduction

The Negro River catchment belongs to the northern part of the Amazon flat surface, bordered by residual hills, inselbergs and *Mesas* of the Guyana shield in the Northeast (Fig. 1). The dissection of this vast surface has generated a plateau-like relief (*Amazonian planalto)*, some tens meters above average river levels (90 to 60m a.s.l.), and the formation of narrow alluvial terraces in major river corridors (Franco et al., 1977; Costa et al., 1978). These low elevation plateaux (*terra firma*) commonly present dissected edges, with flat-top to convex hills, as well as dispersed and ramified depressions in their centre (Franco et al., 1977; Costa et al., 1978; Bezerra, 2003). While the most elevated relieves present some uniformity on their bauxite, iron pans, or reddish and clayey Ferralsols, the widespread low elevation plateaux with their incised edges and ramified depression network show high diversity of soils (Costa et al., 1978; Yamazaki et al., 1978; Dubroeucq et al., 1999). Such soil diversity is also manifest on the vegetation physiognomy that grade from an evergreen forest to a shrub savannah (SILVA et al., 1977; Magnago et al., 1978). Maps of the RadamBrasil Project (1972-78) reveal that diversity. Freely drained soils (Ferralsols and Acrisols) under forest are commonly present on plateau edges whereas waterlogged soils with various types of vegetations occupy the alluvial terraces and the depressions of the plateaux. Waterlogged soils on the plateaux are either clayey or sandy and correspond respectively to Gleyic Plinthosols and Hydromorphic Podzols. In waterlogged Podzols, the development of reducing and acidic conditions enhanced the production of organic acids, the weathering of clay minerals, the formation and downward accumulation organo-metallic complexes and their exportation to the river network (Lundström et al. 2000; Do Nascimento et al, 2004, 2008, Bardy et al., 2007, 2008, Fritsch et al., in review). The abundance of Podzols in the Negro River catchment explains the small quantity of suspended load, the extent of organic colloids and associated metals in most surface waters, and their dominant black colour (Allard at al. 2002, 2004; Benedetti et al. 2003).

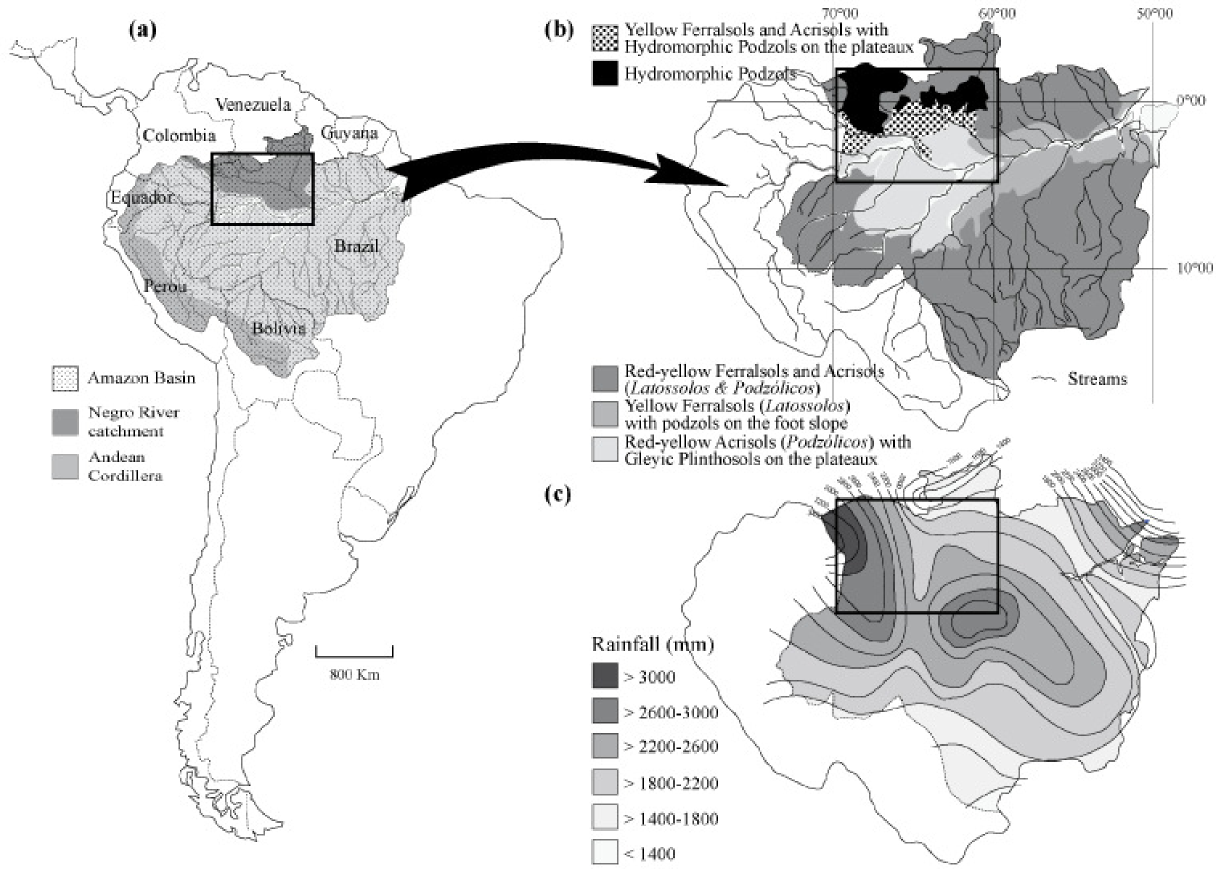


***Figure 1**. (a) The Negro River catchment within the Amazon Basin in South America, (b) broad scale soil map (reduced and simplified from Radam Brazil maps at 1:1000.000) and (c) average annual rainfalls (from ANA) of the Brazilian Amazon Basin (black rectangle insert refers to site location in Fig. 2).*

The low elevation plateaux of the upper Amazon Basin is usually explained based on the principle of planation by erosion cycles, deriving from King's proposition (King, 1953). According to this author, the flat surfaces are elaborated by erosion and lateral slope retreat, mainly under dry climates, generating residual relieves, pediplains and ultimately sandy deposits (*playa* and *bajada*) at low elevations. Base-level lowering due to positive epeirogenesis or marine regression (King, 1953), or climatic oscillations towards the humid (Bigarella & Andrade, 1965; Franco et al., 1977; Costa et al., 1978) would be responsible for river incision phases which, alternating with planation phases, generated polycyclic landscapes. According to this model, the *Mesas,* inselbergs and major hills of the Negro River catchment would correspond to the residual relieves, the widespread flat surface to an active phase of soil denudation and the sandy deposits in depressions (*playa* and *bajada*) to sedimentation (Franco et al., 1977; Costa et al., 1978), generated during the late pediplanation

and sedimentation in the upper Amazon Basin. Deep river incisions and development of a ramified network of brooks (*igarapes*) in the lands would have eroded the edges of the low elevation plateaux and built up the alluvial terraces.

An alternative genetic explanation for the development of low elevation lands follows the principle of soil collapse governed by hypodermic chemical erosion. This approach proposes that geochemical processes, which act into the soil and saprolite mantles, drive landscape evolution towards planation (Bocquier, 1971; Boulet R., 1974; Millot, 1983, Dubroeucq et al., 1991). Indeed, soil change processes that transform laterally one soil type into another (Fanning and Fanning, 1989) are commonly related to losses of matter. Such losses generate soil collapse and therefore surface lowering. They first produce depressions and ultimately vast plains following the upslope expansion of weathering fronts. The importance of this kind of internal erosion depends on the type of weathering process involved in this soil dynamics, which is frequently linked to altered water regimes (e.g. changes from freely drained to waterlogged environments). On this regards, mobilization and export of iron in reducing environments is commonly related to dramatic colour changes in soils (Fritsch et al., 1986; Fritsch et al., 2004) but to limited losses of matter. This process would therefore have weak repercussion on landscape evolution. By contrast, the breakdown of Fe-clay and plasma-skeleton bonds, followed by the mobilization or destruction of clay minerals (Bocquier, 1971; Boulet, 1974; Chauvel et al., 1977) would lead to significant losses of matter, residual accumulation of sands, as thus to relevant change in the physiography of the landscape (Lucas et al., 1987; 1988, Dubroeucq et al.; 1991). Moreover, by producing slope gradients in closed or open depressions, this soil landscape dynamics and associated chemical erosion may generate at or near the surface various types of physical erosion (e.g. sheet, rill, gully and piping) (Planchon et al. 1987, Fritsch et al, 1994). According to this second approach, intense geochemical erosion of weakly or strongly weathered laterites that form clay-depleted soils (Acrisols) and ultimately sandy Podzols would correspond to the major driving process for the development of depressions and vast inundated plains within the low elevation plateaux of the Negro River catchment (Dubroeucq et al., 1991; 1999).

Two opposite interpretations are thus given in the literature to explain the formation of waterlogged Podzols in the Northern part of the upper Amazon basin. The first approach closely links the formation of Podzols to sandy deposits (e.g. Klinge 1965; Bezerra, 2003), suggesting therefore a major sedimentary control in the development of weathering processes. The second approach reveals that waterlogged Podzols may form in poorly drained

environment (between major tributaries of the Negro River) from *in situ* weathering of laterites leading the residual accumulation of quartz sands and major exportations of organo-metallic complexes to the river network (e.g. Lucas et al., 1987; 1988). Both sedimentary and weathering processes could also have acted simultaneously in the Negro River catchment. This highlights that the large development of degraded soil landforms in this catchment, with the ultimate formation of waterlogged and acidic Podzols, must be replaced in the frame of the late Tertiary sedimentation in the upper Amazon Basin and the birth of the Amazon River system during the Quaternary.

We have undergone pedo-geomorphic investigations at three different scales in the Negro River catchment (from global to very detailed field surveys and related laboratory investigations) to reveal major landforms and associated chemical and physical erosion processes that have contributed to the formation of highly degraded lands. In the discussion of this paper, a schematic model of soil landscape evolution is proposed to explain the formation of these lands in the frame on the sedimentary, tectonic and climatic history of that part of the Amazon Basin.

5.2. Environmental Setting

We present in this section the most recent interpretations on the Tertiary history of the Amazon lowlands and the ultimate birth of the Amazon River system. Tectonic events (Quechua I and II), related to the collision between the South American and Nazca tectonic plates and the birth of the Andean cordillera, have strongly altered the physiography of the upper Amazon basin during the Tertiary. From the early to the mid-Miocene Quechua I orogenic phase of Andean tectonism, the drainage system of the Amazon basin discharged sediments into a Pacific embayment. It formed the largest continental deposits of the world, known in Brazil as the Solimões formation (Sampaio and Northfleet, 1973). This sedimentary event was followed by intense phase of erosion associated with the formation of the Andean cordillera during major orogenic events of the Quechua II. This orogenic event cut the western drainage system and forced the rivers to turn east. A very extensive marsh and lake-region was born in the middle of the upper Amazon Basin (Campell et al. 2006). In the late Pliocene, base-level lowering has initiated the development of the modern Amazon River system, the incision of the lowlands and thus formed the low elevation plateaux of the upper Amazon Basin.

A more accurate chronology of the Tertiary events has been recently proposed by Campbell et al. (2006) and generalized to the whole upper Amazon Basin using stratigraphic unconformities and subsequent depositional features at widely separated areas within the Andes of Bolivia, Peru and Ecuador. A Pan-Amazonian surface has been identified and related to major erosion events leading to the formation of the Ucayali Peneplain. Peneplanation within the upper Amazon Basin likely started at the mid-Miocene, i.e. 15 Ma ago at the end of Quechua I, and terminated abruptly near the beginning of the late Miocene Quechua II orogenic event at ~ 9.5 Ma. This was followed by the late Tertiary sedimentation, which starts blanketing the lowlands and forms ultimately deltaic and lacustrine deposits of moderate to low energy within a giant lake (*Lago Amazonas*) following the closure of the gates to the Pacific ocean, in both the South and North directions. These deposits previously assimilated to the Solimões Formation in Brazil are now differentiated from the latter and assigned to the Içá formation (DNPM, 1981). This last continental sedimentation ends up in the late Pleistocene at ~ 2.5 Ma with the birth of the modern Amazon River system.

Detailed and regional surveys on soils derived from the Içá formation in the North region of PortoVelho (Fritsch et al., 2007) reveal less weathered materials and thinner soils (≤ 1 m) than those exposed on the Ucayali Peneplain of the Manaus (Fritsch et al., 2004) or São Gabriel da Cachoeira (Montes et al., 2007) regions (2 - 15 m), suggesting therefore younger soils. On this regards, datation of kaolinite, a ubiquitous clay mineral of tropical soils, using radiation-induced defects, could not be done for the youngest soils due to the presence of residual primary minerals (mostly mica) but gave an age ranging from 25 to 65 Ma for saprolitic materials of deeply weathered soils (Ferralsols) of the Manaus region (Balan et al., 2005). This apparent age is much older than that attributed to the late Tertiary sedimentation (2.5 Ma) and thus ignition of soil weathering on the Içá formation. It is also older than that related to the late orogenic events of the Quechua I (15 Ma) and indicates the formation of deeply weathered lateritic materials prior to the implementation of the Ucayali Peneplain.

The buried Peneplain, described by Campbell et al. (2006) on river cut-banks, separates eroded, often folded, faulted, and weathered, moderately to well consolidated materials from the unconsolidated, near horizontal, upper Tertiary deposits (Içá formation in Brazil). Spectacular faulting through deeply weathered lateritic profiles developed on the Alter do Chão, with hectometric uplifted and sunken blocks are observed on all road cuts of the Manaus region (Fritsch et al., 2004). It thus indicates that the Ucayali Peneplain is exposed at the surface in this region. It also suggests that faulting in old lateritic materials is likely

contemporary to Quechua II orogenic events and attributed to reactivation of the deepest faults of the Amazon graben (Hasui et al., 1984; Bezerra, 2003).

The end of Quecha II, with the ultimate formation of the Andes, is closely followed by the birth of the modern Amazon River System. This is nearly coincident with the onset of the Plio-Pleistocene glacial climatic regime and the lowest sea level stands since the latest middle Miocene (Campbell et al., 2006). This climatic event is likely at the origin of the deepest cuts in the riverbeds and incisions of the edges of the newly formed plateaux. River cuts show strong tectonic controls in the investigated catchment, more specifically at the extremity of the Amazon trough with dominant N45°W and N70°E lineaments in the lower Negro River catchment and N70°W and N-S lineaments in the middle one (Fig. 2). In the main drainage system of the Negro River, major sunken blocks linked to reactivation of deep faults of the Amazon graben has led to the formation of two archipelagos, separated by narrow river corridors with rock outcrops (Latrubesse and Franzinelli, 2005).

The formation of the Andes has also led to the establishment of a climatic gradient, oscillating from humid to dry during the Quaternary. The present climate is hot and humid. Mean annual temperature is elevated and almost constant throughout the Negro River catchment, decreasing slightly from the East (27 ^{o}C) to the West (25 ^{o}C) (Costa et al., 1977; Yamazaki et al., 1978). Mean annual precipitations present significant seasonal and regional changes. They increase westwards, from 1750 mm to more than 3500 mm. At Manaus (lower catchment) the average month precipitations are uni-modal, with a maximum on April (319 mm) and a minimum on August (43 mm) (Yamazaki et al., 1978). At São Gabriel da Cachoeira (upper catchment) precipitations are bi-modal, with maximum on January (289 mm) and April (339 mm) and minima on February (282 mm) and August (124 mm) (Costa et al., 1977).

5.3. Materials and methods

Pedo-geomorphologic investigations were carried at three major scales: (i) at global scale in the Northwestern part of the upper Amazon Basin in order to display the relative distribution of Podzols in the landscapes of the Negro River catchment, (2) at regional scale in two selected sites of the catchment to display contrasted abundance of Podzols in these landscapes and (3) at local scales in both selected sites to show gradual changes of colour and texture in well-drained upland soils observed along selected transects as well as abrupt ones along soil catena (lateral appearance of waterlogged Podzols).

Global scale

For the Negro River catchment, the data sources were the soil, geological, vegetation and geomorphological maps at 1:1.000.000 scale of the RADAM Project, and the Landsat TM satellite images. The three maps generated from these data using GIS softwares display soil types in relation with major geological and geomorphological units (Fig. 2). They revealed the distribution and relative abundance of waterlogged soils (Gleyic Plinthosols and Hydromorphic Podzols) in relation to better-drained ones (Ferralsols and Acrisols) of the uplands as well as the extent of Quaternary and modern deposits in terraces and riverbeds (Gleysols). The tendency of an orderly distribution of Podzols in the landscape and spatial expansion in an ESE-WNW direction, more specifically between two major rivers of the upper Amazon Basin, i.e. the Solimões and Negro Rivers, oriented the selection of two sites for detailed pedo-geomorphological investigations. The two sites belong to the low elevation plateaux of the basin. The first one (Jaú site), located in the lower Rio Negro catchment, marks the appearance of waterlogged Podzols in the uplands. The second one (Curicuriari site), 650 km upstream, belongs to the upper Rio Negro catchment. It is an almost completely podzolized soil landscape. The Jaú site is located within a National Park and the Curicuriari site inside an Indigenous Reserve. Accordingly, the impact of human activities on soil landscapes is negligible.

