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THE FORTALEZA DE MINAS NICKEL, COPPER AND PLATINOIDS DEPOSIT: ORE TYPES, TECTONICS AND VOLCANOLOGICAL ASPECTS

A JAZIDA DE NÍQUEL, COBRE E PLATINÓIDES DE FORTALEZA DE MINAS: ASPECTOS TECTÔNICOS, VULCANOLÓGICOS E TIPOS DE MINÉRIOS.

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Thomas Lafayette Brenner

Rio Claro,___de__________________de____

Resultado:____

DEDICATÓRIA

À minha esposa Léa,

pelo apoio constante e férias e fins de semana sacrificados

1 *"Eadem mutata resurgo"*

"Though changed I shall arise the same"

“Embora em nova forma eu ressurjo novamente o mesmo”

(Citação gravada na lápide do famoso matemático Jacques Bernoulli (1654-1705), e que acreditamos poder ser aplicada, para todos os Depósitos Minerais, que foram submetidos à severas modificações tectono-metamórficas ao longo do tempo geológico, independentemente de sua origem).

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A JAZIDA DE NÍQUEL, COBRE E PLATINÓIDES DE FORTALEZA DE MINAS: ASPECTOS TECTÔNICOS, VULCANOLÓGICOS E TIPOS DE MINÉRIOS.

1. Introdução

O presente trabalho reunindo três artigos científicos sobre a Jazida de Sulfeto Maciço Cupro-Niquelífero de Fortaleza de Minas e já formalizadas para publicação em revistas internacionais, foi confeccionado para ser apresentado como Tese de doutoramento no programa de Pós-Graduação em Geologia Regional, que é vinculado ao curso de Geologia do Instituto de Geociências e Ciências Exatas da Unesp – Campus de Rio Claro.

Distando cerca de 4 Km da pequena cidade de Fortaleza de Minas, localizada no Sudoeste do Estado de Minas Gerais, a Jazida de Fortaleza de Minas hospedada em rochas vulcânicas com quimismo komatiitico, foi descoberta em 1983, através de furos de sondagens, realizados em áreas portadoras de anomalias geoquímicas de Ni-Cu-Co e PGE em solos de natureza gossânica, localmente aflorantes no Greenstone Belt Morro do Ferro. Trabalhos prospectivos posteriores envolvendo trabalhos de geofísica e uma intensa campanha de furos de sondagens, detectaram em profundidade, a presença de um corpo de minério sulfetado maciço, com elevados teores de Níquel, Cobre, Cobalto e Platinóide, com espessura média de 4 metros, mais de 1.500 m de comprimento e atingindo profundidades superiores a 500 m.

O imenso acervo de informações de natureza geológica gerado desde a descoberta do Depósito até o presente, incluindo importantes informações concernentes à fase de Lavra a céu aberto, lavra subterrânea e até sobre o Beneficiamento do Minério, contou sempre com a participação do autor, que durante todo o período em questão, atuava como geólogo residente da Mina.

Todas essas informações são agora reunidas pelo autor, com a finalidade de discutir a fenomenologia envolvida na gênese da jazida nos tempos arqueanos, e sua evolução *a posteriori*, para serem disponibilizadas para a literatura no formato de três artigos principais.

O primeiro “**The Komatiite-Hosted Ni-Cu(PGE) Fortaleza de Minas Deposit: Ore types distribution and genesis”** faz uma abordagem sobre os tipos de minérios presentes na jazida, sua mineralogia e quimísmo e sua distribuição no depósito. São descritos os diferentes tipos de minério onde se identificam tipos primários razoavelmente preservados desde o Arqueano e tipos tectonicamente remobilizados por eventos paleoproterozóicos e neoproterozóicos. É também descrito um novo tipo de minério de natureza hidrotermal formado durante a última reativação no Neoproterozóico com forte enriquecimento em Ni e PGE. É apresentado o perfil de intemperismo do depósito com desenvolvimento de expressiva zona de gossan. É também discutida a distribuição dos diferentes tipos e minério no depósito, sua gênese e evolução.

O segundo "**Tectonics and Mineralization of the Komatiite-Hosted Ni-Cu-(PGE) Fortaleza de Minas Deposit, Minas Gerais, Brasil"** é consagrado à tipologia do minério resultante após sofrer sucessivas deformações. São discutidos o contexto geotectônico da região do depósito e os eventos tectono-metamórficos que afetaram o depósito e a mineralização. A geologia estrutural da jazida e dos tipos de minério é mostrada em suas feições macro e micro bem como a evolução tectono-metamórfica do depósito até a configuração espacial atual. Processos colisionais e transcorrentes afetaram sobremaneira a geometria do depósito e a tipologia do minério, mas o zoneamento primário da jazida foi preservado.

No terceiro "**The Fortaleza de Minas Nickel Sulfide Deposit: An Example of Komatiite-Hosted Ni-Cu-(PGE) Deposit in Highly Fractionated Ponded Flows**" são abordados os aspectos mineralógicos, petroquímicos e a faciologia vulcânica dos derrames komatiíticos que hospedam a mineralização e demais derrames do entorno da jazida. É apresentado o modelo genético para a formação do depósito mostrando que o depósito de Fortaleza de Minas se destaca como um raro exemplo de depósito de níquel vulcanogênico formado em fácies de lago de lava contrastando com a grande maioria dos depósitos komatiiticos mundiais formados em fácies de canal. Dados isotópicos apontam para evidências de assimilação crustal reforçando sua natureza distal, e seu quimísmo e fracionamento são comparados com outros derrames semelhantes. É ressaltada também a sua particular assinatura geoquímica com implicações em modelos exploratórios para este tipo de depósito.

THE FORTALEZA DE MINAS NICKEL, COPPER AND PLATINOIDS DEPOSIT: ORE TYPES, TECTONICS AND VOLCANOLOGICAL ASPECTS

1. Introduction

The current work gathers three scientific papers on the Fortaleza de Minas Ni-Cu massive sulfide deposit already available for issueing in international magazines and prepared for submission as a PhD thesis. The thesis is part of the Regional Geology Post-Graduation Program linked to the Geology Course from the Instituto de Geociências e Ciências Exatas of the State University of São Paulo - Rio Claro Campus.

Located four kilometers to the South of the small Fortaleza de Minas village, in the SW of Minas Gerais State, the Fortaleza de Minas deposit, hosted by komatiitic flows, was discovered in 1983, through follow up diamond drilling to test Ni-Cu-Co and PGE soil anomalies associated to outcroping gossans in the Morro do Ferro Greenstone Belt. Further prospective geophysical works and massive diamond drilling campaignsoutlined at depth a massive sulfide orebody with average width of 4 meters, more than 1,500m long and achieving depths higher than 500m.