Regional scale

For each site, the relative distribution and the abundance of well-drained and waterlogged soils of the uplands (low elevation plateaux) and lowlands (terraces) in relation with major geological formations were estimated from digitized soil and geological maps at 1:100.000 of the RADAM Project (Fig. 2a,b and Fig 3a,b). More detailed maps (Fig. 2c and 3c) and block diagrams (Fig. 2d and 3d) of soil and vegetation in relation to major landforms were elaborated from aerial photographs (1980) for the Jaú site and from Ikonos satellite images (2005) for the Curicuriari site. The mapping was based on the photograph/image texture and tonality and on the degree of relief dissection that are function of vegetation type, soil drainage conditions and intensity of river incision, respectively. Field surveys were carried out in these selected areas to check map unit demarcations and to obtain precise altimetric data using topographic GPSs Topcon Hiper and a pair of Paulin Altimeters under vegetation cover. Aerial photographs or satellite images coupled with topographic GPS and altimeter data allowed the elaboration of the block-diagrams for each site using 3D design softwares.

Local scale

Detailed topographic and soil surveys in pits or drilling cores were conducted in the two sites. They were particularly abundant along two transects, extending from the margin of the river Jaú or Curicuriatri to the central part of the plateaux (Fig. 2e and Fig. 3e). The transects illustrate gradual changes of colour and texture in the soils and underlying deeply weathered rock formations (saprolites). They are 4.3 km long at the Jaú site and 1.6 km long at the Curicuriari site. In the latter, five profiles (P1, P2, P3, P4 and P5 in Fig. 3e), developed on a granitic rock basement, were selected to better illustrate and interpret the vertical and lateral changes of colour and texture in soils and saprolites. Soil colour was determined in the laboratory on dry fine earth samples (< 2 mm) by spectroscopy measurements in the visible range. The samples were gently grounded, oven-dried at 60^oC overnight during 24 h, put into a 27 mm diameter hole in an Al disk 3 mm thick and then gently pressed against a quartz glass. Diffuse reflectance spectra were taken from from 360 to 830 nm at 1 nm steps using a Varian Cary 5G UV/Vis/NIR spectrophotometer. The CIE tristimulus values were calculated using the colour matching functions of the CIE standart illuminant C (Wyszecki & Stiles, 1982) and a software was used to convert these values into Munsell notations (H for Hue, C for Chroma and V for Value). Particle-size distribution was determined by sieving of sand fractions and of clay-silt by pipetting after destruction of organic matter by H_2O_2 and clay dispersion by hexametaphosphate. The particle size classes are: clay (< 0.2 µm), silt (20 – 50 µm), fine sand (50-200 µm) and coarse sand (200 – 2000 µm).

Soil and mineralogical investigations were also performed along two soil catena. The soil catena is 120 m long at the Jaú site and 80 m long at the Curicuriari site. They both exhibit the spectacular lateral transition between freely-drained, clay depleted soils (Acrisols) in upslope positions and waterlogged Podzols in downslope or low-lying positions (Fig. 4). Soil were described in pits or trenches (in particular at the transition) and photographed. Soil horizon or feature demarcations were then extended on the whole soil catena using graphic softwares (Rinder et al. 1994). Detailed geochemical, mineralogical and petrographic investigations were performed on each soil catena (e.g. see Methods in Do Nascimento et al. 2004). In the Curicuriari site, a detailed soil and topographic survey was also conduced in highly incised podzolised area (50 m spaced grid on 32.5 ha) and a ground penetrating radar (GPR) survey was carried out during the early rainy season (Novembre 2006).

5.4. Results

5.4.1 Soil landform distributions at global scale: the Negro River catchment

Figure 2 displays the major geological formations (Fig. 2a), geomorphic landforms (Fig. 2b) and soil units (Fig. 2c) of the Rio Negro catchment. Archean gneisses, granites and migmatites of the Guyana Shield are exposed in the Northern part of the catchment (Fig. 2a). They are covered in the South by the sediment pile of the upper Amazon Basin. The oldest sediments of the catchment outcrop in the East. They belong to Paleozoic (Properança, Trombetas) and Cretaceous (Alter do Chão) deposits, which have filled up the Amazon graben and are now exposed at the margin and central part of the Amazon trough (only the extremity of this Amazon trough is seen in Fig 2a). The Southern part of the catchment is predominantly covered by the Içá formation, the youngest Tertiary deposits overlying the weathered materials of the Guyana Shield in the North and those of the Solimões formation in the South and the West. Four types of erosion and sedimentation surfaces may be identified in the catchment (Fig. 2b): (1) the Ucayali Peneplain, i.e. the widest surface of erosion, (2) the Içá formation, which marks the late Tertiary sedimentation in the Amazon lowlands, (3) the depressions, drains or plains assigned to chemical erosion or physical erosion in former drainage networks of the Içá formation or both and, (4) the incisions and deposits (alluvial terraces) of the modern Amazon River system.

Hydromorphic podzols of the upper Amazon basin are mainly concentrated in the Negro River catchment (Fig. 2c), where they cover 200.000 km^2 of the lands, i.e. 33% of the surface of the catchment. They are formed on different geological formations (Fig. 2a), which are assigned to two major geomorphic surfaces: (i) the depositional surface of the Içá formation, mainly in the lower and middle Negro River catchment and (ii) the Ucayali Peneplain in the upper Negro River catchment (Fig. 2b). Hydromorphic Podzols display similar distribution pattern than Gleyic Plinthosols in the lower and middle Negro River catchment (I and II, respectively in Fig. 2c). Indeed, both kinds of waterlogged soils are lying in ramified networks of drains and depressions, and are both surrounded by slightly higher elevated and better-drained lateritic soils (Ferralsols and Acrisols). As suggested elsewhere by Fritsch et al. (2007), they most likely mark the emplacement of former drainage systems of the Içá formation. Widely extended in the southern part of our investigated region (between the Negro and Madeira rivers), this ancient drainage system is locally cross cut by the modern one, more specifically by the Quaternary alluvial deposits of major Andean rivers (see for example those of the River Solimoes in Fig.2b). This suggests that the development of both

kinds of soils and associated weathering processes (i.e. hydromorphy and podzolisation) in this major sedimentary structure could be prior to the birth of the Amazon River system (i.e. 2.5 Ma).

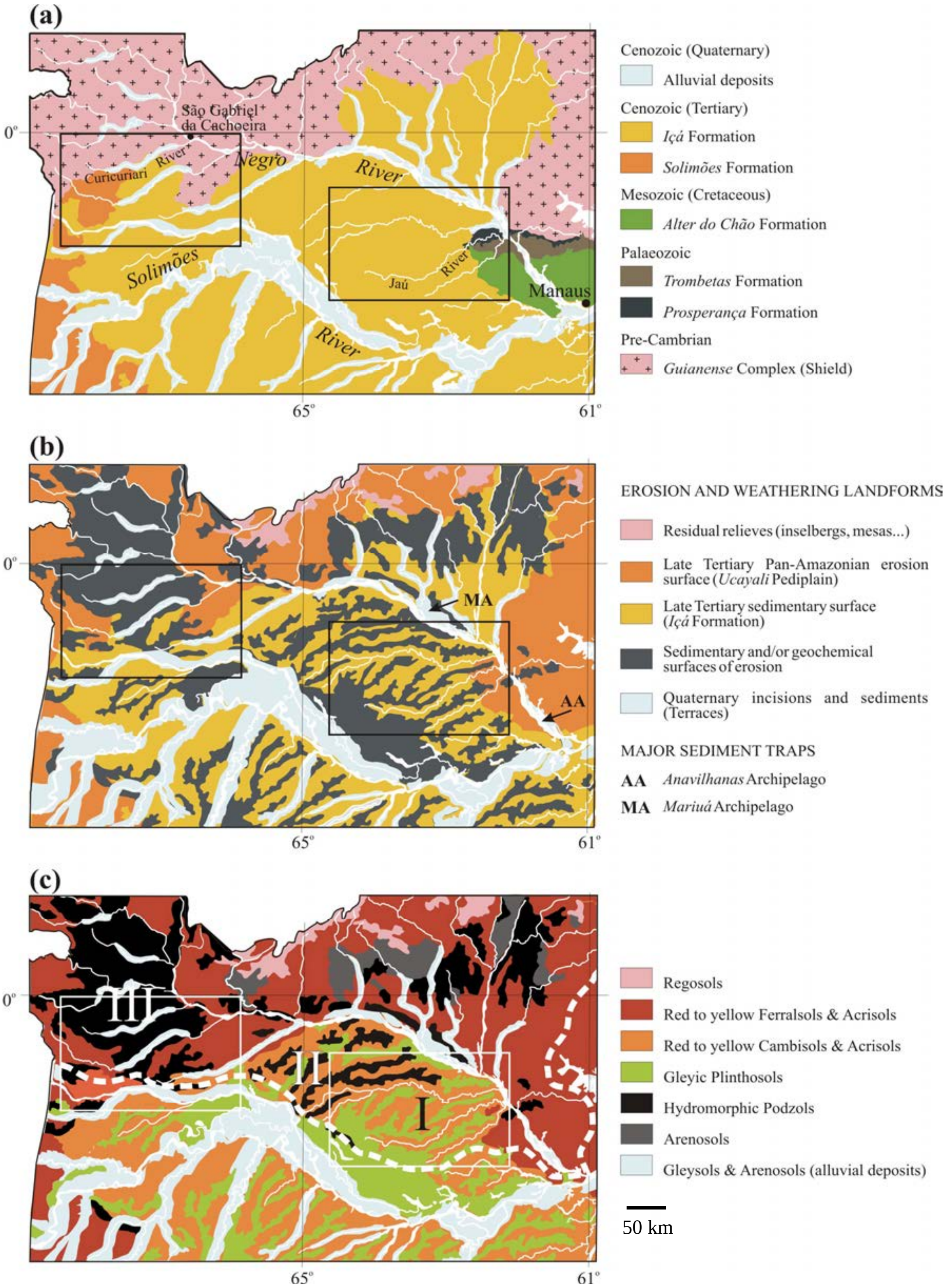


Figure 2*. Broad scale maps of the Northwestern part of the Brazilian upper Amazon Basin showing the major: (a) geological formations (reduced and simplified from DNPM geological*

map at 1:2.500.000), (b) geomorphic landforms (adapted from (a)) and (c) soil units (reduced and simplified from IBGE soil map at 1:5.000.000) of the Negro River catchment. Thick dashed white line refers to the water divide of the Negro River catchment, black or white rectangle inserts refers to regional maps of the Jaú and Curicuriari sites (Figure 3 and 4, respectively).

Figure 2c shows that the superficies covered by Hydromorphic Podzols increase in a Northwestern direction. Such a trend can be related to the establishment of a major climatic gradient after the definitive implementation of the Andean cordillera, with a total annual rainfall that reaches nowadays 1750 mm downstream of the Negro river (Manaus) and becomes greater than 3500 mm upstream. In the lower Negro River catchment (I in Fig. 2c), Hydromorphic Podzols are scarce and scattered whereas Gleyic Plinthosols are widely present in the ramified depressions of the plateaux. The reverse trend is observed in the middle Negro River catchment (II in Fig. 2c), the Gleyic Plinthosols giving rapidly place to hydromorphic Podzols. In the upper Negro River catchment (III in Fig. 2c), the Hydromorphic Podzols, formed on different geological formations of the Ucayali Peneplain, are widely developed on right side of the Negro River and drained by its major tributaries.

In the investigated region, the implementation of the modern river system (Fig. 2) is tectonics controlled and inherited from reactivation of deep structures of the Amazon graben during: (i) the separation of the Gondwanaland and (ii) the early to late Miocene Quechua I and II orogenic events (formation of the Andes). Headwater incisions of the lands by rivers has formed low elevations plateaux but produced weak quantity of sediments in the riverbanks, as the Negro River catchment mostly drained low elevated lands and strongly weathered soils. This is quite different from the major Andean rivers in the South (e.g. the Solimões River in Fig. 2c), which exhibited large alluvial terraces mostly related to active headwater erosion of weakly weathered soils in upstream high elevated Andean lands. However, two major sediment traps have been recognized in the main corridor of the Negro River: (i) the Mariuá Archipelago in the middle catchment (MA in Fig 2c) with white sandy deposits and (ii) the Anavilhanas Archipelago in the lower catchment (AA in Fig. 2c) with dominant clayey or muddy deposits (Latrubesse and Franzinelli, 2005).

5.4.2 Soil landform distribution at regional scale

Jaú River subcatchment (lower Negro River catchment)

Figure 3a better displays at regional scale, the ramified network of waterlogged soils (Gleyic Plinthosols and Hydromorphic Podzols) in the depressions of the plateaux as well as the alluvial deposits in major corridors of the Negro River tributaries. Both kinds of hydromorphic formations are dissociated and separated by better-drained lateritic soils (Ferralsols and Acrisols) on the plateau edges. Soils on the plateaux have formed on different geological formations of the Ucayali Peneplain in the East (Guianense complex, Prosperança and Trombetas formations of the Paleozoic, Alter do Chão Formation of the Cenozoic) and on deposits of the Içá formation elsewhere (Fig. 3b). Headwater incisions have intensely reworked the edges of the plateaux in numerous hills via a dense network of brooks (*igarapés)* and locally built up alluvial terraces (*Igapó*) in narrow river corridors (Fig. 3c,d,e). The brook incisions are less abundant towards the centre of the plateaux. They locally drain the waterlogged Podzols of the depressions (Fig. 3c,d).

This high diversity of soils and associated landforms is also manifest in surface water quality and colour (Do Nascimento et al. 2008, Fritsch et al. in review). Clear waters in brooks are dominant in the region and draining waterlogged areas of lateritic soils (Ferralsols and Acrisols) as well as, near the surface, those of Gleyic Plinthosols. Black waters are restricted to the brooks that drained the waterlogged Podzols in depressions of the plateaux. Both kinds of waters are almost free of suspended clay minerals. By contrast, surface waters of the Jaú River are brown and richer in suspended clay minerals. In the lower course of the Negro River and its major tributaries, suspended particulate phases in surface waters were mostly related by spectroscopic methods to poorly ordered kaolinite and tiny Fe-oxide mineral phases (Allard at al. 2002, 2004), i.e. the ubiquitous minerals systematical identified in the topsoil of deep lateritic profiles from the same region (Balan et al. 2005; Fritsch et al. 2005). This clearly reveals the origin of the deposits in the alluvial terraces of major tributaries of the Negro River. However, plateau edges are colonized by evergreen forest nowadays and do not exhibit wide, fresh eroded lands. Therefore, remobilisation of clay minerals in major river systems of the medium and low Negro River catchment seems to result from the more recent erosion of the alluvial terraces, which have likely contribute to the formation of the Anavilhanas Archipelago, one of the major sediment trap recognized in the lower course of the Negro River (AA on Fig. 2c).

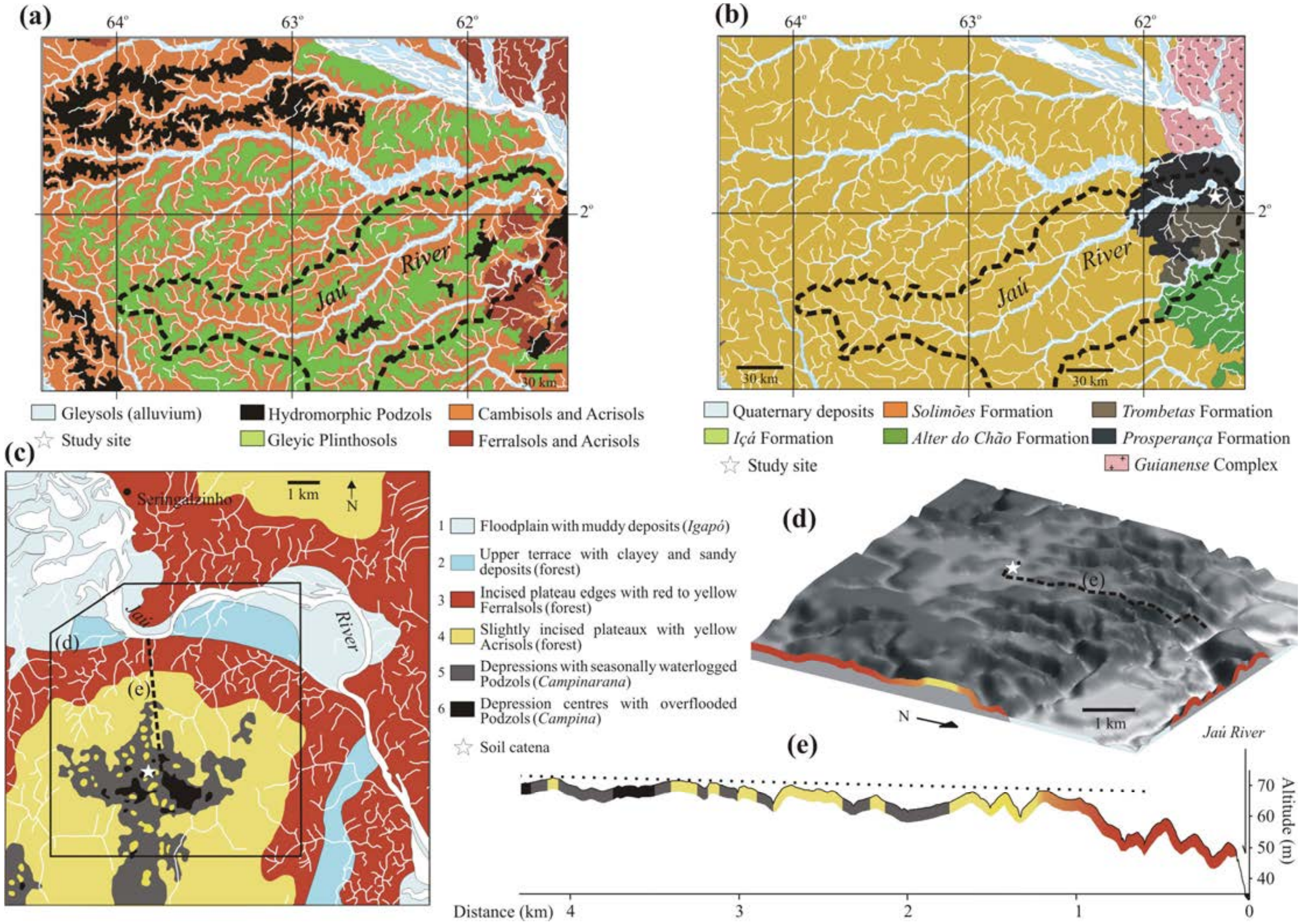


***Figure 3**. (a) Regional soil map and (b) geological map of the Jaú site (extracts from the Radam Brazil maps at 1:1000.000 and modified from the DNPM geological map at 1:2.500.000) plus documents elaborated from aerial photographs and detailed field surveys: (c) map showing major soil landform units and corresponding vegetation covers (see star in (a) and (b) for site location), (d) 3D representation of the same area (see black rectangle insert in (c) for location of the selected zone), (e) soil transect (see dashed line in (c) and (d) for transect location).*