The huge dataset of geological information generated since the deposit discovery until now, including important information from both openpit and underground mining and processing, had always the author`s participation, who, during all this period, acted as the resident mine geologist.

All this information is now gathered by the author, in order to discuss the deposit gênesis during Archean times, and its later evolution, to make it available to the literature in the form of three major articles.

The first “**The Komatiite-Hosted Ni-Cu(PGE) Fortaleza de Minas Deposit: Ore types distribution and genesis”** presents the deposit ore types, their mineralogy, chemitry and distribution throughout the deposit. The different ore types are described including well preserved Archean primary types and tectonically remobilised types during paleoproterozoic and neoproterozoic events. A new hidrothermal ore type is also described which was formed during the last reactivation in the Neoproterozoic associated with Ni and PGE enrichment. The weathering profile of the deposit is also described with its typical gossan zone. The distribution of the different ore types, their genesis and evolution are also discussed.

The second "**Tectonics and Mineralization of the Komatiite-Hosted Ni-Cu-(PGE) Fortaleza de Minas Deposit, Minas Gerais, Brasil"** describes the resulting ore types after sucessive deformations. The geotectonic environment of the deposit and the tectono-metamorfic events which affected the mineralisation are discussed. The deposit and ore types structural geology is presented in its macro and micro aspects. The tectono-metamorfic evolution of the deposit towards its current configuration is discussed. Colisional and transcurrent processes affected the deposit geometry and its ore types, but their primary zoning is still preserved.

The third "**The Fortaleza de Minas Nickel Sulfide Deposit: An Example of Komatiite-Hosted Ni-Cu-(PGE) Deposit in Highly Fractionated Ponded Flows**" describes the mineralogical and petrochemical aspects and volcanologic faciology of the komatiitic host flow and other neighbor flows. A genetic model for the deposit is discussed and shows that Fortaleza de Minas is an uncommon example of volcanogenic nickel deposit developed on a lava lake facies contrasting with the majority of komatiitic deposits, which are formed preferably on channel facies. Isotopic data show indications of crustal assimilation reinforcing its distal environment. Its chemistry and fractioning pattern are compared to other similar flows. The unique chemical signature of the deposit is highlighted with implications to exploratory models.

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The Komatiite-Hosted Ni–Cu–(PGE) Fortaleza de Minas Deposit: Ore types distribution and genesis

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Abstract

After 20 years of exploration and mining in the Fortaleza de Minas nickel deposit (formerly known as O`Toole) a better understanding of the geological framework and the volcanic environment was achieved. The different ore types observed in the deposit and its distribution revealed the original volcanic setting for the ore formation and also the geological evolution and transformation of the different ore types. The nickel mineralization is classified as a Type 1 deposit (Lesher and Keays, 2002). It is associated to an open trough structure of lava pathway. Later metamorphism and deformation obliterated most of the original volcanic textures and promoted a strong stretching of the ore zone and remobilization of the massive breccia ore along a major shear zone installed at the base of an upper fractionated host flow unit in contact with a footwall BIF. In the upper proterozoic Brasiliano Cycle (0.6 Ga) a new ore type was formed of hydrothermal origin with extremely high nickel grades and PGE nuggests.

Introduction

Having completed 20 years of continuous exploratory and infill drilling in the Fortaleza de Minas Ni - Fe sulfide deposit (Brenner et al. 1990), aided by the opening of both open pit and underground mines since 1998, a better understanding of the geological framework of its volcanic environment can now be achieved. Within this period several academical studies were carried out with under-graduated and graduated students from the University of São Paulo State – UNESP at Rio Claro Campus (Santos, 1996; Santos et al., 1997; Carvalho, 1998; Carvalho et al., 1999). Detailed mapping and sampling in both mines in addition to core logging allowed the understanding of the geometry of the mineralized flow revealing troughs within a broader embayment structure similar to other Type 1 deposits related to komatiiites (Lesher and Keays, 2002). The primary ore types typical of Type 1 deposits – disseminated, matrix and massive – were strongly affected by late metamorphism and shearing giving origin to other ore types and squeezed the sulfides away from the original trough environment along the olivine-cumulate host and footwall BIF contact. Strong squeezing associated to transcurrent shear displacement and the remobilization of the primary ore types masked the identification of the original trough structures. However, detailed mapping of the ore type distributions and modeling of footwall BIF thinning interpreted as an indication of mechanical-thermal erosion, led to the tentative identification of possible lava pathways in the deposit.

Geological setting

The geology of the Fortaleza de Minas deposit area was described in Marchetto et al. (1984), Teixeira et al (1987) and Brenner et al (1990) and has been reviewed more recently with new studies (Zanardo et al, 1996; Zanardo, 1992; Zanardo, 1990 and Morales, 1993). The area is comprised by an archean crustal nuclei of granite-greenstone terrain within a broad nappe structure of proterozoic meta-sediments named as Passos Nappe. This block was once part of the Archean Paramirim Craton which was reworked during the Proterozic into the Araxá mobile belt. The Fortaleza de Minas Ni–Fe sulfide deposit is locate in the SW side of the northern portion of the Guariroba-Peroba segment (Fig. 1), considered to represent the basal part of the Morro do Ferro greenstone belt (Teixeira and Danni, 1979a,b). The upper portion being represented by the thick chemical-detritical sediments in the northeastern side of the Peroba area to the South. Sm/Nd isotopic results from the Ni deposit host flow revealed an age of ca. 2.86 Ga for the cristalization of the lavas (Pimentel & Ferreira Filho, 2002), suggesting that these rocks are coeval to the Piumhi greenstone belt (ca. 2.9–3.1 Ga). The area was esposed to regional metamorphism during the paleoproterozoic Transamazonian Orogeny (2.16–2.0 Ga), achieving high amphibolite facies in the deposit area, whith temperatures higher than 650 ^{o}C (Fernandes, 1998). The region was later affected by intense transcurrent shearing during the Brasiliano Cycle (900–520 Ma) with reactivation of major regional faults associated with retrograde metamorphism with temperature not higher than 300^{o}C.

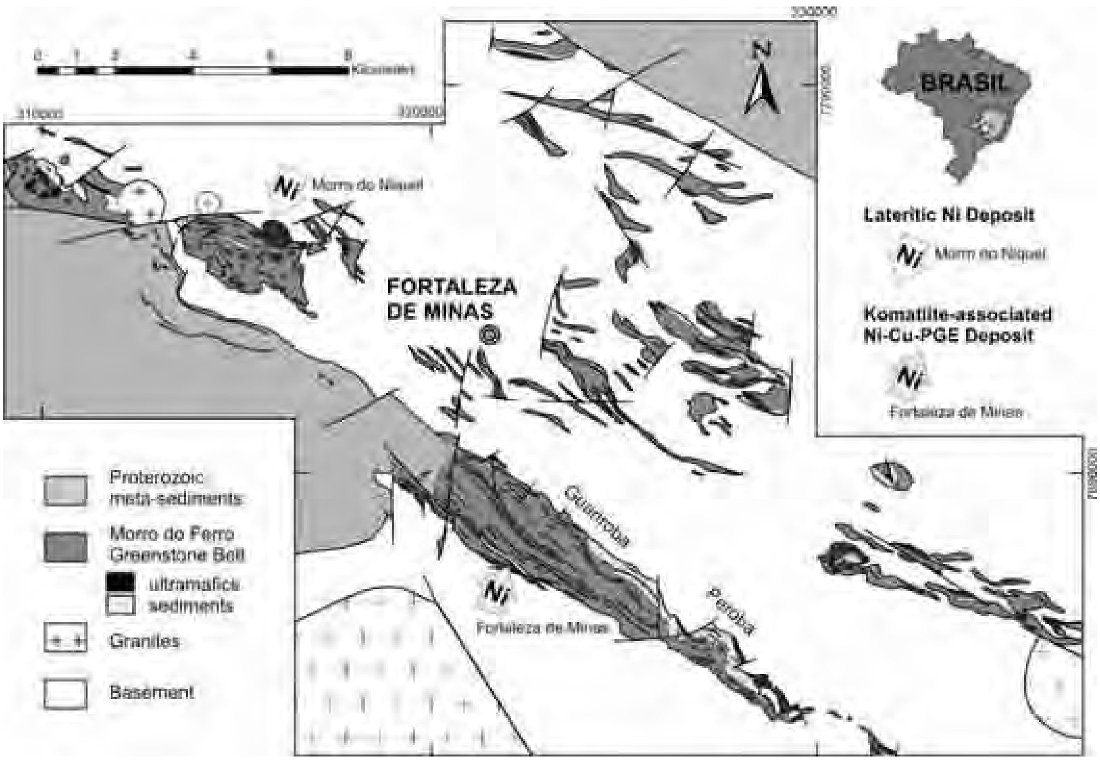

Fig. 1. Morro do Ferro Greenstone Belt geology and deposits.

Geology of the Fortaleza de Minas deposit area

Brenner et al (1990) identified four cicles or flow units in the deposit area of serpentinite-clino-pyroxenite- gabbro separated by banded iron formations. The nickel deposit occur in the uppermost flow unit (Fig. 2). The flow units were named 'intermediate sequence` having a lower and an upper sequences represented by komatiitic basalt flows and subordinately komatiite flows and graphitic meta-cherts and tuffs (black shales). The upper and lower sequences represent the dominant units in the Guariroba-Peroba area. The intermediate sequence is currently interpreted as a thick highly fractionated flow (Hill et al., 1995; Hill, 2001), where the individual cycles represent individual flow units separated by thin BIF. The volcanic environment of the Fortaleza de Minas deposit is interpreted as of a Ponded facies in a distal shallow lava lake (Brenner and Carvalho, 2006).

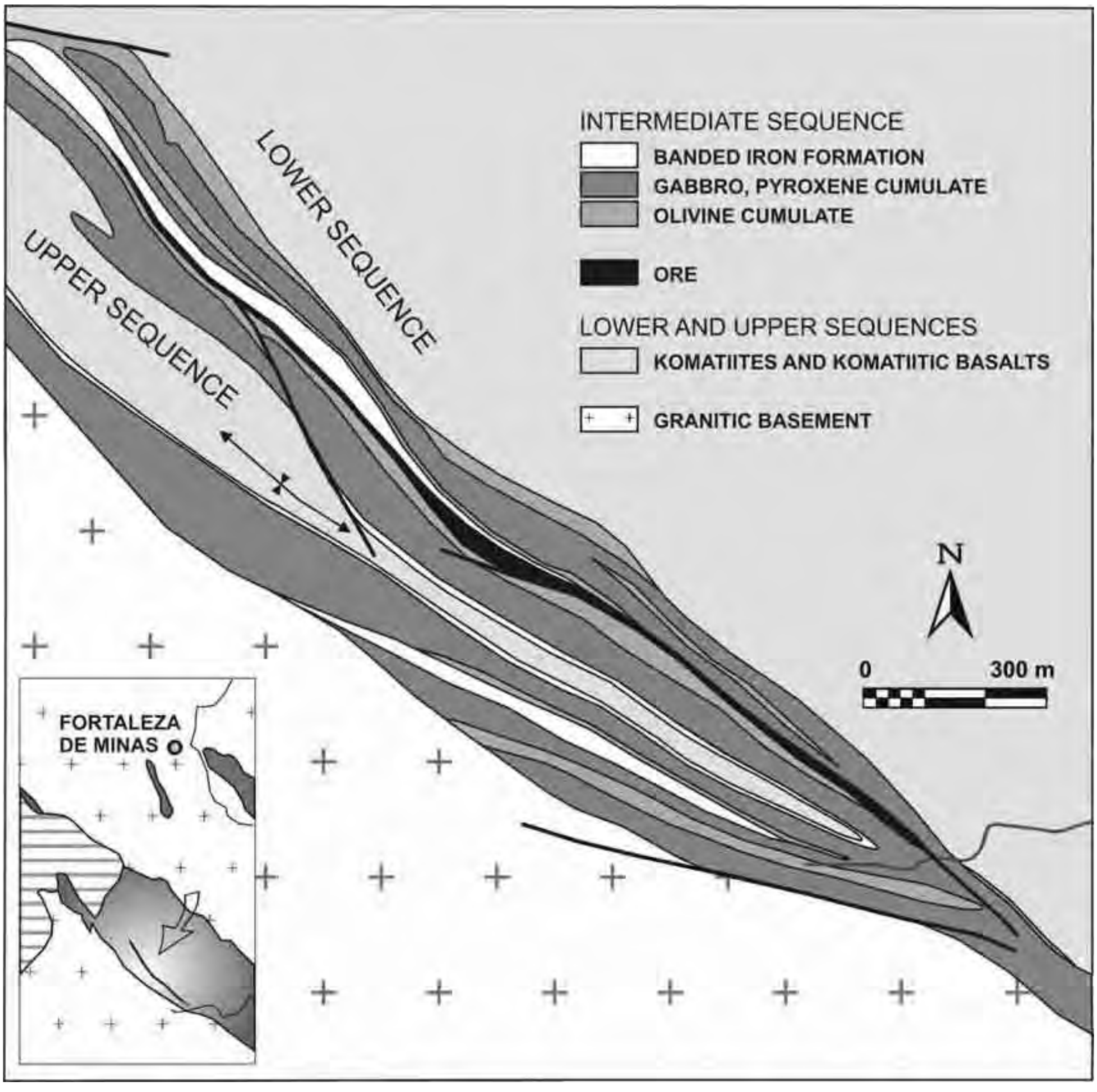

Fig. 2. Geological map of the Fortaleza de Minas Ni – Fe sulfide deposit. Pale grey color representing the upper and lower sequences from Brenner et al, 1990 and the intermediate sequence interpreted herein as a thick highly fractioned flow. The orebody is extremely elongated by shearing along a transcurrent sinistral shear zone. Southwestern limb of syncline displays marginal mineralization at depth.