Within the Jaú catchment, waterlogged Podzols in ramified depressions of the plateaux only represent 5% of the lands. One of them has been investigated in detail downstream and on the right bank of the Jaú River (star in Fig. 3a,b, Fig. 3c,d,e). In the study site, soils (Fig. 3a) have formed on sandstones of the Prosperança formation (Fig. 3b). The plateau surface is almost at 40 m above the average water levels of the Jaú River (Fig. 3e). The deeply incised edges of the plateau are bearing reddish-yellow, clayey, low activity clay soils (Ferralsols), covered by evergreen forests (unit 3 in Figure 3c). These clayey soils have built up the Ancient and Recent alluvial terraces in the twisted corridor of the Jaú River (units 1 and 2 in Fig. 3c, respectively). Towards the centre of the plateau, the low activity clay soils turn yellow in their upper part and become progressively depleted in fine particles (Acrisols). They are still covered by the evergreen forest and are weakly incised by a diffuse network of brooks (unit 4 in Fig. 3c). An elongated and ramified depression, locally drained by the brooks, marks the extent of the podzolic area in the centre of the plateau. It is 5 m lower than the plateau surface. The margin of the podzolic area (unit 5 in Fig. 3c) is periodically waterlogged, slightly incised by numerous rills of less than 0.2 m depth and covered by a high density population of smaller trees (*Campinaranas*). The centre of the podzolic area (unit 6 in Fig. 3c) is permanently inundated during the rainy season and covered by a shrub savannah (*Campinas*). Small hill-like landforms bearing Acrisols with evergreen forest and altitudes equivalent to that measured on the plateau are abundant in the depression (Fig. 3c). They have to be considered as lateritic remnants in strongly podzolised lands and thus highlights the contribution of specific processes in the chemical erosion of the lands.

Curicuriari River subcatchment (upper Negro River catchment)

Figure 4a reveals the large extent of Hydromorphic Podzols in the upper Negro River catchment. Podzols occupy huge inundated plains and are thus directly connected to major tributaries of the Negro River. All these tributaries belong to black water systems and are then almost devoid of suspended clay particles (Allard at al. 2002, 2004). As for the Jaú region but at a much larger scale, remnants of freely drained lateritic soils (Ferralsols and Acrisols) are restricted to some dissected plateau edges, near major river corridors, and residual hills or “islands” in huge and weakly elevated inundation plains (Fig. 4a). Podzols in the region are supposed to have formed on weathering products of the *Guianense* shield in the North and the Solimões formation in the West that are both related to the Ucayali Peneplain but also on the Içá formation in the South (Fig. 4b). However, the accumulation of unconsolidated sands in

these huge inundated plains makes difficult the recognition of their parent materials. This is in particular highlighted by the soil map patterns (Fig. 4a), which display certain inconsistencies with that allowed to geological formations (Fig. 4b). Indeed, this study tends to assign the “dendritic” pattern of waterlogged soils developed on the low elevation plateaux (Gleyic Plinthosols and Hydromorphic Podzols) to domains covered by the Içá formation, and therefore to admit the lack of such a pattern for waterlogged soils developed on eroded lands of the Ucayali Peneplain.

As for the other parts of the Negro River catchment, the production of deposits in river beds is limited. However, headwater erosion by the brook and major tributaries of the Negro River now act in unconsolidated sandy materials of Podzols, highly prone to physical denudation. Accordingly, bright white sands are carried in the black waters of the region during periods of high water falls. They have formed waving sandy benches on each side of the rivers. They have also built up the major sandy deposits of the Mariuá Archipelago (MA in Fig. 2b), the other major sediment trap of the Negro River. These bright sandy deposits are certainly one of the most striking features of these highly degraded lands.

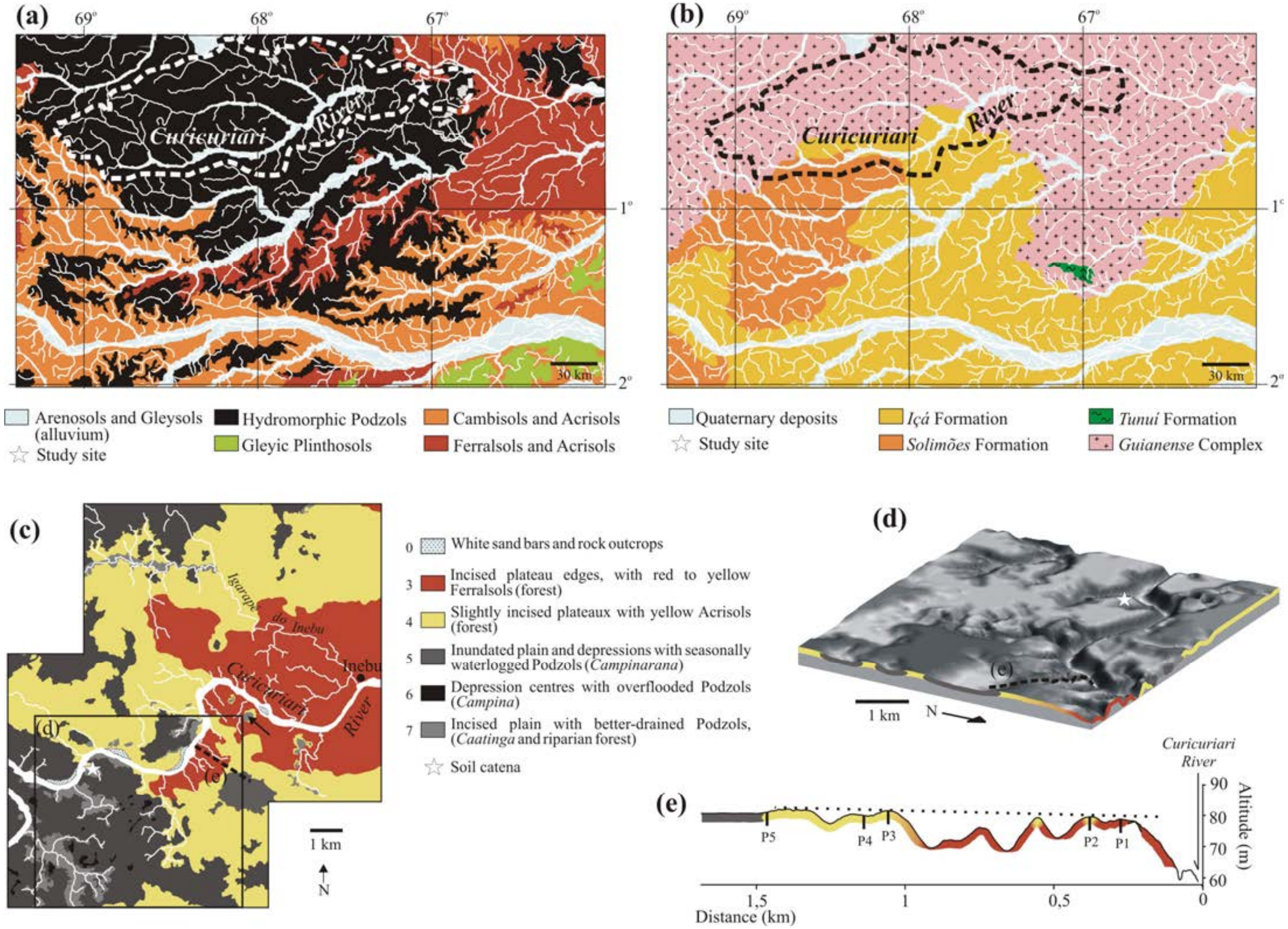


***Figure 4**. (a) Regional soil map and (b) geological map of the Curicuriari site (extracts from the Radam Brazil maps at 1:1000.000 and modified from the DNPM geological map at 1:2.500.000) plus documents elaborated from satellite images and detailed field surveys: (c) map showing major soil landform units and corresponding vegetation covers (see star in (a) and (b) for site location), (d) 3D representation of the same area (see black rectangle insert in (c) for location of the selected zone), (e) soil transect (see dashed line in (c) and (d) for transect location) with selected profiles (from P1 to P5) for colorimeric and particle size distribution of soil and saprolite samples (see Fig. 5).*

Waterlogged podzols cover 95% of the surfaces of the Curicuriari River subcatchment. Detailed field surveys were conducted downstream of the Curicuriari River at the transition between the huge inundated plain with Podzols in the West and the better drained, low activity clay laterites (Ferralsols and Acrisols) in the East (Fig. 4c,d,e). Both types of soils are developed on granitic rocks. Their transition is strongly indented and also characterized by the occurrence of spots of waterlogged Podzols in the freely drained and clay-depleted low activity clay soils (Acrisols). As for the Jaú site, these Podzols are lying in depressions of different sizes and shapes and are thus precursors of the huge podzolised plain (Figure 4c,d). They are 3 to 7 m lower than the low elevation plateau and the latter is about at 20 m above the average water level of the Curicuriari River (Fig. 4e), which is about half of that measured in the lower Negro River catchment (Jaú site). Landform units similar to that recognized in the Jaú site were also identified from the freely drained Ferralsols under the forest to the Hydromorphic Podzols of the depressions or inundated plains under tree or shrub savannahs (units 1 to 5 in Fig. 4c,d,e). One major difference is however reported and assigned to the incisions of the podzolic areas by brook and rivers that drained these areas and enable the development of an open forest (*Caatinga*) (unit 6 in Fig. 4c,d,e).

5.4.3 Detailed soil distributions along transect and catena

Pre-weathering processes along transects: Iron and clay-depletion

In both study sites (Jaú and Curicuriari), the freely drained, reddish-yellow, low activity clay soils (Ferralsols) turn yellow and become progressively depleted in fine particles (Acrisols), before to be podzolised in waterlogged depressions or large inundated plains (Figs 3c,d and 4c,d). Clay-depletion thus appears to be as a pre-existing and necessary process for soil podzolisation (Lucas et al., 1989; Bravard & Righi, 1990; Do Nascimento et al., 2004). Mineralogical, geochemical investigations and mass balance calculations carried out in 5 selected profiles of a 1.6 km long transect (Bueno et al. submitted) illustrating these gradual colorimeric and textural changes in the Curicuriari site (P1 to P5 in Fig. 4e) first indicate a total loss of alkali and alkaline earth elements at the base of the profiles and the residual accumulation of Si, Fe and Al in clay and oxide minerals, mainly kaolinite, gibbsite and Fe-oxides (data not shown). The losses in Fe and Al are enhanced vertically between the saprolite (> 2.2 m) and the overlying soil (0 - 2.2 m) and laterally from P1 to P5. They are mostly assigned in the field to colorimeric (for Fe speciation and content) and textural (for Al

contents) changes. The lack of sedimentary structures, geochemical and mineralogical unconformities and the gradual losses in Fe and Al let us to assign these changes to chemical erosion.

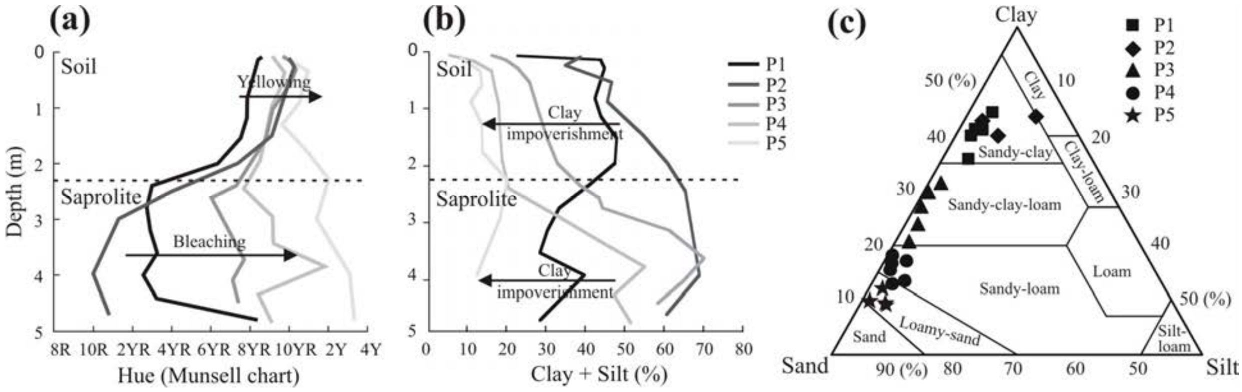


***Figure 5**. (a) Hue of the Munsell colour chart calculated from spectroscopic data in the visible range (H) versus depth, (b) clay + silt (< 50µm) weight percent versus depth, and (c) ternary representation of the percentage of clay, silt and sand in soil samples (B horizons) of the five profiles (from P1 to P5) selected in the transect of the Curicuriari site (see (e) in Fig. 4).*

Colorimeric (Fig. 5a) and textural (Fig. 5b,c) changes affect separately soils and saprolites. Soil yellowing (increase of Hue value in Fig. 5a) and Fe losses first affects the upper part of the weathered profiles that conserve the same type of texture (between P1 and P2 in Fig. 5b). Significant losses of clay minerals occur later on in soils and are related to gradual changes of texture from sandy-clay to loamy-sand (P2 to P5 in Fig. 5c). Soil yellowing first results from selective dissolution of Fe-oxides, first hematite than goethite (Fritsch et al., 1989, 2004; Peterschmitt et al. 1996), whereas the ultimate clay depletion is mostly assigned to the dissolution of Al-bearing minerals, mostly kaolinite and gibbsite (Chauvel, 1977; Fritsch et al., 1989; Bravard & Righi, 1990). Such processes indicate greater water activity and soil leaching in Acrisols than in Ferralsols due to larger periods of soil wetting and reduction in unsaturated soils.

At greater depth, the bleaching of red saprolites (between P2 and P4 in Fig 5a) is mainly assigned to a massive dissolution of Fe-oxides and exportation of ferrous iron by groundwater in waterlogged and strongly reduced environment. Close to the podzolic area (P5), the upper part of the saprolite, bleached by the groundwater, becomes also strongly clay-depleted (Fig. 5b). Clay depletion could either be due to the dissolution or the eluviation of clay minerals and associated with greater trough flows in groundwater (Bueno et al. submitted).

Accordingly the gradual lateral losses of matter from Ferralsols to Podzols, via the intermediate Acrisols, increase at two levels in highly weathered laterites: (i) in the soil from the soil surface (unsaturated zone) and at depth in the upper part of the saprolite (saturated one). They favor at macro-scale the formation of a double tongue-like transition and the development at micro-scale of macrovoids between adjacent quartz (Fritsch et al., 1989) that will favor the migration of humus compounds in soils and thus allow the formation of Podzols in waterlogged environments.

Weathering fronts along soil catena: Podzolisation

Structural and mineralogical investigations were carried out along soil catena at the transition between Acrisols and Podzols in both study sites (Jaú and Curicuriari) (Do Nascimento *et al.* 2004 ; Bueno *et al.* submitted). The soil catena of the Jaú site (Fig. 6a) belongs to a waterlogged depression of a plateau partly drained by small brooks (Fig. 3c). It presents a concave sloping side and extends from a small remnant of a forest on a hill-top to a periodically inundated shrub savannah (*Campina*) in a low-lying position. It is 120 m long and the depression is about 2 m lower than the hill-top. The soil catena of the Curicuriari site (Fig. 6b) marks the transition between the inundated podzolic plain and the upslope well-drained Acrisols. It is close from the Curicuriari River and is incised by a brook in low-lying positions (Figure 4c). It presents a convex sloping side and extends from a forest on a hill-top to a *Caatinga* in the midslope position and an inundated riparian forest close to the brook. This soil catena is 80 m long and the hill-top is 5 m higher than the brook. Many similarities exist for both soil catena suggesting highly representative structures and bio-chemical patterns, assigned to soil podzolisation, that could be extended to the whole upper Amazon basin. However remarkable differences are also reported between each site. They will be attributed to brook incisions that have altered the hydrological regime of Podzols.