The Fortaleza de Minas Ni – Fe sulfide mineralization

The Ni, Cu, Co, PGE deposit (Brenner et al, 1990) has a 1.5 km strike length and an average width of 5 meters. Reserves are indicated to a 500m depth below surface. The Ni – Fe sulfide mineralization occur along a sinistral shear zone installed at the base of a mineralized olivine-cumulate in contact with a footwall BIF (Fig. 3). The typical hanging wall is represented currently by a massive serpentinite or a talc – carbonate schist both metamorphic products formed after an olivine-cumulate basal zone from a fractionated komatiitic flow. The most common footwall is a banded iron formation although it can be locally represented by talc-carbonate schist, pyroxene-cumulates or sepentinite. The deposit displayed a global resource of the order of 6 Mt with an average grade of 2.5% Ni, 0.40 % Cu, 500 ppm Co and 0.7 g/t Pt, Pd, Au. The current underground mine has still one year of mine life after the start up in 1998.

Major ore types

Three major ore types have been defined in the Fortaleza de Minas deposit (Brenner et al, 1990), from top to base, as follows: Disseminated ore (DS), Matrix ore (MX) and Breccia ore (BR) (Fig. 3). Other remobilized ore types has also been identifyied and include Sheared ore (SU), BIF hosted ore (SC) and a late hydrothermal massive sulfide (HMS).

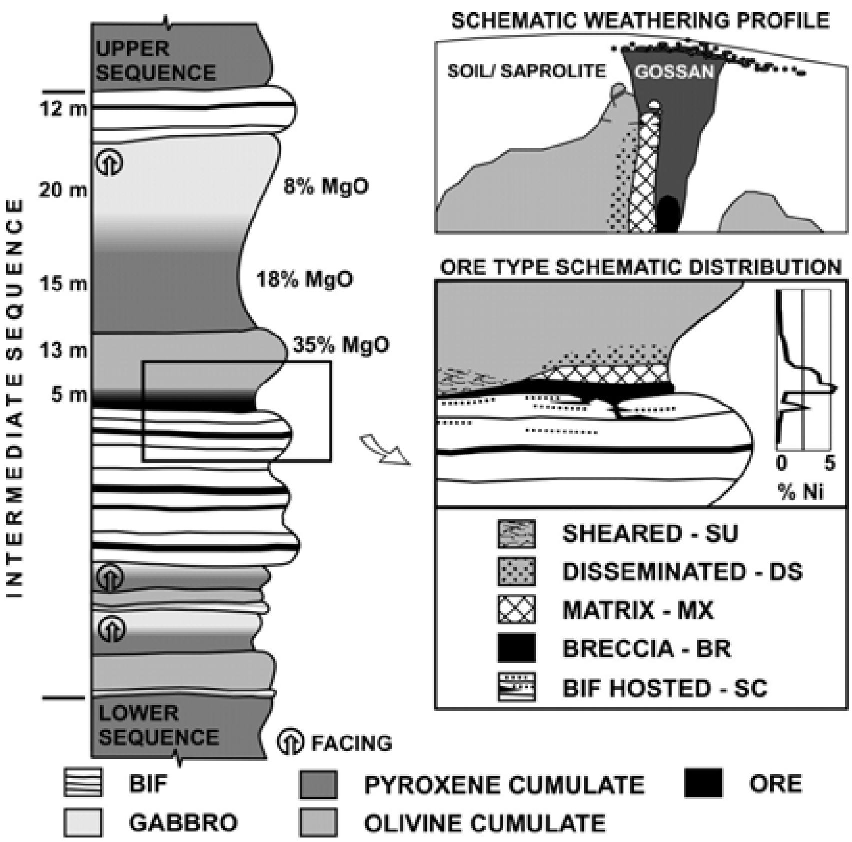

Fig. 3. Schematic stratrigraphic column of the Fortaleza de Minas deposit and ore types distribution profiles.

From the different ore types the disseminated and matrix are considered to be primary magmatic ore types with variable degree of deformation but still preserving magmatic textures under superimposed cataclastic textures. The Breccia ore is fully recristalized with indications of polyphasic evolution from ductile to brittle regime. It is interpreted as derived after originally magmatic massive sulfides and, partially, after reworked matrix ore in intensely sheared zones. The distribution of breccia, matrix and disseminated ore follows the model proposed by Naldrett (1973) named as billiard ball model (Fig. 4).

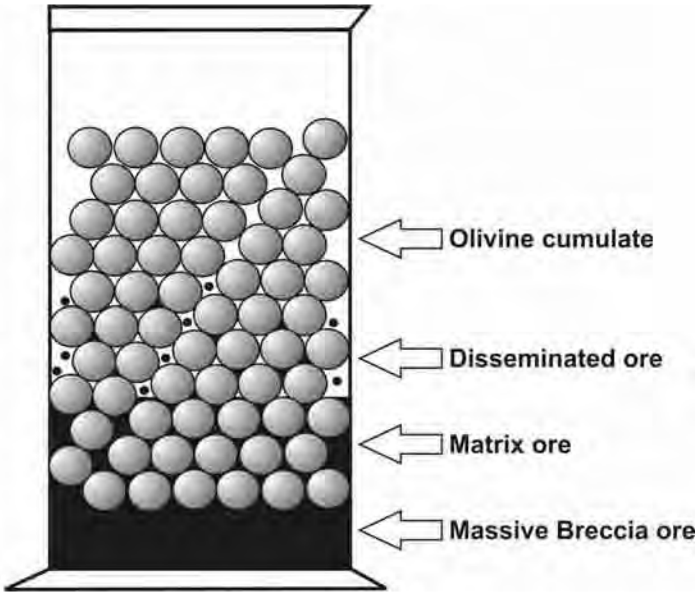

Fig. 4. The billiard ball model modified after Naldrett, 1973. The grey circles representing billiard balls (olivines), mercury (sulfides) in black and water (melt) in white.

The mean mineralogical composition of the major ore types from the Fortaleza the Minas deposit is shown in Table 1. The mean compositon is based in a detailed sampling program and petrographic work carried out in the open pit mine. The different ore types major characteristics are described below.

Table 1. Average wt% modal composition of major ore types in the Fortaleza de Minas deposit.

(wt%)	host	sulf	mgt	ant	chl	crb	trm	act	tlc	qtz
DS	SS	21	15	46	*5*	*4*	*4*	*1*	*4*	
MX	SS	51	16	27	*1*	*3*	*<1*		*3*	
BR1	-	65	12	*3*	*2*	*2*	*<1*	10	6	*1*
BR2	-	62	11	*<1*	*2*	*3*	*<1*	8	14	
SU	TT	22	14		11	7	8		38	
SC	BIF	28	*<1*		*1*	*<1*		60	*<1*	9

DS - Disseminated ore, MX - Matrix ore, BR1 - Breccia ore (trough), BR2 - Breccia ore (talc bearing remobilized), SU - Sheared ore (talc bearing remobilized), SC - BIF hosted ore.

sulf - sulfides (PoPnCp), mgt - magnetite, ant - antigorite, chl - chlorite, crb - carbonate (dolomite), trm - tremolite, act - actinolite, tlc - talc, qtz - quartz. SS - serpentinite (Ocm), TT - talc schist, BIF - banded iron formation

Disseminated ore (DS)

The disseminated ore occurs as the first ore type developed towards the base of the differentiated flow in the trough zones. It is hosted by serpentinites and its defined by a 0.60% Ni natural cut-off. It has in average 15 to 25 wt% total sulphides with the following proportion: 65% pirrhotite, 30% pentlandite, 5% chalcopyrite (Table 1). It has an average grade of about 1% Ni and at depth, in the lower portions of the underground mine, it averages 0.8% Ni. Like the serpentinite host it shows a magnetite content of 15 wt%. The sulfides are finelly grained and normally well disseminated through the serpentinite. In the hanging wall contact, transitional at a small scale, the sulphides start to concentrate into clouds or small nucleus but rapidly they tend to evolve into a well distributed dissemination. Tipical grades are: 0.95% Ni, 0.25% Cu, 260 ppm Co, 2.70% S, 0.13 g/t Pt, 0.24 g/t Pd, 0.08 g/t Au. It gradually but rapidly increase the sulfide content downwards to the matrix ore (Fig. 5a, 5b and 5c).

Matrix ore (MX)

The transition from disseminated ore to matrix ore is marked by the 2.00% Ni natural cut-off. Because of the intense shearing observed in the mine area most of the contacts observed between the disseminated and matrix ores are tectonic marked by a thin talcose fine grain mylonitic zone. Sometimes tectonic wedges or slabs of disseminated and matrix ore types can be intercalated. However, in many places, in both open pit and underground mine, a clear transition between the two ore types were mapped and sampled. The average sulfide content is 50 wt% with similar proportion as for the disseminated ore: 65% pirrhotite, 30% pentlandite, 5% chalcopyrite, and also same amount of magnetite (16 wt%). The average grade for the matrix ore is about 3.00 to 3.50% Ni. In the transitional contact zone the disseminated ore increases the grade to 1.60 and 1.80% Ni and gradually assumes the typical matrix ore texture achieving grades of 2.2 to 2.5% Ni and higher (Figs. 5b and 5c). The matrix ore has a distinctive fabric similar to many other net-textured ore from volcanogenic massive sulfide deposits (Lesher, 1989; Lesher and Keays, 2002). Rounded shaped serpentine magnetite gangue is involved by a sulfide network. The rounded masses of serpentine + magnetite are interpreted as metamorphosed cumulate olivine crystals surrounded by sulfide (Fig. 5d). This texture is interpreted as a primary magmatic texture. The matrix is a very isotropic and uniform ore type (Fig. 5e e g). Under the microscope and in hand specimen the matrix ore usually displays a cataclastic texture but still preserving its primary texture (Figs. 5d and 5f). Variations in grain size may occur ranging from a fine to coarse texture. In some places an alternation of finer and coarser ore were interpreted as primary flow layering structures. The matrix ore typical grade composition is: 3.40% Ni, 0.63% Cu, 724 ppm Co, 13.2% S, 0.53 g/t Pt, 0.74 g/t Pd, 0.14 g/t Au.