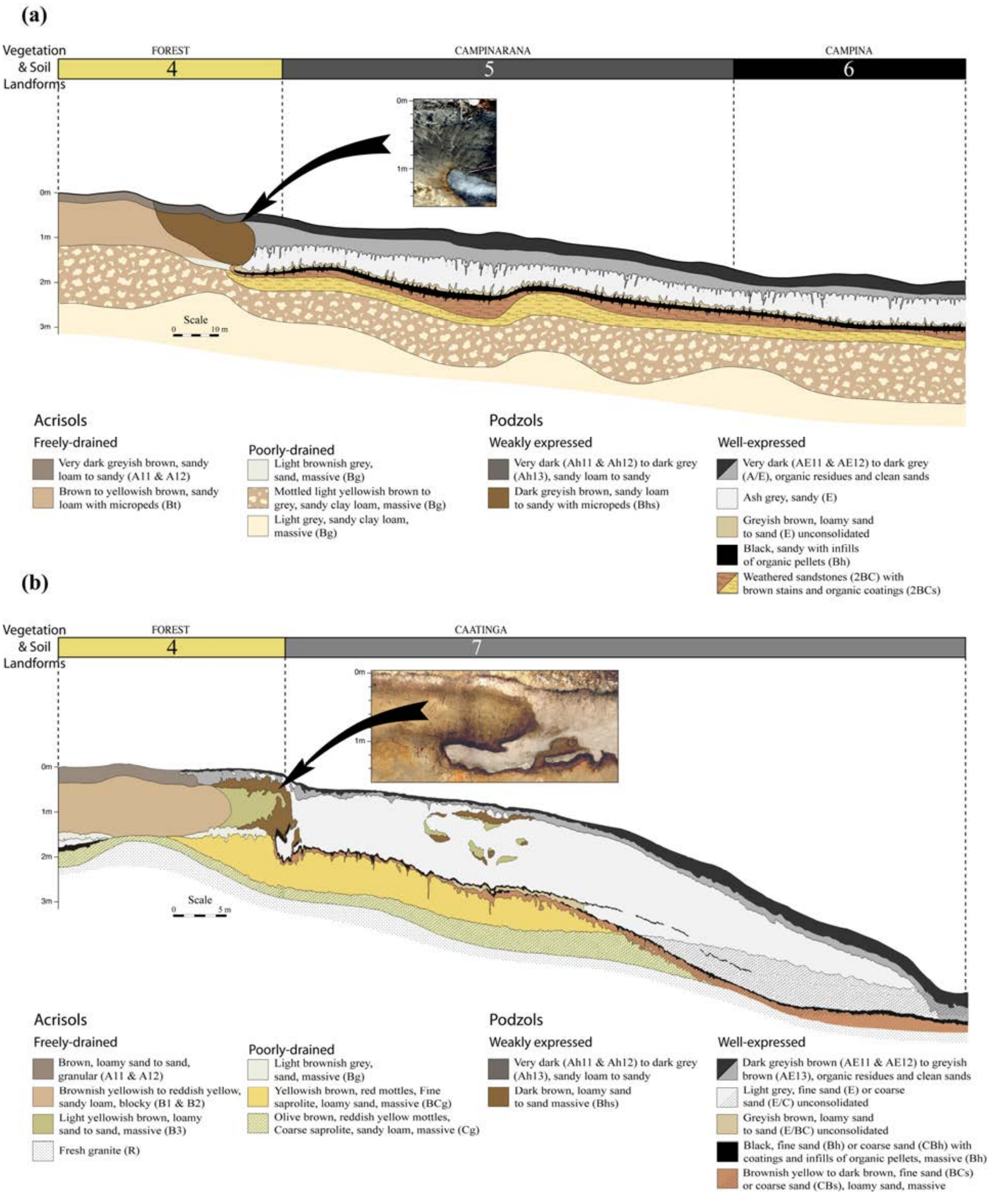


***Figure 6**. Soil catena of the (a) Jaú site in a depression of a plateau (see star in Fig. 3c for catena location) and (b) Curicuriari site at the margin of an incised inundated plain (see star in Fig. 4c for catena location) showing the main types of vegetation and soil horizons according to topographic gradient.*

In both study sites, a double tongue-like shaped transition marks the transition between the upslope Acrisols and the downslope Podzols. This kind of transition has been systematically observed elsewhere at the margin of podzolic areas (Lucas et al., 1989; Bravard & Righi, 1990; Veillon 1990; Dubroeucq et al., 1999; Do Nascimento et al., 2004). The upper tongue is associated with shallow and weakly expressed humus Podzols, which form on top of Acrisols. In such a place, the organic compounds accumulate and deeply impregnate the clay-depleted soils, which contain predominantly quartz but also residual kaolinite, gibbsite and goethite. The organic acids enhance the weathering of clay minerals and contribute to the downward accumulation of organo-metallic complexes (mainly Al and Fe). This first weathering step forms topsoil eluviated A horizons with numerous plant remains and clean sands over subsoil illuviated (or spodic) Bhs horizons with organic coatings (Bardy et al. 2008). In the Curicuriari site, a thin and discontinuous bleached E horizon is also formed between the A and Bhs. The lower tongue is related to the downward but also upslope expansions of Podzols into subsoil B-horizons of Acrisols. This second weathering step marks the almost total loss of clay minerals in AE and E horizons of better-expressed podzols and therefore the residual accumulation of bleached sands as well as the accumulation at greater depths of a second generation of organo-metallic complexes in well-differentiated Bh and BCs spodic horizons (Bueno et al. submitted). By expanding upslope into the clay-depleted and hydromorphic B-horizons of Acrisol, the eluviated E horizon forms the lower tongue of the transition. This horizon may even expand on more than 10 m upslope, at the favor of twisted channels (one of them is cut perpendicularly upslope in the Curicuriai catena, see Fig. 6b). It locally establishes a remarkable structural discontinuity in the vertical differentiation of horizons in Acrisols. This lateral soil differentiation is due to greater through flow in the upper part of the groundwater. Accordingly the convoluted shape of the transition between Acrisols and Podzols and the occurrence in the latter of remnants of B-horizons of Acrisols or Bhs horizons of weakly expressed Podzols (see midslope profiles in Fig. 6b) provide strong evidences of the upslope expansion of the latter into the former.

In both study sites, the development of Podzols is impeded vertically as soon as a more compact and less permeable material is reached. In the Jaú site, this is assigned to a thin slab of weakly weathered sandstones seated on top of a mottled sandy clay loam and loose subsoil. Such kind of material corresponds to the upper part of the saprolitic mantle developed on a granitic basement for the Curicuriari site. Accordingly, textural and structural contrasts in the vertical differentiation of weathered profiles seem to play a major control in the deepening of

Podzols. As soon as a less permeable layer is reached, the lateral development of Podzols will then start to become predominant. The most active weathering front will no longer act at the base of the podzolic areas but at their periphery (Do Nascimento *et al.* 2008). Podzolisation will then be considered as a soil change process (Faning and Faning, 1989) that expands laterally in the landscape (e.g. Sommer et al. 2000). Moreover, the textural contrast at the periphery and base of these podzolic areas will favor the physical fractionation of humus compounds during the spatial differentiation of Podzols, with the accumulation of the smallest fractions (mostly the dissolved organic carbon) in the outer and less permeable materials (respectively the B-horizons of the upslope Acrisols and the top of the underlying saprolitic layer) and the accumulation of coarser fractions (i.e. black organic colloids) at the periphery and base of the inner sandy horizons of Podzols (Fritsch et al. in review). This physical fractionation of humus compounds thus forms on one hand the dark brown Bhs and BCs horizons of Podzols and on another hand their black Bh horizons. Both types of organic accumulation will also reduce the hydraulic conductivity of the soil at the periphery of the podzolic areas and thus favor the development of reducing and acidic conditions in perched groundwaters. This led Do Nascimento et al. (2008) and Fritsch et al. (submitted) to link the formation of Podzols in the lateritic landscape of the upper Amazon basin to the development and dynamics of perched groundwaters. Perched groundwaters rise very quickly in sandy horizons of Podzols. They become enriched in dissolved and suspended organic loads (black waters) and rapidly feed the brooks and rivers of the region. In semi confined environments such as that investigated in the Jaú site (Do Nascimento et al. 2008), the perched groundwater seeps at the margin of the podzolic area and fluctuate in the upper tongue of weakly expressed Podzols during periods of major rainfalls of the wet season. It fluctuates at greater depth, within the lower tongue of better-expressed Podzols, in the early dry or wet seasons and exports large amounts of organic carbon and associated metals to the rivers.

In the Jaú site, Podzols are weakly incised by the river network and systematically observed in open depressions with concave sloping sides (Figs 3c and 6a). By contrast, the highly podzolised plain of the Curicuriari site appears deeply incised by major brooks and rivers. Highly podzolised lands then exhibit convex sloping sides with the river network (Figs 4c and 6b). Comparison of both soil catena (Fig. 6a,b), reveal that physical denudation of the downslope Podzols may have significant consequences on soil differentiation and vegetation cover. Two major differences are reported in soils (Bueno et al. submitted).

First of all, physical denudation of Podzols in low-lying positions may reactivate the deepening of Podzols and contribute to the formation of a second generation of eluviated and illuviated (or spodic) horizons. Indeed, as the slope gradient slowly increases toward the brook incision, a new bleached E horizon is formed just beneath the Bh horizon of the upslope Podzols (Fig. 6b). This sandy horizon expands downward in the saprolitic mantle. It first develops in a clay-depleted and strongly weathered fine saprolite (BC) and ultimately in a coarser, sandier and less weathered saprolite (C). The Bh horizon of the upslope Podzols is partly preserved in bleached E horizons, as a discontinuous line, and a second generation of spodic horizons is formed at greater depth on top of the fine and then of the coarse saprolite (CBh and CBs). Although eroded, the thickness of the Podzols then remains unchanged, or slightly increases donwslope, except in low-lying positions where greater incisions lead to rock outcrops in river beds. Soil survey in other parts of the landscape also shows that podzolisation is not reactivated when brook incisions cut deeper and more abruptly in the landscape (Figs 4c and 7a). Spodic horizons that sustain the perched groundwater on top of saprolitic materials then outcrop in major incisions of the low elevation plateau and numerous springs can be observed on the edges of these newly formed flat surfaces (Fig. 7b). GPR survey clearly reveals the soil organization with a dominant horizontal distribution of podzolic horizons on these incised plateaux as well as the position of the sustained groundwater in the early rainy season (Fig. 7c).

By lowering the local base-level, soil denudation has also significant impacts on the transient accumulation of organic compounds in Podzols. This accumulation of organic matter is much less in upslope positions, at the lateral weathering front between Acrisols and Podzols, and by contrast very important in downslope positions, in the newly formed Podzols. Indeed both the topsoil AE horizons and subsoil Bhs horizons of weakly expressed Podzols appear much thinner in the Curicuriari catena (Fig. 6b) than in the Jaú catena (Fig. 6a). By contrast, the thicknesses of the eluviated topsoil AE horizons and subsoil spodic horizons of better-differentiated Podzols increase significantly toward downslope positions (Fig. 6b). Such changes must be related to better drained environments in the upslope Podzols and the maintenance of waterlogged and reducing conditions in the downslope Podzols. Indeed shorter periods of waterlogging in the upslope Podzols will enhance the turnover of organic compounds whereas longer ones in low-lying positions will increase the residence time of organic compounds and thus favour their accumulation in soils. These changes have also major consequences on the physiognomy and dynamics of the vegetation cover. Indeed the

development of better-drained Podzols in the highly podzolised landscapes of the Curicuriari site enables the return of an open forest (*Caatinga*), which replaces the much denser forest (*Campinarana*) and shrub savannah (*Campina*) of the waterlogged Podzols observed in the weakly podzolised landscapes of the Jaú site.

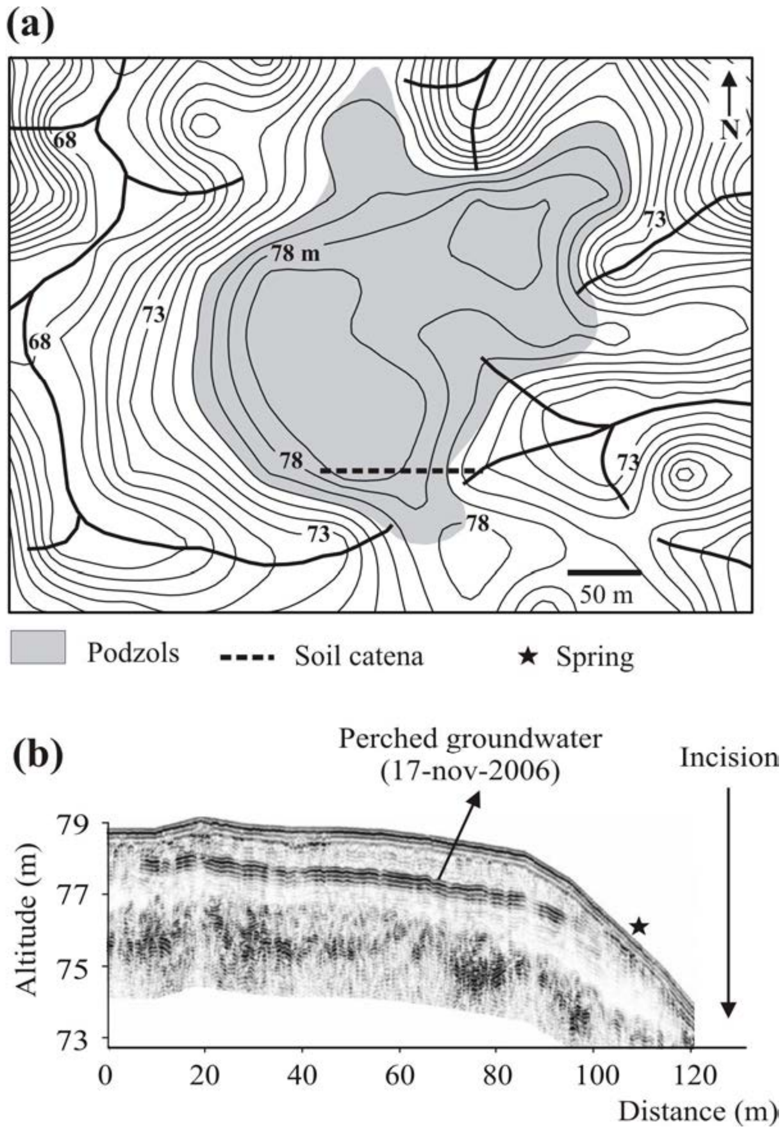


Figure 7. *(a) Small spot of Podzols on a low elevation plateau (see arrow in Fig. 4c for site location) deeply incised by brooks, (b) soil catena (see dashed line in (a)) showing a deep incision in the vertical differentiation of Podzols and groundwater seepage (spring) on the plateau edge in the early rainy season, and corresponding ground penetrating radar (GPR) image (from J. Porsani).*

5.5. Discussion

Pedo-geomorphic investigations carried out at three different scales, from the global scale to the very detailed field surveys, have permitted to recognize major landforms and processes associated with the development of highly degraded lands (mainly Podzols) in waterlogged environments of the Negro River catchment. Regional and detailed field surveys and related soil characterizations led us to propose a schematic model of soil landscape evolution that incorporate, in a sequence of block diagrams, major chemical and physical erosion processes and dominant trends in their spatial expansion (Fig. 8). The development of such processes in the different landforms recognized at regional and global scales are discussed in the frame of the most recent interpretations on the geological history of that part of the Amazon Basin to reveal the main sedimentary, tectonic and climatic controls in the development of these degraded lands.

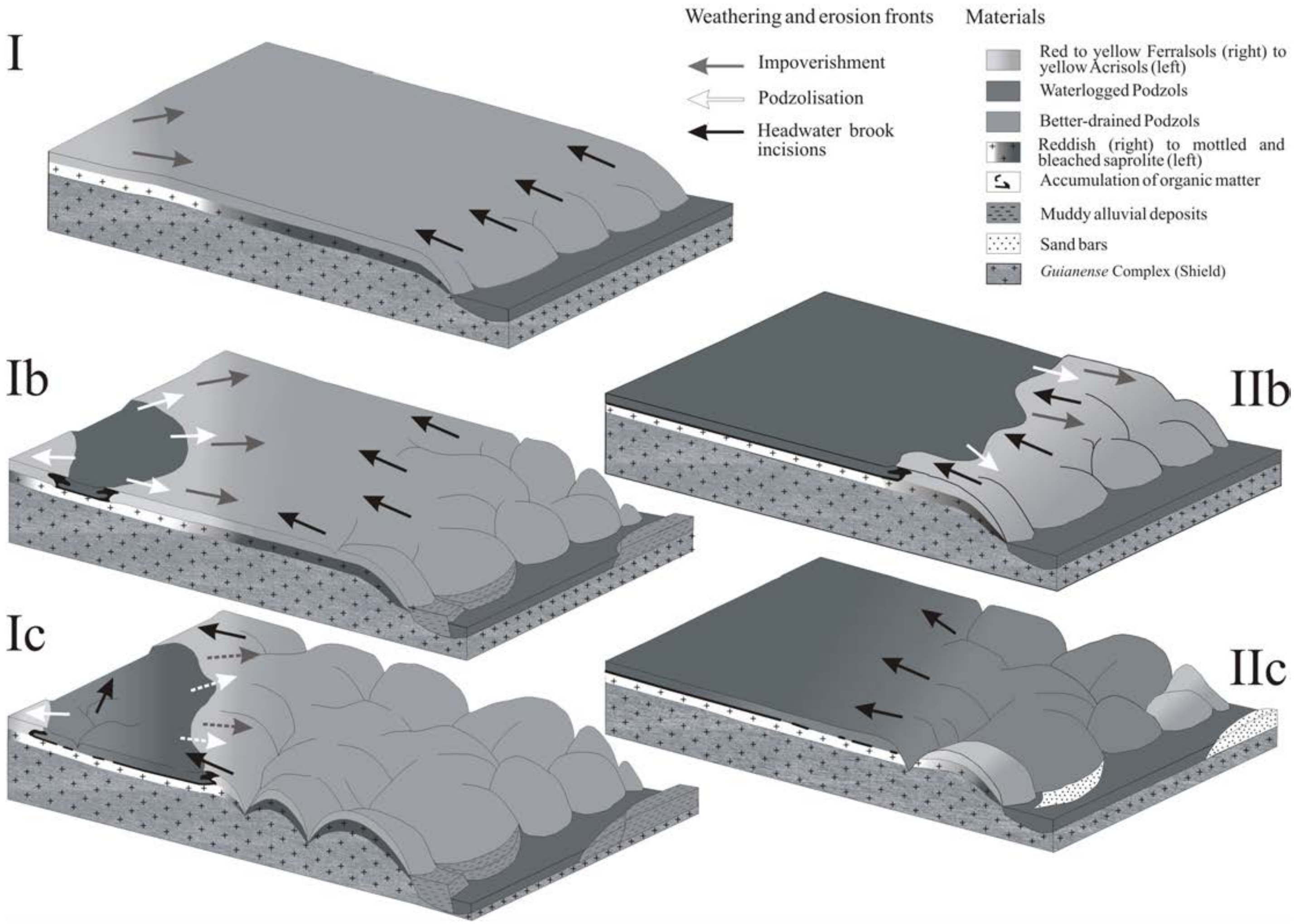


***Figure 8**. Schematic model of soil landform dynamics with their three major weathering and erosion processes: from the waterlogged podzols of the low elevation plateaux), iron and clay impoverishment (grey arrows) and podzolisation (white arrows); and from the river network, headwater brook incisions (black arrows), adapted for the lower and middle (Ia, Ib and Ic sequence), and for the upper (Ia, IIb, IIc sequence) Negro River catchment.*