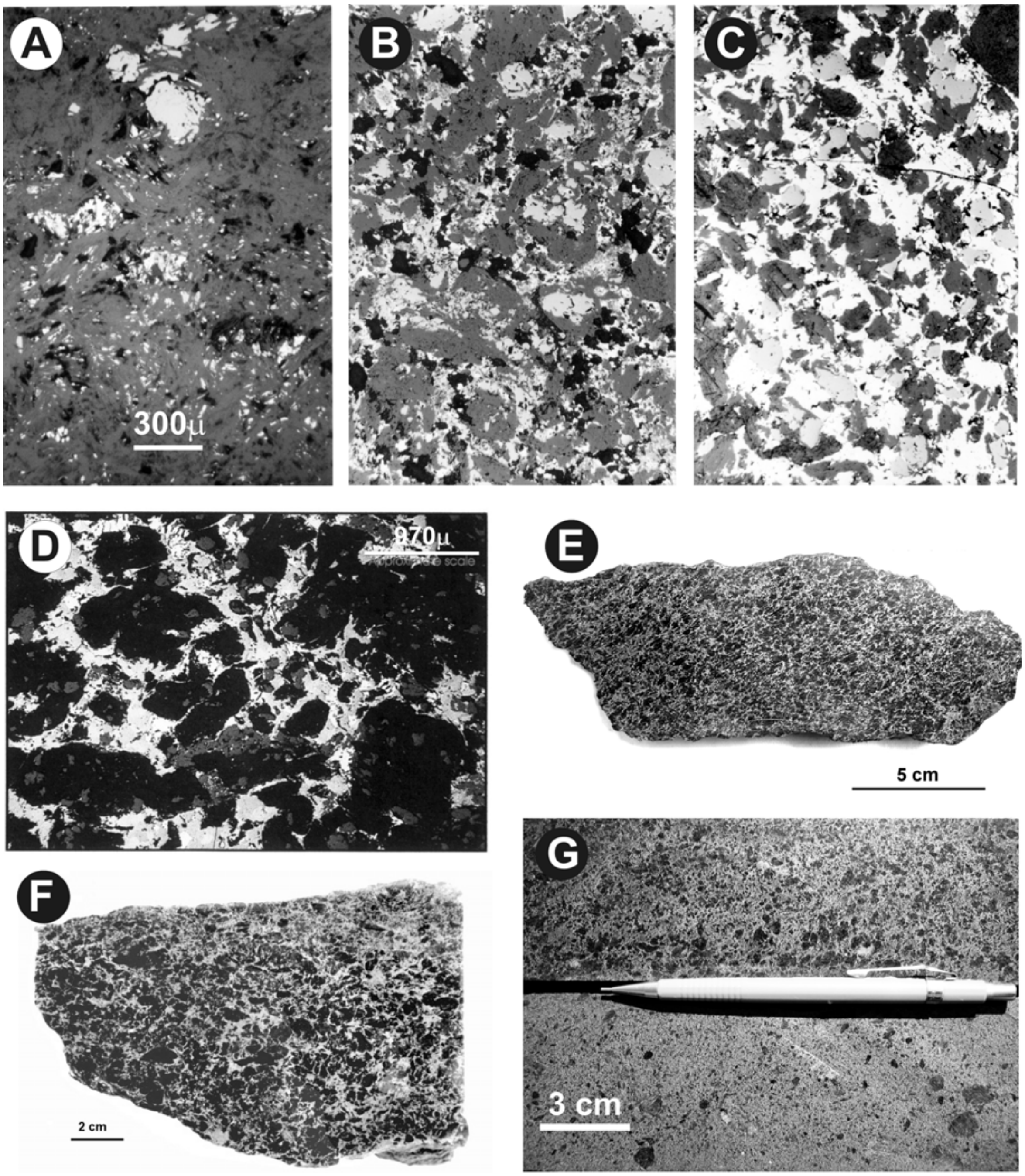

Fig. 5. Fortaleza de Minas ore types DS/MX. For photomicrographies a to c sulfides are displayed in light grey to white, antigorite (serpentine) in medium grey and magnetite in black. **a** photomicrography of typical disseminated ore. **b** photomicrography of matrix ore in the transition zone from disseminated ore. **c** photomicrography of matrix ore. **d** photomicrography of a typical matrix ore displaying pseudomorphs of rounded olivines now replaced by serpentine (black) and magnetite (grey) surrounded by sulfides (light grey to white). **e** hand specimen of matrix ore. **f** close up of coarse matrix ore showing cataclastic net texture. **g** core samples from matrix (top) and breccia (bottom) ores displaying antigorite replaced olivine cumulus in matrix ore and BIF fragments in breccia ore.

Breccia ore (BR)

Due to its high plasticity the breccia massive sulfide ore is the most widely spread ore type occurring throughout the entire deposit. It is commonly well recrystalized (Fig. 6a) but can also be intensely sheared due to continuos processes of shearing and recrystalization under a transcurrent ductile-brittle regime. Its typical emplacement is at the hanging wall serpentinite and footwall BIF contact, usually extending beyond the primary embayment limits (Fig. 6b). It shows a gradational decay in both grade and amount of sulfide from the center to the lateral extensions of the deposit. When sheared it displays rounded and elongated fragments of wall rocks and occasionally segregation of pentlandite in layers along the foliation plane (Fig. 6c).

The Breccia ore (BR) has been subdivided into BR1 and BR2 sub-types reflecting the remobilization process under transcurrent shear regime. The BR1 has higher Ni grade and occur in the central embayment structure, typically and commonly below the matrix and disseminated ores. An exception is the immediate North extension from the embayment zone where very high grade recrystalized BR occurs remobilized into the footwall BIF.

BR1 has a clean recristalised groundmass where clasts of both serpentinite (fig. 6d) and BIF (Figs. 6e and 6f) are common. Minor fragments of talc schist may also occur. The fragments are usually rounded and slightly flattened but angular fragments are also common. They vary in size from milimetric to decimetric but can achieve metric sizes eventually. In some places fragments of disseminated ore and also matrix ore can be found in the breccia ore (Fig. 6c). At the footwall contact BIF fragments are more common and exposures in the open pit mine revealed a continuous process of fragmentation and incorporation of the footwall BIF into the brecciated massive sulfide along the sheared contact and fault offsets (Fig. 6g). The BR2 shows a dirty talcose sulfide matrix with consequently average lower Ni grades than the BR1 sub-type.