The model opposes dominant weathering processes, which have first acted in the Amazon lowlands to major phases of incision and deposition associated with the birth of the modern Amazon River system, which has formed the low elevation plateaux and built up the alluvial terraces in the upper Amazon basin. According to Fanning and Fanning (1989) and Fritsch et al. (1994), weathering of continental surfaces is either ascribed to soil forming processes commonly observed in freely drained environments (i.e. lateritisation in tropical regions) or to soil change processes, which mainly result from altered water regimes, leading to the individualization of waterlogged environments. In the upper Amazon Basin, broad scale soil maps suggest that lateritisation has either acted on very long geological times or on shorter ones. Indeed, deeply weathered lateritic materials (Ferralsols also known as *Latosols* in Brazil) developed on different geological formations (rocks and sediments) were likely formed prior to the implementation of the Pan-Amazonian Ucayali Peneplain, i.e. before 15 Ma (Campbell et al., 2006). From the early Paleocene, they likely result from the intense weathering under warm and hot climate of rock basements of the *Guianense* and Brazilian shields and the erosion of weathered products at a period where the drainage system of the Amazon basin discharged sediments into a Pacific embayment and built up most of the continental deposits of the basin (mainly Alter do Chão and Solimões formations). This interpretation is in agreement with results of Balan et al. (2005) who provide an age ranging from 65 to 20 Ma for kaolinite of deeply weathered continental deposits of the Manaus region. It is also consistent with paleomagnetic results of Théveniaut and Freyssinet (2002) who attributed a Paleocene-Eocene age to the “Sul Americano” laterization cycles of paleo-surfaces from Guyana, with average relative ages of 60, 50 and 40 Ma. Such lateritic products either *in situ* (paleo-surfaces) or transported (sediments) were deeply faulted in the Amazon trough (Fritsch et al. 2004) during major Andean orogenic events (Quecha I and II) and partly washed out by erosion during the Ucayali Peneplanation. By contrast, less weathered lateritic materials (Cambisols or Acrisols also known as *Podzólicos* in Brazil) have formed on the Late Tertiary sediments accumulated in a huge lacustrine environment in the middle region of the upper Amazon basin (Içá formation), at a period were the Andean Cordillera was formed and at the beginning of the implementation of the modern Amazon River system, i.e. ~ 2.5 Ma (Campbell et al., 2006). This leads us to admit that deposits of the Içá formation came mainly from the erosion of weakly weathered soils of the Andes.

Soil change processes in the Negro River catchment are mostly assigned to: (1) iron and clay impoverishment, and (2) soil podzolisation. They have acted in the Tertiary Amazon

lowlands, including different geological formations of the Ucayali Peneplain and the late Tertiary sediments of the Içá formation. Iron impoverishment has acted alone in some parts of the catchment, leading to the formation of waterlogged clayey soils, namely Gleyic Plinthosols (Fritsch et al., 2007). It has been closely followed by clay impoverishment in podzolic environments. Both iron and clay impoverishment (i.e. development of Acrisols) are thus pre-existing and necessary steps to the ultimate formation of waterlogged sandy soils (i.e. Hydromorphic Podzols) in the Negro River catchment (Bueno et al., submitted) (see grey and white arrows in Fig. 8). Waterlogged Podzols have expanded in the Amazon lowlands in a Northwestern direction according to a major climatic gradient established following the definitive formation of the Andean cordillera. In the lower and middle Negro River catchment (I and II in Fig. 8), they have explored the most confined areas of the Içá formation, which were attributed to former drainage patterns by Fritsch et al. (2007). Podzols have expanded in a huge inundated area of the Pan-Amazonian Ucayali Peneplain in the upper catchment (III in Fig. 8). Development of these Podzols in the Amazon lowlands is related to geochemical erosion, which has contributed to the development of depressions, drains or inundated plains in the most confined areas of the landscapes.

Major incisions associated with the birth of the modern Amazon River system have formed low elevation plateaux in the upper Amazon basin and built up alluvial terraces during the Quaternary. Headwater incisions in the ramified brook networks of the tributaries of the Negro River have strongly reworked the edges of the incised plateaux in numerous hills. The rates of soil denudation on plateau edges and sedimentation in major river corridors was mostly controlled by difference in altitude between the plateau surface and the regional base-level, which was optimum in the early Quaternary during the first major glaciations. Nowadays, the difference of altitude from the plateau surface to the regional base-level increases gradually from upstream (20 m at the Curicuriari site) to downstream positions (40 m at the Jaú site and 50 m at Manaus), suggesting greater rates of soil denudation in the same direction. However, higher stage heights in the lowermost reaches of the Solimões River strongly reduced water discharge of the Negro River at the confluence (Meade et al., 1991). Moreover eroded lands on the plateau edges are actually covered by evergreen forest and most of the suspended clays in rivers most likely result from the rework of alluvial terraces. Suspended clays from major downstream tributaries (e.g. Jaú River) have accumulated in the *Anavilhanas* Archipelago, the major sediment trap recognized in the lower course of the Negro River. Incisions has also generated freely drained conditions in the soils of the plateau

edges and thus favoured the vertical development of laterites. Besides, such incisions (arrow 3 in Fig 8) have acted in an opposite direction that soil change processes (arrows 1 and 2 in Fig 8).

In the lower and middle Negro River catchment, iron and clay impoverishment (arrow 1) closely followed by soil podzolisation (arrow 2) has led to the formation of hydromorphic Podzols in depressions and drains of the plateaux (I in Fig. 8). Regional soil maps suggest that Hydromorphic Podzols have replaced Gleyic Plinthosols from the lower to the middle Negro River catchment (from I to II in Fig. 2c). The weak expansion of Podzols on these landforms must be related to the nature of their underlying geological substrate (i.e. the Içá formation) and the relatively youngest ages of the soils on which they have formed (less than 2.5 MA). Accordingly, the greater rates of soil denudation on plateau edges and the smaller rates of geochemical erosion in more confined areas of the Içá formation thus restrict the lateral expansion of Podzols on the plateaux and therefore their drainage by the river network (I in Fig. 8). Podzols thus remain strongly waterlogged and become deeply impregnated by organic acids, more specifically at the lateral weathering front with their clay-depleted, lateritic upslope counterpart (Acrisols).

The reverse trend can be reported for the upper Negro River catchment. Podzols there have predominantly formed on deeply weathered materials of the Ucayali Peneplain. This kind of materials is highly prone to podzolisation, more specifically in the low elevation plateaux (small water storage capacity in soils) and high rainfall regions of that part of the catchment. Geochemical erosion then acts on a much greater scale and forms huge inundated plains of Podzols that become drained by the brooks and tributaries of the Negro River (II in Fig. 8). Physical erosion of the unconsolidated topsoil horizons of Podzols then provides bleached sands to river systems in periods of high water stages, leading with time to the formation and displacement of wavy sandy bars in major river corridors. This transfer has built up the major sandy repository of the Mariuá Archipelago (MA in Fig. 2b), the second major sediment trap of the Negro River just downstream of the largest podzolised and incised area of the upper catchment. In the lower section of the trap, input of sands from the Branco River has built an internal delta that largely contributes to the accretion of sands in the upper trap. We also reveal that freely-drained Podzols can form from waterlogged ones close to major river incisions. By lowering the groundwater table in Podzols, this will in return restrict the lateral expansion of the podzolised plain but enhance the exportation of organic colloids and associated metals in rivers. Podzolisation will no longer act efficiently at the margin of the

podzolised plain but in low-lying positions and close to major river incisions, expanding then vertically in less permeable weathered materials such as saprolites.

The almost lack of Podzols in the incised landforms of the Quaternary, particularly in the middle and lower Negro River catchment is an additional argument to reveal the great age of the Podzols observed on the low elevation plateaux, which could have started to form on strongly weathered materials at the end of the Ucayali Peneplaination, i.e. 9.5 Ma ago. However and contrary to geological formations, soil change process such as podzolisation, which might have been initiated some Ma ago, could also have been reactivated more recently in some part of the landscapes. This process is also still on-going nowadays, as indicated by the large amount of organic colloids and associated metals transferred to the black waters of the Negro River. This points out the difficulty or impossibility to date weathering processes. Nevertheless, we have also some strong evidences that podzolisation has been reactivated at some times in the past. This led to the formation of Podzols in foot slope positions of Quaternary incised landforms or alluvial terraces. This second generation of Podzols is widely spread downstream of the Negro River, more specifically in footslope positions of the deeply incised plateaux of the Manaus Region (Lucas et al., 1984; 1988; Righi 1990). As reported in this paper, it has also been initiated on incised landforms of the inundated plains of the upper Negro River catchment.

At least, the study also highlights that the development of waterlogged and acidic conditions and the ultimate return to better-drained conditions in podzolic and incised landforms have also a remarkable effect on the dynamics of the vegetation cover. Indeed the first trend will favours the development in the forest of shrub savannah on inundated Podzols (*Campina*), whereas the second one will, on the opposite, lead to the development of an open forest (*Caatinga*) in better-drained Podzols. Soils and vegetations have therefore similar dynamics in the Negro River catchment, which not necessary result from climatic changes during the Quarternary, as stated by some authors (Haffer, 1969).

5.6. Conclusion

The major weathering and erosion processes were replaced in the frame of the main geomorphic surfaces implemented during the Cenozoic history of the Amazon Basin. The detailed mineralogical and structural approach applied in this study has been used in the past on small landscape units to reveal major processes and hydro-geochemical cycles in degraded

landscapes (e.g. Fritsch et al. 1992, 1994). Fritsch et al. (2007) have recently used this approach with detailed and broad scale soil maps to interpret the formation of waterlogged soils on the the Içá formation, which is commonly related to the implementation in the past of a giant lascustrine area (*Lago Amazonas*) and to the switch of the Amazon river drainage system. We used in this paper the same procedure at continental scale, on different geomorphic surfaces, which have formed in the past and are still forming highly degraded landforms in waterlogged and acidic environments, i.e. in the podzolic lands of the Negro River catchment.

We bring new insights on the formation and development of these degraded lands. In particular, we reveal the main controls of geomorphic surfaces and associated geological formations in the development of weathering and erosion processes, which are driving processes in our study site to (1) lateritisation, (2) iron and clay impoverishment, (3) podzolisation, and (4) headwater incisions or regressive erosion in freely-drained and waterlogged lands. We also highlight the contribution of climatic and tectonic factors, closely related to the formation of the Andean Cordillera during the Tertiary, in the development of these processes. We are conscientious of the restrictions imposed by the lack of detailed cartographic documents and believe that integration of major soil patterns in geological and geomorphic maps would greatly improve our understanding on the formation and evolution of the continental surfaces of the Amazon Basin. On this regards, we suggest to restrict the extend of the Içá formation to low elevation plateaux with shallow (~1m deep), weakly weathered soils developed on near horizontal, mottled and compact deposits as well as to occurrence on the plateaux of ramified drains and depressions with waterlogged soils (Fritsch et al. 2007). Indeed, this soil pattern is consistent with an Andean origin of the sediment (weakly weathered), a deposition in lacustrine environment and the relatively young age of the soils (< 2.5 Ma). It is easily recognised in the field and is assigned on all Brazilian soil maps (Radam Brazil, 1972-78; EMBRAPA, 1981; IBGE, 2001) to a vast area in the central part of the upper Amazon Basin. This definition led us to revise the geomorphic map presented in Figure 2c and restrict the extent of the Içá formation to the right bank of the Negro River (Fig. 9).

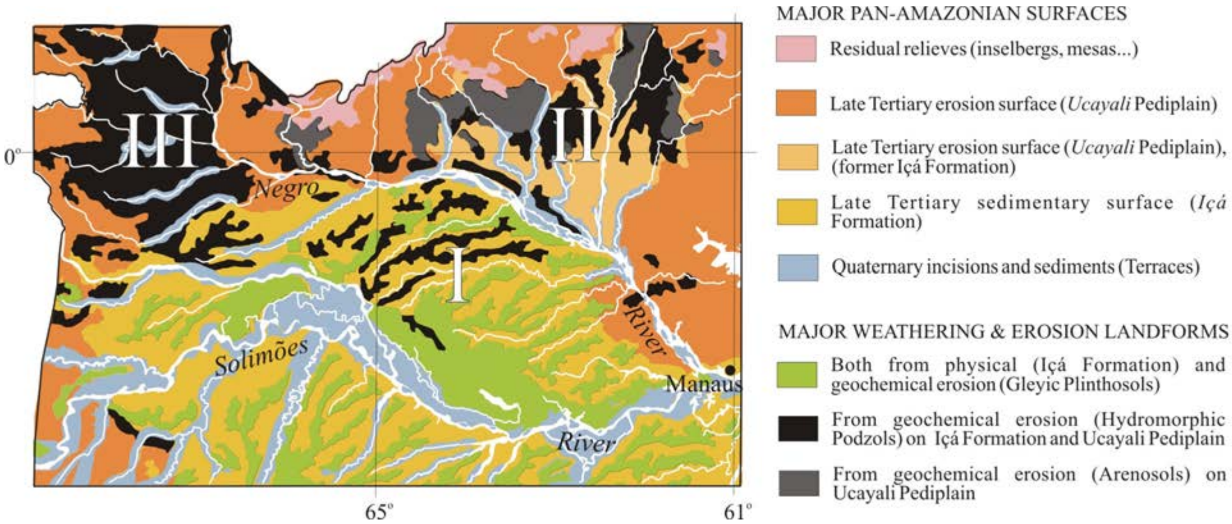


***Figure 9**. Re-interpretation of the major geomorphic landform units presented in Figure 2b for the Northwestern part of the Brazilian upper Amazon Basin from results and interpretations given in this study.*

Figure 9 reveals thee major land surfaces with hydromorphic Podzols (I, II and III). The first one in the South (I in Fig. 9) corresponds to the Içá formation. Podzols less than 2.5MA old are weakly present and lying in the ramified drains and depressions of the formation. They are replacing other waterlogged soils (Gleyic Plinthosols) in higher rainfall areas of the Negro River catchment. By contrast, Podzols are widely spread on the two other land surfaces (II and III in Fig. 9). They have formed on much older and deeply weathered materials (either *in situ* or transported) exposed at the surface after the late Pan-Amazonian Ucayali Peneplaination. Unit II is easily differentiated from unit III, as it comprises large and elongated regions of Podzols alternating with wide strips of deep sands (Arenosols), closely related in the North to residual relieves (inselbergs) of the crystalline rocks of the Guyana Shield. This unit, with its characteristic strip river pattern, comprises most of the giant Podzols of the Negro River catchment. It most likely results from exposure and podzolisation of coarse grained saprolitic materials of old lateritic formations following the Ucayali Peneplaination. Accordingly, weathering processes enhance on continental surfaces geological and geomorphic patterns acquired on geological times. They also contribute by intense chemical weathering to the development of eroded landforms (depressions, plains), which are abundant in the highly degraded podzolic regions of the Negro River catchment (Fig. 9). These eroded landforms are much widely expressed on old lateritic land surfaces (II and III in Fig. 9) than on younger ones (I in Fig. 9) and may also explore structures acquired

during sedimentary processes (e.g. Içá formation). Further remote sensing and field investigations are required to better reveal these structures and the contribution of weathering and erosion processes in the redistribution of major and trace elements in river systems, more specifically in key areas of units I and II.

Acknowledgements

This work benefits from the financial support of CAPESCOFECUB (project 483/05), FAPESP (Fundação de Apoio a Pesquisa do Estado de São Paulo) and INSU (Institut National des Sciences de l’Univers du CNRS), through the “Ecosphère continentale” programme: “Podzolisation des latérites du haut bassin amazonien: impacts environnementaux sur le milieu physique, biologique et sur les exportations de matières (matières organiques et métaux)”. We gratefully acknowledge J. Porsani who performed the ground penetrating radar (GPR) survey in our study site.