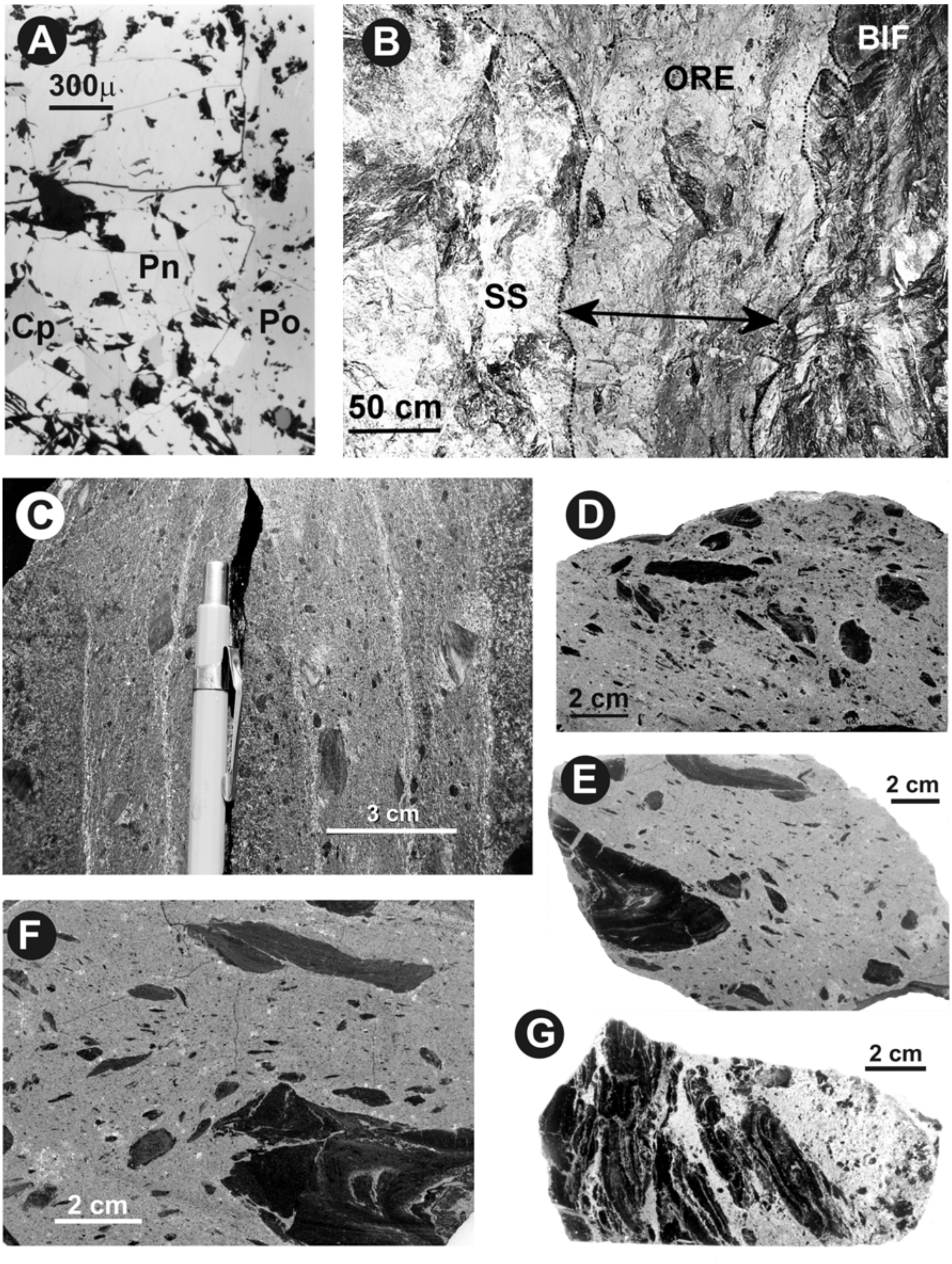

Fig. 6. Fortaleza de Minas ore types BR1. **a** photomicrografy of coarse breccia ore showing pyrrhotite (Po), pentlandite (Pn) and chalcopyrite (Cp). **b** underground exposure of breccia ore in the northern extension of the primary embayment following the sheared serpentinite (left)/ BIF (right) contact. **c** sheared breccia ore with trails of lighter color pentlandite along foliation plane also displaying matrix ore fragment contact. **d** breccia ore with angular and rounded fragments of serpentinite and minor BIF. **e-f** hand specimes of typical breccia ore (BR1 sub-type) with dominant BIF fragments and minor serpentinite fragments (darker). Note folded exhalative bedded sulfide bands in larger BIF fragments. Fine grained massive sulfide groundmass formed by Po, Pn, Cp. Individual larger Pn crystals can be outline by its distinctive cleavage (lighter color).

The fragments are strongly deformed within the foliated BR2 matrix (Fig. 7a). Fragments are dominantly talc schist and BIF (Fig. 7b). Talc fragments are extremely flattened and in general the majority of the fragments are well oriented and of smaller size when compared to the BR1 ore sub-type. They BR2 typically occur at the lateral extentions of the embayment zone where the ore shows a consistent reduction in both width and grades. At the limits of the economic central shoots the BR2 gradually merge into the Sheared ore (SU) where the cataclastic texture typical of the BR2 ore remains quite unchanged but the total amount of sulfides drops considerably into the sheared low grade talcose ore SU (Fig. 7c). The breccia ore typical grade composition is: 4.14% Ni, 0.56% Cu, 870 ppm Co, 16.0% S, 0.42 g/t Pt, 0.69 g/t Pd, 0.14 g/t Au. The average sulfide content is 65 wt% (BR1) and 62 wt% (BR2) with proportions of 65% pirrhotite, 25% pentlandite, 10% chalcopyrite, and the amount of magnetite (10 – 12 wt%) is also similar to the disseminated and matrix ore types.

Sheared ore (SU)

This ore type occurs outside of the trough zones where the disseminated and matrix ores are dominant. The sheared ore displays a flaser mylonitic fabric (Fig. 7c), and although displaying low grades similarly to the disseminated ore, it shows a clear relationship and gradation to the also sheared breccia ore (BR2 sub-type). Talc is the typical gangue mineral, and smaller amounts of carbonate, chlorite and magnetite are met with. The sulfides are interconnected as anastomosed veinlets with typical triangular cuspade junctions. Because of this interconnected mylonitic fabric this ore type behaves as massive sulfide in response to ground EM surveys. The distribution of this ore type is widespread troughout the external zones of the deposit extending hundreds of meters from the primary central embayment zone. It is positioned at the base of the hanging wall serpentinite or talc schist but sometimes it makes contact with pyroxenites when the serpentinite is pinched out by shearing. It may occur alone or intermixed with the BR2 ore and may also occur associated with the BIF hosted ore, sometimes tectonically intercalated. Based in it’s distribution and relationship to the BR2 ore it has been interpreted as a tectonically remobilized ore type derived after the BR2 ore originated by intense shearing with continuous decay in sulfide content from the massive sulfide ore and being squeezed along the talcose contact shear zone. In the outer limits of the deposit this ore type can be very persistent occurring as a continuous centimetric sheared talcose zone which can be traced by drilling hundreds of meters away from the mineable part of the deposit. The typical grades for the sheared ore are: 1.23% Ni, 0.22% Cu, 308 ppm Co, 5.1% S, 0.23 g/t Pt, 0.32 g/t Pd, 0.09 g/t Au. The average sulfide content is 22 wt% with proportions of 65Po:25Pn:10Cp with magnetite content of 14 wt%.