CONCLUSIONS GENERALES ET PERSPECTIVES

Cette étude contribue à une meilleure connaissance des environnements podzoliques amazoniens. Ces environnements extrêmes (engorgements prolongés, résidus sableux peu fertiles, forte acidité des eaux, faible activité et diversité biologique) associés à des paysages insolites d'une grande beauté mais d'un intérêt économique plus limité sont particulièrement bien développés dans la partie nord du haut bassin amazonien qui reçoit les plus fortes précipitations du bassin. Ils couvrent un tiers de la superficie du bassin du Rio Negro. Ce bassin d'une superficie de 600.000 km2 présente la plus grande concentration de rivières à eaux noires et exporte de ce fait des quantités considérables de matières organiques et de métaux à l'océan. Nous nous sommes dès lors intéressés aux processus et fonctionnements associés à la dynamique évolutive de ces podzols dans les paysages. Nous avons étudié ces processus et fonctionnement à la fois aux échelles locales dans des positions clés de ces paysages et à des échelles régionales afin de resituer cette évolutive dynamique des podzols dans un contexte géodynamique plus global, associé à la formation des Andes et aux grandes surfaces d'érosion du bassin sédimentaire attenant. Cette démarche multi-échelle et fortement pluridisciplinaire nous a amené à utiliser des approches très variées pour acquérir nos données. Ces approches débutent avec les outils spectroscopiques pour la caractérisation des phases minérales du sol et s'achèvent avec les outils de la télédétection pour l'identification des principales facettes des paysages et des grands ensembles structuraux du bassin du Rio Negro, sans oublier bien sûr l'approche structurale essentielle pour la reconnaissance des organisations pédologiques sur le terrain que nous avons utilisée lors des nombreuses missions sur nos sites d'étude. Comme nous l'avons déjà signalé en introduction, les documents cartographiques du projet RadamBrasil ont été décisifs dans le choix de ces sites et la reconnaissance des grandes unités structurales du bassin. À l'échelle des profils d'altération et des séquences de sols, des approches géochimiques couplées à des calculs des fonctions de transfert ont permis d'apprécier l'importance des pertes de matières lors de la transformation ou dégradation des couvertures latéritiques.

Les travaux présentés dans ce mémoire apportent une contribution majeure à la compréhension des dégradations successives qu'ont subi ces couvertures latéritiques au court du temps. Ces dégradations sont essentiellement attribuées à des pertes de matières (principalement Fe et Al en régions tropicales) qui peuvent être sélectives, conjointes, très progressives ou brutales. Elles témoignent des changements des conditions d'altération et de

drainage qui se relayent dans l'espace et se succèdent aussi dans le temps. Dans le bassin amazonien, ces dégradations suivent deux grandes voies. Dans la première voie, les pertes de matières sont ménagées et concernent essentiellement Fe. Elles sont de ce fait attribuées à des engorgements et au développement de conditions réductrices provisoires ou plus permanentes dans les profils d'altération (oxydo-réduction). La caractérisation de ces systèmes (Latosols-Gleysols) sort des objectifs de cette étude. Elle a toutefois été abordée de façon très détaillée dans des études antérieures de séquences de sols à la fois sur des formations latéritiques très épaisses (sur la surface d'érosion de Manaus) ou beaucoup plus minces et moins altérées (sur les sédiments de la Formation Içá au Nord de Porto Velho).

La deuxième voie est celle que nous avons abordée et étudiée dans le cadre de cette thèse. Elle est associée à des pertes de matières beaucoup plus importantes et se réalise en deux grandes étapes (appauvrissement et podzolisation). Dans le cadre de l'appauvrissement (cf article du Chapitre 3), les pertes de matières s'expriment différemment suivant qu'on se situe en milieu non saturé (partie supérieure des profils latéritiques) ou en milieu saturé (partie inférieure de ces profils). Dans la partie inférieure des profils latéritiques, les pertes de matières liées à la fluctuation et aux écoulements de nappes sont brutales. Elles sont d'abord attribuées à l'exportation massive du fer (dissolution des oxydes de fer) puis de minéraux argileux (vraisemblablement par soutirage ou lessivage latéral) lorsque les conditions de drainage de la partie supérieure des nappes est accrue. Dans la partie supérieure de ces profils latéritiques, les pertes de matières sont à l'inverse très progressives. Elles sont saisonnières et vraisemblablement attribuées à des périodes d'hydratation plus prolongées. Elles sont sélectives et affectent d'abord l'hématite (jaunissement du sol) puis les minéraux argileux (kaolinite et goethite) vraisemblablement par des mécanismes de dissolution et lixiviation dominants. Ces exportations de matière en surface mais aussi en profondeur aboutissent à l'individualisation à l'aval des versants de réservoirs sableux dont la bordure latérale présente une forme caractéristique en double langue. Le développement de ces réservoirs très poreux et perméables est propice à la migration des matières organiques et de ce fait à la podzolisation ultime des latérites (cf article du Chapitre 4 et aussi articles en annexe). Cette étape ultime marque le colmatage de la bordure des réservoirs sableux par les substances organiques acides qui altèrent les minéraux résiduels argileux et forment des complexes organo-métalliques. Elle est de ce fait étroitement associée à la mise en place de nappes perchées et de conditions réductrices qui favorisent l'accumulation de matières organiques dans ces sols et leur exportation au réseau hydrographique. Le calcul des fonctions de transfert dans ces systèmes

montre que les exportations de matières (Fe et Al) sont minimes lors de la podzolisation et à l'inverse bien plus importantes lors de l'étape préalable d'appauvrissement des latérites en minéraux argileux. Toutefois, la podzolisation marque un changement de spéciation drastique pour les métaux, qui deviennent alors étroitement liés aux matières organiques.

Nous avons également étudié l'effet des incisions linéaires sur la morphologie et dynamique des podzols (rabattement des nappes perchées, érosion des matériaux sableux des podzols). Cette étude minéralogique et structurale réalisée dans la région de São Gabriel da Cachoeira (cf article du Chapitre 4) a de ce fait été comparé à celle entreprise antérieurement sur des systèmes podzoliques à nappe non incisés (région du Jaú). Dans ces podzols drainés par les incisions du réseau hydrographique, le rabattement des nappes à l'amont des systèmes podzoliques favorise la minéralisation des matières organiques dans les fronts latéraux de podzolisation et de ce fait la libération des métaux préalablement accumulés. Cette minéralisation accrue, liée à une oxygénation plus marquée de ces sols, entraîne une nette réduction de l'épaisseur des horizons organiques de ces podzols, en surface (dans les horizons éluviés à résidus organiques) mais aussi en profondeur dans les fronts de podzolisation (horizons illuviés à complexes organo-métalliques). Cette oxygénation du sol peut aussi favoriser la formation d'oxydes de fer mal cristallisé dans les systèmes hydromorphes qui jouxtent les podzols de l'amont. Enfin l'érosion régressive des bas de versants, qui alimente en sables blancs les lits des rivières, peut favoriser la descente des fronts de podzolisation dans niveaux altéritiques moins perméables et de ce fait initier la formation d'une nouvelle génération d'horizons illuviés (ou spodiques) à l'aval. A ce niveau, le maintien de conditions anoxiques en milieu faiblement acide est propice à une grande accumulation de complexes organo-métalliques. Les métaux initialement présents à l'amont de ces systèmes podzoliques s'accumulent à l'aval dans une seconde génération d'horizons spodiques. Cette étude comparative montre aussi que les podzols sont associés à des systèmes de nappe et que le drainage de ces podzols marque une étape ultime dans leur évolution qui permet aussi (soit de façon naturelle soit de façon artificielle) de limiter leur expansion dans l'espace.

Dans une dernière et ultime étape, nous avons resitué ces processus et fonctionnement à l'échelle du bassin amazonien, plus particulièrement dans la région où les podzols sont les plus abondants : le bassin versant du Rio Negro (cf article du Chapitre 5). Cette étape décisive dans la compréhension de la mise en place de ces formations et de leur expansion dans les paysages s'est avérée très riche d'informations. Nous avons ainsi pu montrer que leur expansion dans l'espace était à la fois contrôlée par la nature du support sur laquelle elles se

forment et par les apports pluviométriques. Leur expansion est en effet très nettement accrue dans la partie Nord et Nord Ouest, c'est-à-dire dans les zones les plus pluvieuses et sur la surface d'aplanissement *Ucayali* qui exposent localement les latérites les plus altérées et anciennes du bassin. A l'inverse, elles sont beaucoup moins abondantes dans la partie sud du bassin, plus particulièrement sur la Formation Içá où elles occupent, comme les sols hydromorphes plus classiques (les Gleysols), les parties déprimées des plateaux. La grande expansion des systèmes podzoliques sur ces surfaces Tertaires et leur bien moindre abondance sur les surfaces d'incision et de dépôt du Quaternaire suggèrent fortement que ces systèmes aient pu être mis en place sur le bassin avant la naissance du réseau modern de drainage du fleuve Amazone, il y a prêt de 2.5 Ma. Par ailleurs, l'incision des surfaces basses du bassin par ce réseau de drainage a permis de drainer les aires les plus podzolisées situées au Nord Ouest de ce bassin, de stopper l'expansion de ces podzols ou limiter fortement leur expansion dans les paysages et d'alimenter en sables les lits des rivières.

Suite aux travaux réalisés dans le cadre de cette étude, deux incertitudes majeures subsistent. En effet, nous montrons qu'il existe deux voies possibles dans l'érosion chimique des couvertures latéritiques qui sont toutes deux associées, lors de leur évolution ultime, à la mise en place de systèmes de nappes dans les paysages. Dans la première voie, l'érosion chimique est sélective (dissolution des oxydes de fer) et les sols blanchissent mais restent argileux et peu perméables (formations des Gleys à nappes). Dans la deuxième voie, l'érosion chimique beaucoup plus importante (dissolution de l'ensemble des minéraux argileux) est propices à l'appauvrissement des latérites et ultérieurement à leur podzolisation (formations des Podzols à nappes). Sur la Formation Iça, les deux types de sols (Gleys et Podzols) occupent les mêmes positions topographiques (dépressions et chenaux des plateaux) et se relayent du Sud Est (Gleys) vers le Nord Ouest (Podzols). Quels sont les facteurs qui permettraient d'expliquer l'évolution vers l'une ou l'autre de ces voies à partir d'un même matériau parental ? N'y aurait-il pas içi l'influence de structures sédimentaires (e.g. dépôts plus sableux) qui pourrait favoriser l'une de ces voies plutôt que l'autre (e.g. podzolisation) ? La seconde incertitude correspond aux principaux processus à l'origine de la formation des nombreuses dépressions et chenaux de la Formation Içá. Faut-il y voir içi la marque d'anciennes structures fluvio-lacustres comme ça semble être le cas lorsqu'on les observe à petites échelles ou le résultat d'une fonte géochimique dans les parties centrales les moins bien drainées de ces plateaux, avec l'individualisation ultime de sols à nappes (Gley et Podzols) ?

L'ensemble de ces données permet également de dégager quelques perspectives dans l'optique d'une meilleure connaissance de ces systèmes. La première consisterait à mieux dissocier à méso-échelles les structures sédimentaires de celles attribuées à l'altération et la pédogenèse sur des sites clés de la Formation Içá de façon à mieux répondre aux précédentes incertitudes. La seconde viserait à mieux caractériser les matières organiques et leur charge en métaux dans les podzols drainés du site de São Gabriel da Cachoeira de façon à faire également une étude comparative avec ce qui a été établi au Jaú pour des podzols à nappe. En effet, il serait bon d'attribuer à ces changements de régime hydrique des facies pédologiques différents et des signatures spectrales tranchées pour la matière organique et les métaux, ce qui a encore jamais été réellement fait à notre connaissance. Enfin, il serait aussi souhaitable d'aborder le problème de l'age et de la dynamique de ces systèmes podzoliques par datation (^{14}C) et par des approches isotopiques (^{13}C, ^{15}N) et ce dans les différents ensembles structuraux reconnus aux échelles locales (séquence de sols) et régionales (eaux, sédiments). Des travaux dans ce sens sont en cours. Ils montrent des temps de résidence très contrastés des matières organiques dans les horizons des podzols et des fractionnements isotopiques opposés par rapport à ceux attribués aux environnements minéraux, comme les latérites (pour C, N mais aussi pour les métaux tels que Fe).

CONCLUSÕES GERAIS E PERSPECTIVAS

Este estudo vem contribuir para um melhor conhecimento dos meios podzolizados amazônicos. Estes meios extremos (encharcamentos prolongados, resíduos arenosos pouco férteis, forte acidez das águas, fraca atividade e diversidade biológicas) associados a paisagens insólitas de grande beleza, mas de interesse econômico limitado, são particularmente bem desenvolvidos na parte norte da alta bacia amazônica, que recebe os maiores volumes de precipitação pluviométrica da bacia. Eles cobrem um terço da superfície da bacia do Rio Negro. Essa bacia, com uma superfície de 600.000 km^2, apresenta a maior concentração de rios de águas negras e exporta por isso quantidades consideráveis de matéria orgânica e metais para o oceano. Os processos e funcionamentos associados à dinâmica evolutiva destes podzóis na paisagem nos chamaram a atenção. Estes processos e funcionamentos foram estudos tanto nas escalas locais, em posições-chave destas paisagens, quanto em escalas regionais, visando reconstituir a evolução dinâmica dos podzóis em um contexto geodinâmico mais global, associado à formação dos Andes e às grandes superfícies de erosão da bacia sedimentar. Essa ***démarche*** multiescalar e fortemente pluridisciplinar nos conduziu a utilizar abordagens diversificadas para obtenção dos dados. Essas abordagens se iniciaram pelas análises espectroscópicas para a caracterização das fases minerais do solo e terminaram com o estudo de produtos do sensoriamento remoto para a identificação das principais unidades de paisagem e dos grandes conjuntos estruturais da bacia do Rio Negro, sem deixar de lado, é claro, a abordagem estrutural, essencial para o reconhecimento das organizações pedológicas na escala de campo. Como já assinalado na Introdução, os documentos cartográficos do Projeto RadamBrasil foram decisivos para a escolha dos sítios de estudos e para o reconhecimento das grandes unidades estruturais da bacia. Na escala dos perfis de alteração e das seqüências de solos, abordagens geoquímicas acopladas a cálculos de funções de transporte permitiram a constatação de importantes perdas de matéria durante a transformação ou degradação das coberturas lateríticas.

Os trabalhos aqui apresentados contribuem para a compreensão das degradações sucessivas que as coberturas lateríticas sofreram ao longo do tempo. Estas degradações são essencialmente atribuídas a perdas de matéria (principalmente Fe e Al na região tropical) que podem ser seletivas, conjuntas, progressivas ou brutais. Elas testemunham mudanças das condições de alteração e drenagem que variam no espaço e se sucedem no tempo. Na bacia amazônica estas degradações seguem duas vias. Na primeira via as perdas de matéria são

menos intensas e afetam essencialmente o Fe. Elas são, por isso, atribuídas à saturação hídrica e ao desenvolvimento de condições redutoras provisórias ou mais permanentes nos perfis de alteração (óxido-redução). A caracterização destes sistemas (Latossolos-Gleissolos) vai além dos objetivos deste estudo. Ela foi realizada de forma bastante detalhada em estudos anteriores de seqüências de solos, tanto sobre formações lateríticas espessas (da superfície de erosão da região de Manaus) quanto sobre formações lateríticas delgadas e menos alteradas (sobre os sedimentos da Formação Içá, na região de Porto Velho). A segunda via é aquela que abordamos e estudamos nesta tese. Ela é associada a perdas de matéria muito mais importantes e acontece em duas grandes etapas (empobrecimento e podzolização). Quanto ao empobrecimento (tratado no Capítulo 3), as perdas de matéria se exprimem diferentemente segundo a posição no perfil: na parte inferior, em meio saturado, as perdas associadas à flutuação e ao escoamento dos lençóis são intensas. Elas são inicialmente atribuídas à exportação maciça do ferro (dissolução dos óxidos e lixiviação) e depois dos minerais de argila (aparentemente por lessivagem lateral), desde que aumentem os fluxos na parte superior dos lençóis. Na parte superior dos perfis lateríticos, não saturadas, as perdas são menos progressivas. Elas são sazonais e aparentemente associadas a períodos de hidratação mais prolongados. Elas são seletivas e afetam inicialmente a hematita (amarelecimento do solo) e depois a goethita e os minerais de argila, provavelmente por mecanismos de dissolução e lixiviação. Estas exportações de matéria na superfície, mas também em profundidade, conduzem à individualização, na parte de jusante das vertentes, de reservatórios arenosos cujos limites têm a forma de "dupla língua". O desenvolvimento destes reservatórios bastante porosos e permeáveis é propício à migração da matéria orgânica e, assim, à podzolização última dos solos lateríticos (tratadas no Capítulo 4 e também em artigos no Anexo). Esta última etapa marca a colmatação da borda dos reservatórios arenosos por substâncias organo-metálicas. Ela é, assim, estreitamente associada ao aparecimento de lençóis suspensos e de condições redutoras que favorecem a acumulação de matéria orgânica nos solos e sua exportação para a rede hidrográfica. O cálculo das funções de transporte nestes sistemas mostra que as exportações de matéria (Fe e Al) são mínimas durante a podzolização, mas são muito mais importantes durante a etapa antecedente, de empobrecimento dos solos lateríticos em minerais argilosos. Entretanto, a podzolização marca uma mudança drástica na especiação dos metais, que passam a se associar à matéria orgânica.

Foram também estudados os efeitos das incisões lineares sobre a morfologia e a dinâmica dos podzóis (rebaixamento dos lençóis suspensos, erosão dos materiais arenosos dos podzóis).

Este estudo mineralógico e estrutural realizado na região de São Gabriel da Cachoeira (apresentado no Capítulo 4) foi comparado àquele feito anteriormente sobre sistemas podzolizados com lençol suspenso e pouco afetados pelas incisões dos canais de drenagem (região do Jaú). Nestes podzóis drenados pelas incisões, o rebaixamento dos lençóis na parte de montante dos sistemas podzólicos favorece a mineralização da matéria orgânica nas frentes laterais de podzolização e, conseqüentemente, a liberação dos metais previamente acumulados. Esta mineralização mais intensa, ligada a uma maior oxigenação destes solos, conduz a uma clara redução da espessura dos horizontes orgânicos destes podzóis, em superfície (nos horizontes eluviais com resíduos orgânicos), mas, também, em profundidade, nas frentes de podzolização (horizontes iluviais com complexos organo-metálicos). Esta oxigenação do solo pode também favorecer a formação de óxidos de ferro mal cristalizados nos sistemas hidromórficos que afetam os podzóis de montante. Enfim, a erosão regressiva na base das vertentes, que alimenta com areias brancas os leitos dos rios, pode favorecer o aprofundamento das frentes de podzolização sobre os saprolitos menos permeáveis e, assim, iniciar a formação de uma nova geração de horizontes iluviais (ou espódicos). Neste nível, a permanência de condições anóxicas em meio fracamente ácido é propícia a uma grande acumulação de complexos organo-metálicos. Os metais inicialmente presentes na parte de montante dos sistemas podzólicos se acumulam na parte de jusante, em uma segunda geração de horizontes espódicos. Este estudo comparativo mostra, também, que os podzóis estão associados a sistemas de lençol e que a drenagem destes podzóis marca uma etapa última na sua evolução, podendo, de forma natural ou artificial, limitar sua expansão no espaço.

Numa última etapa, os processos e funcionamentos foram discutidos na escala da bacia amazônica, particularmente na região onde os podzóis são mais abundantes: a bacia do Rio Negro (Capítulo 5). Esta etapa, decisiva para a compreensão da gênese destas formações e de sua expansão nas paisagens, trouxe importantes informações. Foi possível, assim, mostrar que sua expansão espacial é condicionada tanto pela natureza do substrato sobre o qual se formam quanto pela pluviometria. Sua expansão é, de fato, claramente mais importante nas partes norte e noroeste, isto é, nas zonas mais pluviosas e sobre a superfície de aplanamento *Ucayali*, coberta pelos perfis lateríticos mais alterados e antigos da bacia. Ao contrário, elas são muito menos abundantes na parte sul da bacia, particularmente sobre a formação Içá, onde ocupam, ao lado dos solos hidromórficos mais clássicos (Gleissolos), as partes deprimidas dos platôs. A grande expansão dos sistemas podzólicos sobre estas superfícies terciárias e sua menor incidência sobre as superfícies mais recentes, do Quaternário, sugerem fortemente que estes

sistemas podem ter se desenvolvido na bacia antes da instalação da rede de drenagem moderna do Rio Amazonas, há aproximadamente 2.5 Ma. Além disso, a incisão desta rede fluvial sobre as superfícies baixas foi responsável pela drenagem das áreas mais podzolizadas da parte noroeste da bacia, pela interrupção ou a limitação da expansão destes podzóis nas paisagens e pelo fornecimento de areias brancas para os canais fluviais.

Após os trabalhos realizados no âmbito deste estudo, duas incertezas maiores persistem. De fato, foi mostrado que existem duas vias possíveis para a erosão química das coberturas lateríticas. Estas duas vias estão associadas, na sua evolução final, ao aparecimento de sistemas de lençóis na paisagem. Na primeira via, a erosão química é seletiva (dissolução dos óxidos de ferro) e os solos se tornam mais brancos, mas permanecem argilosos e pouco permeáveis (formação de Gleissolos com lençóis). Na segunda via, a erosão química mais importante (dissolução do conjunto dos minerais argilosos) é propícia ao empobrecimento dos solos lateríticos e posteriormente à sua podzolização (formação de Podzóis com lençol). Sobre a Formação Içá, os dois tipos de solos (Gleissolos e Podzóis) ocupam as mesmas posições topográficas (depressões e canais mal drenados dos platôs) e se alternam do sudeste (Gleissolos) para noroeste (Podzóis). Quais são os fatores que permitiriam explicar a evolução rumo a uma ou outra destas duas vias a partir de um mesmo material de origem? Não haveria aqui a influência de estruturas sedimentares (ex: depósitos mais arenosos) que poderiam favorecer uma destas vias em detrimento da outra (ex: podzolização)? A segunda incerteza corresponde aos principais processos que explicam a origem das inúmeras depressões e canais mal drenados dos platôs da Formação Içá. É necessário verificar se se trata de antigas estruturas flúvio-lacustres, associadas a antigas redes de drenagem, como parece ser o caso quando observadas em pequena escala, ou o resultado de uma perda geoquímica mais acentuada nas partes centrais de pior drenagem destes platôs, seguida da individualização última de solos com lençóis (Gleissolos e Podzóis).

O conjunto destes dados permitiu igualmente apontar algumas perspectivas na ótica de um melhor conhecimento destes sistemas. A primeira consistiria em melhor dissociar, em meso-escala, as estruturas sedimentares daquelas atribuídas à alteração e à pedogênese sobre sítios-chave da Formação Içá, para melhor responder às referidas incertezas. A segunda visaria uma melhor caracterização das matérias orgânicas e de sua carga em metais nos podzóis drenados do sítio de São Gabriel da Cachoeira, para fazer um estudo comparativo com aquele realizado no sítio do Jaú sobre os podzóis com lençol. De fato, seria bom atribuir, a estas mudanças de regime hídrico, diferentes fácies pedológicas e assinaturas espectrais para a matéria orgânica e

para os metais, o que não foi ainda feito segundo nosso conhecimento. Enfim, seria também desejável abordar o problema da idade e da dinâmica destes sistemas podzólicos por datação (^{14}C) e por abordagens isotópicas (^{13}C, ^{15}N), isto para os diferentes conjuntos estruturais identificados nas escalas locais (seqüências de solos) e regionais (águas e sedimentos). Trabalhos neste sentido estão em curso. Eles indicam tempos de residência da matéria orgânica muito contrastados nos horizontes dos podzóis e fracionamentos isotópicos muito diferentes daqueles atribuídos aos meios minerais, como os solos lateríticos (para C, N, mas, também, para metais como o Fe).

BIBLIOGRAFIA

Anderson H.A., Berrow M.L., Farmer V.C., Hepburn A., Russel J.D., Walker A.D. (1982). A reassessment of podzol formation processes. *J. Soil Sci*. **33**, 125-136.

Allard T., Ponthieu M., Weber T., Filizola N., Guyot J.L., and Benedetti M. (2002). Nature and properties of suspended solids in the Amazon Basin. *Bull. Soc. Géol. France* **173**, 67-75.

Allard T., Menguy N., Salomon J., Calligaro T., Weber T., Calas G., Benedetti M.F. (2004). Revealing forms of iron in river-borne material from major tropical rivers of the Amazon Basin (Brazil). *Geochimica et Cosmochimica Acta* **68**, 3079-3094.

Aubert G. (1954). Les sols latéritiques. *Actes et Comptes Rendus du V^e Congrès International de la Science du Sol.* Léopoldville **1**, 103-118.

Balan E., Allard T. Boizot B., Morin G., Muller J.P. (1999). Structural Fe^{3+} in natural kaolinites: new insights from electron paramagnetic resonance spectra fitting at X and Q-band frequencies. *Clays and Clay Minerals* **47**, 605-616.

Balan, E., Trocellier , P., Jupille, J., Fritsch, E., Muller, J.-P., Calas, G. (2001). Surface chemistry of weathered zircons. *Chemical Geology* **181**, 13-22.

Balan E., Allard T., Fritsch E., Sélo M., Falguères C., Chabaux F., Pierret M.C., Calas G. (2005). Formation and evolution of lateritic profiles in the middle Amazon basin: Insights from radiation-induced defects in kaolinite. *Geochimica et Cosmochimica Acta* **69**, 2193-2204.

Bardy M., Bonhomme C., Fritsch E., Maquet J., Hajjar R., Allard T., Derenne S., Calas G. (2007). Al speciation in tropical Podzols of the upper Amazon basin : a solid-state ^{27}Al MAS and MQMAS NMR study. *Geochimica et Cosmochimica Acta* **71**, 3211-3222.

Bardy M., Fritsch E., Derenne S., Allard T., Do Nascimento N.R., Bueno G.T. (2008). Micromorphology and spectroscopic characteristics of organic matter in waterlogged Podzols of the upper Amazon basin. *Geoderma* **14**, 222-230.

Beaudou A.G. & Chatelin Y. (1972). Les mouvements d'argile dans certains sols ferrallitiques centrafricains. ORSTOM, 9p.

Bedidi, A., Cervelle, B., Madeira, J., Pouget, M. (1992). Moisture effects on visible spectral characteristics of lateritic soils. *Soil Science* **153**, 129-141.

Bezerra P.E.L., (2003). Compartimentação morfotectônica do Interflúvio Solimões-Negro. Tese de doutorado, 335p**.**

Bish D.L. & Reynolds J. (1989): Sample preparation for X-ray diffraction. *Reviews in Mineralogy : Modern Powder Diffraction*, Vol. 20, Mineralogical Society of America, Washington, 73-99.

Benedetti M.F., Mounier S., Filizola N., Benaim J., Seyler P. (2003a). Carbon and metal concentrations, size distributions and fluxes in major rivers of the Amazon Basin. *Hydrological Processes* **17**, 1363-1377.

Benedetti M.F., Ranville J.F., Allard T., Bednar A.J., Menguy N. (2003b). The iron status in colloidal matter from the Rio Negro, Brasil. Colloids and Surfaces A. *Physicochem. Eng. Aspects* **217**, 1-9.

Bigarella J.J. & Andrade G.O. (1965). Contribution to the study of the Brazilian Quaternary. In: WRIGHT H.E. Jr., FREY D.G. (eds.). *International Studies on the Quaternary. Geological Society of America Special Papers* **94**, 433-451.

Blancaneaux P. (1981). Essai sur le milieu naturel de la Guyane Française. Travaux et Documents de l'ORSTOM, 137, 126p.

Bocquier G. (1971). Genèse et évolution de deux toposéquences de sols tropicaux du Tchad – Interprétation biogéodynamique. *Cah. ORSTOM* **9**, 509-515.

Boulet R. (1974). Toposéquences de sols tropicaux en Haute-Volta. Equilibres dynamiques et bio-climatiques. Thèse Sci. Strasbourg, Mémoire ORSTOM, 85, 1978, 272p.

Boulet R., Bocquier G., Millot G., (1977). Géochimie de la surface et formes du relief : 1. Déséquilibre pédobioclimatique dans les couvertures pédologiques de l'Afrique tropicale de l'Ouest et son rôle dans l'aplanissement des reliefs. *Sciences Géologiques Bulletin* **30** (4), 235-243.

Boulet R., Chauvel A., Humbel F.X., Lucas Y. (1982). Analyse structurale et cartographie en pédologie: I - Prise en compte de l'organisation bidimensionnelle de la couverture pédologique: les études de toposéquences et leurs principaux apports à la connaissance des sols. *Cah. ORSTOM* **19**, 309-321.

Boulet R., Lucas Y., Fritsch E., Paquet H. (1993). Géochimie des paysages : le rôle des couvertures pédologiques. *In* Coll. "Sédimentologie et Géochimie de la Surface" à la mémoire de Georges Millot. H. Paquet et N. Clauer eds., Les colloques de l'Académie des Sciences et du Cadas, Paris, 55-76.

Boulet R., Lucas Y., Fritsch E., Paquet, H. (1997). Geochemical processes in tropical landscapes: role of the soil covers. In: Paquet, H. & Clauer N. (Eds). Soils and Sediments - Mineralogy and Geochemistry, Springer-Verlag, Heidelberg, 67-96.

Bousserrhine N, Gasser U.G., Jeanroy E., Berthelin J. (1998). Bacterial and chemical reductive dissolution of Mn-, Cr- and Al-substituted goethithes. *Geomicrobiology Journal* **16**, 245-258.

Bravard S. & Righi D. (1989). Geochemical differences in an oxisol-spodosol toposéquence of Amazonia, Brazil. *Geoderma* **44**, 29-42.

Bravard S. & Righi D. (1990). Podzols in Amazonia. *Catena* **17**, 461-475.

Brimhall G.H. & Dietrich W.E. (1987). Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis. *Geochimica et Cosmochimica Acta* **51**, 567-587.

Braun, J.J., Pagel, M., Herbillon, A., Roisin, C. (1993). Mobilization and redistribution of REEs and thorium in a syenitic lateritic profile. A mass balance study. *Geochimica et Cosmochimica Acta* **57**, 4419-4434.

Braun J.J., Ngoupayou J.R.N., Viers J., Dupre B., Bedimo J.P., Boeglin J.L., Robain H. Nyeck B., Freydier R., Nkamdjou L.S., Rouiller J., Muller J.P. (2005). Present weathering rates in a humid tropical watershed : Nsimi, South Cameroon. *Geochimica et Cosmochimica Acta* **69**, 357-387.

Bravard, S. & Righi, D. (1989). Geochemical differences in an Oxisol-Spodosols Toposequence of Amazonia, Brazil. *Geoderma* **44**, 29-42.

Bravard S. & Righi D. (1990). Podzols in Amazonia. *Catena* **17**, 461-475.

Brewer R. (1964). Fabric and mineral analysis of soils. J. Wiley and Sons, N.Y., Sydney, 470p.

Brimhall, G.H., Lewis, C.J., Ford, C., Bratt, J., Taylor, G., Warin O. (1991). Quantitative geochemical approach to pedogenesis: importance of parent material reduction, volumetric expansion, and eolian influx in lateritization. *Geoderma* **51**, 51-91.

Brinkman R. (1970). Ferrolysis, a hydormorphic soil forming process. *Geoderma* **3**, 199-206.

Bruand A., Braudeau E., Fritsch E. (1990). Evolution de la géométrie de l'espace poral des sols lors du passage du domaine ferrallitique au domaine ferrugineux et hydromorphe : exemple du bassin de Booro Borotou. *In* Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, Paris, 90-96.

Büdel J. (1957). Die “Doppelten Einebnungsflächen” in den feuchten Tropen. *Z. Geomorphol.* **1**, 201-228.

Buurman P. (1987). pH-dependent character of complexation in podzols. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 191-186.

Buurman P. & Jongmans A.G. (2005). Podzolisation and soil organic matter dynamics. *Geoderma* **125**, 71-83.

Campbell K.E. Jr., Frailey C.D., Romero-Pittman L. (2006). The Pan-Amazonian Ucayali Peneplain, late Neogene sedimentation in Amazonia, and the birth of the modern Amazon River system. *Palaeogeography, Palaeoclimatology, Palaeoecology* **239**, 166-219.

Chadwick O.A., Brimhall G.H., Hendricks D.M. (1990). From a black to a grey box: a mass balance interpretation of pedogenesis. *Geomorphology* **3**, 369-390.

Chauvel A., Bocquier G., Pedro G. (1977). Géochimie de la surface et formes du relief III. Les mécanismes de la disjonction des constituants des couvertures ferrallitiques et l’origine de la zonalité des couvertures sableuses dans les régions intertropicales de l’Afrique de l’Ouest. *Sci. Géol., Bull.* **30**, 255-263.

Chauvel A., & Pedro G. (1978). Genèse de sols beiges (ferrugineux tropicaux lessivés) par transformation des sols rouges (ferrallitiques) de Casamance (Sénégal) – Modalités de leur propagation, *Cah. ORSTOM* **16**, 231-249.

Chauvel A., Lucas Y., Boulet R. (1987). On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. *Experientia* **43**, 234-241.

Colin F., Vieillard P., Ambrosi J.P. (1993). Quantitative approach to physical and chemical old mobility in equatorial rainforest lateritic environment. *Earth Planet. Sci. Let.*, **114**, 269-285.

Cornu S., Lucas Y., Lebon E., Ambrosi J.P., Luizão F, Rouiller J, Bonnay M, Neal, C. (1999). Evidence of titanium mobility in soil profile Manaus, central Amazonia. *Geoderma* **91**. 281-295.

Costa R C.R., Natali Filho T., Oliveira A.A.B. (1978). Projeto RADAMBRASIL – Geomorfologia. Manaus, 18, 165-244.

De Coninck F. (1980). Major mechanisms in formation of spodic horizons. *Geoderma* **24**, 101-128.

DNPM. (1981). Mapa geológico do Brasil, Brasília, escala 1:2.500.000.

Dubroeucq D. & Volkoff B. (1988). Évolution des couvertures pédologiques sableuses à podzols géants d'Amazonie (Bassin du Haut rio Negro). *Cahiers ORSTOM, Série Pédologie* **26** (3), 191-214.

Dubroeucq D. & Volkof B. (1998). From Oxisols to Spodosols and Histosols: evolution of the soil mantles in the Rio Negro basin (Amazonia). *Catena* **32**, 245-280.

Dubroeucq D., Volkoff B., Faure P. (1999). Les couvertures pédologiques à Podzols du Bassin du Haut Rio Negro. *Étude et Gestion des Sols* **6**, 131-153.

Duchaufour P. (1972). Processus de formation des sols. Biochimie et Géochimie. Nancy : Editions CRDP, Coll. Etudes et Recherches, 182 p.

Duchaufour P. (1982). Pedology: Pedogenesis and Classification. London: George Allen and Unwin, 481p.

EMBRAPA. (1981). Mapa de Solos do Brasil. Brasília. escala 1:5.000.000.

Fanning D.S. & Fanning M.C. (1989). Soil, morphology, genesis and classification. John Wiley & Sons, New York, 395p.

FAO. (1998). World Reference Base for Soil Resources. World Soil Resources Report n° 84. Rome, 172p.

Farmer V.C., Russel J.D., Berrow M.L. (1980). Imogolite and proto-imogolite alophane in spodic horizons: evidence for a mobile aluminium silicate complex in podzol formation. *J. Soil Sci.* **31**, 673-784.

Farmer V.C. (1987). The role of inorganic species in the transport of aluminium in podzols. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 187-194.

Fauck R. (1972). Les sols rouges sur sables et sur grès d'Afrique Occidentale. Mémoires ORSTOM, 261p.

Fernandes P.E.C.A, Pinheiro S.S., Montalvão R.M.G., Issler R.S., Abreu A.S.; Tassinari C.C.G. (1977). Geologia. Içá, 14. DNPM/Projeto Radambrasil, 19-123.

Fitzpatrick, E.A., (1970). A technique for preparation of large thin sections of soils and unconsolidated materials. In: Osmond, D.A. & Bullocck, P. (Eds.), Soil Survey of England and Wales, Harpenden, Technical Monograph. Micromorphological Techniques and Applications, vol. 2, 3-13.

Franco E.M.S., Moreira M.M.M.A, Barbosa G.V. (1977). Projeto RADAMBRASIL – Geomorfologia. Içá, 14, 127-180.

Fritsch E., Bocquier G., Boulet R., Dosso M., Humbel F.X. (1986). Les systèmes transformants d'une couverture ferrallitique de Guyane française. Analyse structurale d'une formation supergène et mode de représentation. *Cah. ORSTOM* **22**, 361-395.

Fritsch E., Herbillon A.J., Jeanroy E., Pillon P., Barres O. (1989). Variations minéralogiques et structurales accompagnant le passage "sols rouges - sols jaunes" dans un bassin versant caractéristique de la zone de contact forêt-savane de l'Afrique occidentale (Booro-Borotou, Côte d'Ivoire). *Sci. Géol. Bul.* **42**, 65-89.

Fritsch E., Valentin C., Morel P., Leblond P. (1990a). La couverture pédologique : interactions avec les roches, le modelé et les formes de dégradation superficielles. In : Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 31-57.

Fritsch E., Chevallier P., Janeau J.L. (1990b). Le fonctionnement hydrodynamique du bas de versant. In : Structure et fonctionnement hydro-pédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 185-206.

Fritsch E, Peterschmitt E., Herbillon A.J. (1992). A structural approach to the regolith: Identification of structures, analysis of structural relationships and interpretations. *Sci. Géol. Bul.* **45** (2), 77-97.

Fritsch E. & Fitzpatrick R.W. (1994). Interpretation of Soil Features Produced by Ancient and Modern Processes in Degraded Landscapes. I. A new method for constructing conceptual soil-water-landscape models. *Aust. J. Soil Res.* **32**, 889-907.

Fritsch E., Montes-Lauar C.R., Boulet R., Melfi A.J., Balan E., Magat Ph. (2002). Lateritic and redoximorphic features in a faulted landscape near Manaus, Brazil. *European Journal of Soil Science* **53**, 203-218.

Fritsch E., Morin G., Bedidi A., Bonnin D., Balan E., Caquineau S., Calas G. (2005). Transformation of haematite and Al-poor goethite to Al-rich goethite and associated yellowing in a ferralitic clay soil profile of the middle Amazon basin (Manaus, Brazil). *European Journal of Soil Science* **56**, 575-588.

Fritsch E., Herbillon A. J., Nascimento Do N. R., Grimaldi, M., Melfi M. J. (2007). From Plinthic Acrisols to Plinthosols and Gleysols : iron and groundwater dynamics in the tertiary sediments of the upper Amazon basin. *European Journal of Soil Science* **58**, 989-1006.

Fritsch E., Allard T., Benedetti M.F., Bardy M., Nascimento Do N. R., Li, Y., Calas G. (2009). Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. *Geochimica et Cosmochimica Acta*, (doi: 10.1016/j.gca.2009.01.008).

Fritsch E., Allard T., Benedetti M.F., Bardy M., Do Nascimento N. R., Li, Y., Calas G. Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. *Geochimica et Cosmochimica Acta*, (submitted).

Gombeer R. & D'Hoore H. (1971). Induced migration of clays and other moderately mobile soil constituents. III. Critical soil/water dispersion ratio, colloid stability and electrophoretic mobility. *Pedologie* **21**, 311-342.

Grybos M., Davranche M., Gruau G., Petitjean P. (2007). Is trace metal release in wetland soils controlled by organic matter mobility or Fe-oxyhydroxides reduction? *Journal of Colloid and Interface Science* **314**, 460-501.

Gouveia S.E.M., Pessenda L.C.R. Aravena, R. Boulet R., Roveratti R., Gomes B.M. (1997). Dinâmica de vegetações durante o Quaternário recente no sul do Amazonas, indicada pelos isótopos do carbono (^{12}C, ^{13}C, ^{14}C) do solo. *Geochimica Brasiliensis* **11**, 355-367.

Gustafsson J.P., Bhattacharya P., Karltun E. (1999). Mineralogy of poorly crystalline aluminium phases in the B horizon of Podzols in southern Sweden. *Applied Geochemistry* **14**, 707-718.

IBGE. (2001). Mapa de solos do Brasil, Rio de Janeiro, escala 1: 5.000.000.

Jansen B., Nierop K.G.J., Verstraten J.M. (2003). Mobility of Fe(II), Fe(III) and Al in acidic forest soils mediated by dissolved organic matter: influence of solution pH and metal/organic carbon ratios. *Geoderma* **113**, 323-340.

Jeanroy E., Rajot J.L., Pillon P., Herbillon A.J. (1991). Differential dissolution of hematite and goethite in dithionite and its implication on soil yellowing. *Geoderma* **50**, 79-94.

Jenny H. (1941). Factors of soil formation. New York: McGraw-Hill, 109p.

King L.C. (1953). Canons of landscape evolution. *Bull. Geol. Soc. Am.* **64**, 721-752.

Klinge H. (1965). Podzol soils in the Amazon Basin. *Journal of Soil Sci.* **16**, 95-103.

Kronberg B. & Melfi,A. J. (1987). The geochemical evolution of lateritic terranes. *Z Geomorph N F Suppl Bd*. **64**, 25-32.

Kosmas, C.S., Curi, N., Bryant, R.B. & Franzmeier, D.P. (1984). Characterization of iron oxide minerals by second derivative visible spectroscopy. *Soil Science Society of America Journal* **48**, 401-405.

Latrubesse E.M., Franzinelli E., (2005). The Late Quaternary evolution of the Negro River, Amazon, Brazil : Implications for island and floodplain formation in large anabranching tropical systems. *Geomorphology* **70**, 372-397.

Linton D.L. (1955). The problem of tors. *Geogr. Journal*. **121**, 470-487.

Lucas, Y. (1989). *Systèmes pédologiques en Amazonie brésilienne. Equilibres, déséquilibres et transformations*. Thèse de Doctorat, Université de Poitiers, 157p.

Lucas Y., Chauvel A., Boulet R., Ranzani G., Scatolini F. (1984). Transição latossolos-podzóis sobre a Formação Barreiras na região de Manaus, Amazônia. *Revista Brasileira de Ciência do Solo* **8**, 325-335.

Lucas, Y., Boulet, R., Veillon, L. (1987). Systèmes sols ferrallitiques – podzols en région amazonienne. In: *Podzols et Podzolisation* (eds D. Righi & A. Chauvel), Association Française pour l'Etude du Sol, INRA, 53-65.

Lucas Y., Boulet R., Chauvel A. (1988). Intervention simultanée des phénomènes d'enfoncement vertical et de transformation latérale dans la mise en place des systèmes de sols de la zone tropicale humide. Cas des systèmes sols ferrallitiques-podzols de l'Amazonie Brésilienne. *C. R. Academie des Sciences de Paris* **306**, 1395-1400.

Lucas Y., Nahon D., Cornu S., Eyrolle F. (1996). Genèse et fonctionnement des sols en milieu équatorial. *C. R. Acad. Sci. Paris* **322**, 1-16.

Lundström U.S. (1993). The role of organic acids in soil solution chemistry in a podzolized soil. *J. Soil Sci.* **44**, 121-133.

Lundström U.S., van Breemen N., Bain, D. (2000). The Podzolisation process. A review. *Geoderma* **94**, 91-107.

Macias-Vasquez F, Fernandez-Marcos M.L., Chesworth W. (1987). Transformations minéralogiques dans les podzols et les sols podzoliques de Galice (NW. Espagne). In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 163-177.

Magnago H., Barreto R.A.A., Pastore U. (1978). Vegetação. Manaus, Projeto RadamBrasil, 18, 413-530.

Maurin J.C., Gilbert F., Robert M., Churlaud C. (2005). L'érosion chimique et l'érosion mécanique à long terme du substrat granitique (Vendée, France). *C. R. Geosciences* **337**, 841-848.

Malengreau, N., Beddidi A., Muller, J.P., Herbillon, A.J. (1996). Spectroscopic control of iron oxide dissolution in two ferralitic soils. *European Journal of Soil Science* **47**, 13-20.

Meade R., Rayol J.M., Da Conceição S.C., Natividade J.R., (1991). *Environmental Geologic Water Science* **18** (2), 105-114.

Mehra, O.P. & Jackson, M.L. (1960). Iron oxide removal from soils and clays by a dithionite-citrate buffered with sodium bicarbonate. *Clays and Clay Minerals* **7**, 317-327.

Melfi A.J. & Pedro G. (1977). Estudo geoquímico dos solos e formações superficiais do Brasil. Parte 1 - Caracterização e repartição dos principais tipos de evolução pedogeoquímica. *Revista Brasileira de Geociências* **7**, 271-286.

Middelburg J.J., Van der Weijden C.H., Woittiez J.R.W. (1988). Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks. *Chemical Geology* **68**, 253-273.

Millot G. (1983). Planation of continents by intertropical weathering and pedogenetic processes. In: Melfi A.J. & Carvalho A. Lateritisation Processes – Proceedings of the II International Seminar on lateritisation processes, 53-64.

Montes C.R., Lucas Y., Melfi A.J., Ishida D.A. (2007). Systèmes sols ferrallitiques–podzols et genèse des kaolins / Ferralsols–podzols soil systems and kaolin genesis. *C. R. Geosciences* **339**, 50-56.

Mortland M.M. (1968). Protonation of compounds at clay minera1 surfaces. *Transactions IX Int. Cong. Soi1 Sciences*, Adelalde (Australie) 1, 691-699.

Nahon, D.B. (1991). *Introduction to the Petrology of Soils and Chemical Weathering*. New York: John Wiley & Sons, 313p.

Nascimento Do N.R., Bueno G. T., Fritsch E., Herbillon A.J., Allard Th., Melfi A.J., Astolfo R., Boucher H., Y. Li. (2004). Podzolisation as a deferralitization process. A study of an Acrisol-Podzol sequence derived from Paleozoic sandstones in the northern upper Amazon Basin. *European Journal of Soil Science* **55**, 523-538.

Nascimento Do N.R., Fritsch E., Bueno G.T., Bardy M., Grimaldi C., Melfi A.J. (2008). Podzolization as a deferralitisation process: dynamics and chemistry of ground and surface waters in an Acrisol–Podzol sequence of the upper Amazon Basin. *European Journal of Soil Science* **59**, 911-924.

Oliva P., Viers J., Dupré B., Fortuné J.P., Martin F., Braun J.J., Nahon D.B., Robain H. (1999). The effect of organic matter on chemical weathering : Study of a small tropical watershed : Nsimi-Zoétélé site, Cameroon. *Geochimica et Cosmochimica Acta* **63**, 4013-4035.

Patel-Sorrentino N., Lucas Y., Eyrolle F., Melfi A.J. (2007). Fe, Al and Si species and organic matter leached off a ferrallitic and podzolic soil system from Central Amazonia. *Geoderma* **137**, 444-454.

Pedro G. (1987). Podzols et Podzolisation: un problème pédologique fort ancien, mas toujours d'actualité. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 1-10.

Peterschmitt E., Fritsch E., Rajot J.L., Herbillon A.J. (1996). Yellowing bleaching and ferritization in a hydrotoposequence of the Western Ghâts, South India. *Geoderma* **74**, 235-253.

Petersen L. (1984). The Podzol concept. In: Buurman, P. (Ed.), Podzols. New York: Van Nostrand Reinhold Company, 12-19.

Plaisance G. & Cailleux A. (1958). Dictionnaire des Sols. Paris: La Maison Rustique, 604 p.

Planchon O., Fritsch E., Valentin C. (1987). Rill development in a wet savannah environment. *Catena sup*. **8**, 55-70.

Projeto Radam (or Radam Brazil) (1972-78). *Levantamento de Recursos Naturais.* Vol. 1 - 15. Ministério das Minas e Energia. Departamento Nacional da Produção Mineral. Rio de Janeiro, Brazil.

Rinder G.E., Fritsch E., Fitzpatrick R.W. (1994). Computing procedures for mapping soil features at sub-catchment scale. *Aust. J. Soil Res*. **32**, 909-913 (colour figs 886-887).

Robinson G.W. (1949). *Soils, their origin, constitution and classification*. London: Thomas Murby and Co., 573p.

Sampaio, A. & Northfleet, A. (1973). Estratigrafia e correlação das bacias sedimentares brasileiras. In: Ann. 27 Congr. Soc. Bras. Geol., Aracajú, 3, 189-206.

Schwartz D. (1987). Les podzols tropicaux sur sable Batéké en R.P du Congo:description, caracterisation et genèse. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 25-36.

Ségalen P. (1966). Le processus de ferrallitisation et ses limites. ORSTOM s.n., 15-20.

Silva F.C.F., Jesus R.M., Ribeiro A.G. (1977). Vegetação. Içá, 14. DNPM/Projeto Radambrasil, 229-396.

Simonson, R.W. (1959). Outline of a generalized theory of soil genesis. *Soil Sci. Soc. Am. Proc.* **23**, 152-156.

Soil Survey Staff. (1975). Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S. Dept. of Agric. Handb. 436p.

Taboada T., Cortizas A. M., García C., García-Rodeja E. (2006). Particle-size fractionation of titanium and zirconium during weathering and pedogenesis of granitic rocks in NW Spain. *Geoderma* **131**, 218-236.

Tardy Y. (1993). *Pétrologie des latérites et des sols tropicaux*. Paris : Masson, 459p.

Théveniaut, H. & Freyssinet, Ph. (2002). Timing of lateritzation on the Guiana Shield: synthesis of paleomagnetic results from the French Guiana and Suriname. *Palaeogeography, Palaeoclimatology, Palaeoecology* **178**, 91-117.

Thompson C.H. (1992). Genesis of Podzols on Coastal Dunes in Southern Queensland. I. Field Relationships and Profile Morphology. *Australian Journal of Soil Research,* **30**, 593-613.

Torrent J., Schwertmann U., Barron V. (1987). The reductive dissolution of synthetic goethite and hematite in dithionite. *Clay Miner*. **22**, 329-337.

Trescases J.J. (1975). L'évolution géochimique supergène des roches ultrabasiques en zone tropicale. Formation des gisements nickélifères de Nouvelle-Calédonie. *Mém. ORSTOM* 78, 259p.

Turenne, J.F. (1975). *Modes d'humification et différenciation Podzolique dans deux toposéquences guyanaises*. Thèse de Doctorat, Université Nancy I, 185p.

Turenne J.F. (1977). Modes d'humification et différenciation podzolique dans deux toposéquences Guyanaises. *Mém. ORSTOM* 84, Paris, 174p.

Ugolini F.C. & Dahlgren R. (1987). The mechanism of podzolisation as revealed by soil solution studies. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. AFES-INRA, 195-203.

Valentin C. & Fritsch E. (1990). Un résumé des processus pédologiques ouest-africains. *In* Structure et fonctionnement hydropédologique d'un bassin versant de savane humide. Booro Borotou. *Collection "Etudes et Thèses"*, ORSTOM, 227-232.

Van Breemen N. (1985). Effects of seasonal redox-processes involving Fe on the chemistry of periodically reduced soils. In: Stucki J. W., Goodman A., Schwertmann O. (Eds.) Iron in soils and clay minerals. Bad Windsheim: Nato Advanced Study Institute, 858-875.

Van der Weijden C.H. & Van der Weijden R. (1995). Mobility of major, minor and some redox-sensitive trace elements and rare-earth elements during weathering of four granitoids in central Portugal. *Chemical Geology* **125**, 149-167.

Van Hees P.A.W. & Lundström U.S. (2000). Equilibrium models of aluminium and iron complexation with different organic acids in soil solution. *Geoderma* **94**, 201-221.

Van Ranst F. & De Coninck F. (2002). Evaluation of ferrolysis in soil formation. *European J. Soil Science* **53**, 513-520.

Viers J., Dupré B., Polvé M., Schott J., Dandurand J.L., Braun J.J. (1997). Chemical weathering in the drainage basin of a tropical watershed (Nsimi-Zoetele site, Cameroon): comparison between organic poor and organic rich waters. *Chem. Geol.*, **140**, 181-206.

Wesemael B., Verstraten J.M., Sevink J. (2005). Pedogenesis by clay dissolution on acid, low-grade metamorphic rocks under mediterranean forests in southern Tuscany (Italy). *Catena*, **24**, 105-125.

Wyszecki, G. & Stiles, W.S. (1982). Color science: Concepts and Methods, Quantitative Data and Formulae. John Wiley & Sons, New York, 950p.

Yamazaki D.R., Costa A.M.R., Azevedo W.P. (1978). Projeto RADAMBRASIL – Pedologia. Manaus, 18, 245-410.