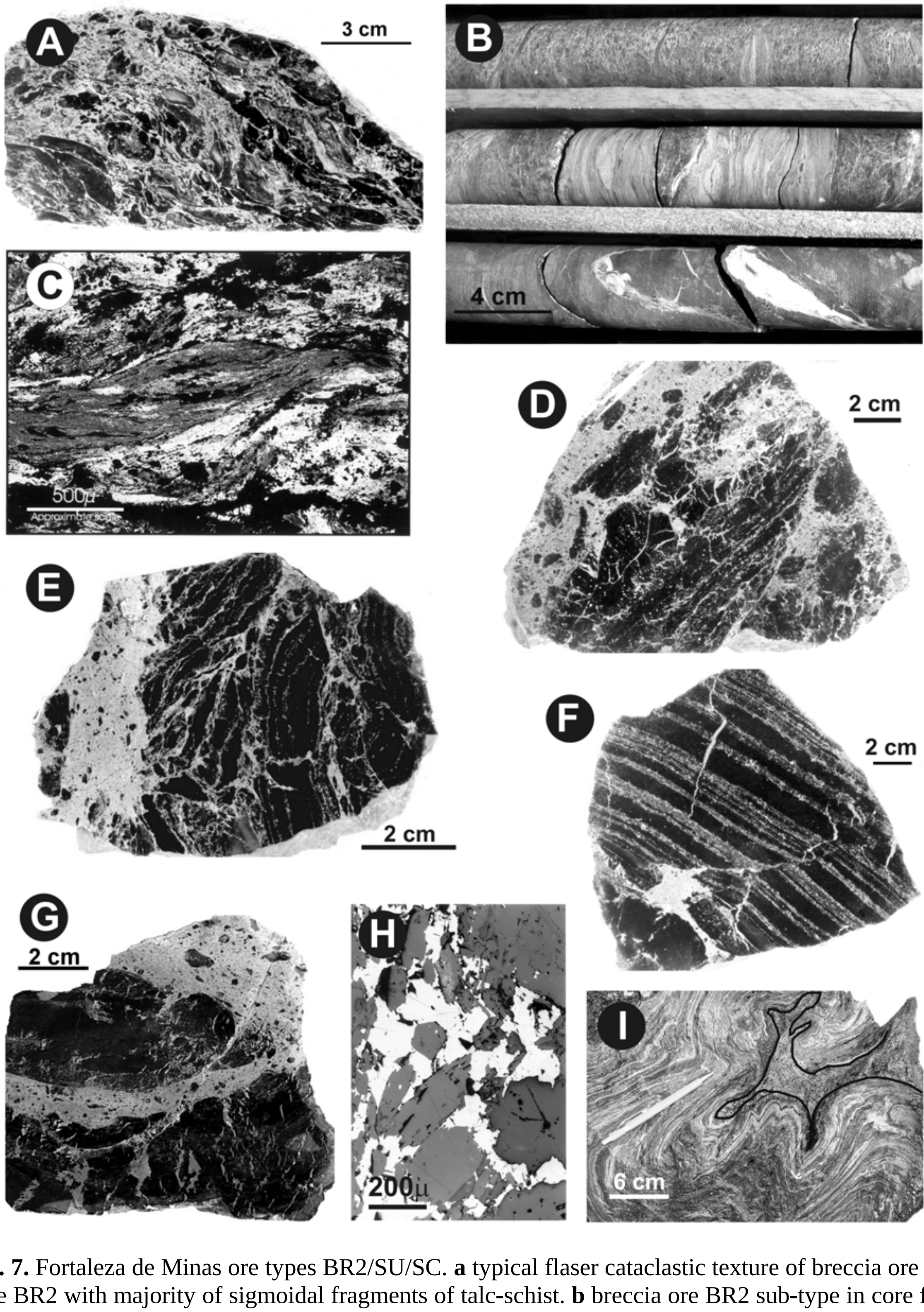

Fig. 7. Fortaleza de Minas ore types BR2/SU/SC. **a** typical flaser cataclastic texture of breccia ore sub-type BR2 with majority of sigmoidal fragments of talc-schist. **b** breccia ore BR2 sub-type in core from underground drilling. Foliated and sheared breccia ore with larger fragments of BIF and smaller highly elongated fragments of talc schist. **c** photomicrography of low grade SU ore type showing anastomosed cataclastic texture in a chlorite, carbonate, talc groundmass with sulfides along shear planes. **d-e** BIF hosted ore displaying injection of Ni sulfides along R and P shear planes. Augen shaped BIF fragments being individualized and assimilated by the breccia ore. Contact zone between BR1 and SC in the North portion of the open pit mine. **f** baren and banded exalative sulfide bearing BIF with Ni sulfide remobilized into fractures and tension gashes. **g** contact between BR1 and BIF hosted ore (SC) showing breccia ore veinlet and chalcopyrite filling tension gashes (bottom). **h** photomicrography of BIF hosted ore showing recristalized sulfides in a actinolite-cummingtonite gangue. **i** highly folded BIF with massive sulfide squeezed into complex fold axis (outlined).

BIF hosted ore (SC)

The BIF hosted ore occur in the footwall contact zone between the Breccia and Sheared ore types and the footwall BIF. It is a remobilized ore type formed during transcurrent shearing polyphasic events. Ni sulfides in the BIF occur as massive or breccia sulfide veins, veinlets, stringers, tension gashes fillings or as disseminated banded sulfides (Figs. 7d, e, f, g). Most of the time, Ni sulfide stringers and veinlets invade a silicate facies baren BIF achieving economic grades. In places, banded exalative baren sulfides (Po) were locally replaced by Ni bearing sulfides along the original bedding (Fig. 7f). In the trough zones the SC ore is normally absent or rare. The footwall BIF is also absent or rare and thin in the trough zones. The absence or thinning of the BIF has been interpreted as result of thermal erosion of the thick BIF unit. In the North of the central embayment there is a gradation between breccia ore (BR1) and the BIF hosted ore. Bench exposures in the north of the open pit revealed a front of well recrystalised breccia ore being tectonically translocated into the footwall BIF along fractures and faults parallel to the foliation and bedding and breaking and absorbing BIF fragments. A continuous process of breccia ore veining along foliation with subsequent merging of the BR1 veins into a single massive sulfide body with fragments of the BIF walls can be observed in this area where the breccia ore occurs surrounded by a halo of BIF hosted ore (Figs 7d, e, g). The BIF hosted ore type is usually well recristalized with good liberation at the mill (Fig. 7h). In the underground mine, in highly folded areas in the footwall, massive sulfide offset veins can be squeezed into the footwall BIF along faults and fold nucleus (Fig. 7i). The typical grades for the BIF hosted ore are: 1.00% Ni, 0.35% Cu, 239 ppm Co, 4.4% S, 0.11 g/t Pt, 0.20 g/t Pd, 0.08 g/t Au. The average sulfide content is 28 wt% with proportions of 65Po:25Pn:10Cp similar to the sheared ore. Magnetite is rare in the SC ore type, but locally can exceed 15 wt%.

Hydrothermal massive sulphide (HMS)

With the opening of the open pit mine a new ore type was identified with remarkably differences from the previous ore types. A high grade massive sulfide with characteristic coarse pentlandite crystals was mapped in steep oblique hanging wall faults and fractures in the southern portion of the open pit. This ore type displays a post-tectonic fabric with lack of metamorphic foliation although can be locally sheared. It occurs as typical fault plane or fracture infills in the immediate hanging wall of the ore zone (Fig. 8). It shows a clear relationship to the breccia ore (BR) from which it seems to be derived. It normally shows a faulted contact to the BR including tectonic slabs of other ore types and host rocks like serpentinite and BIF. As it moves away into the hanging wall it looses gradually thickness acting a typical vein until it pinches out a few meters to tens of meters from the main ore zone. In some cases it can be split into smaller veinlets along vertical to horizontal fractures in a stockwork array. With continuous mapping and underground mine development this ore type proved to be persistent although intermittent towards the deeper portions of the deposit displaying sub-vertical plunges but moving south as it goes deeper as a broad en echelon structure.

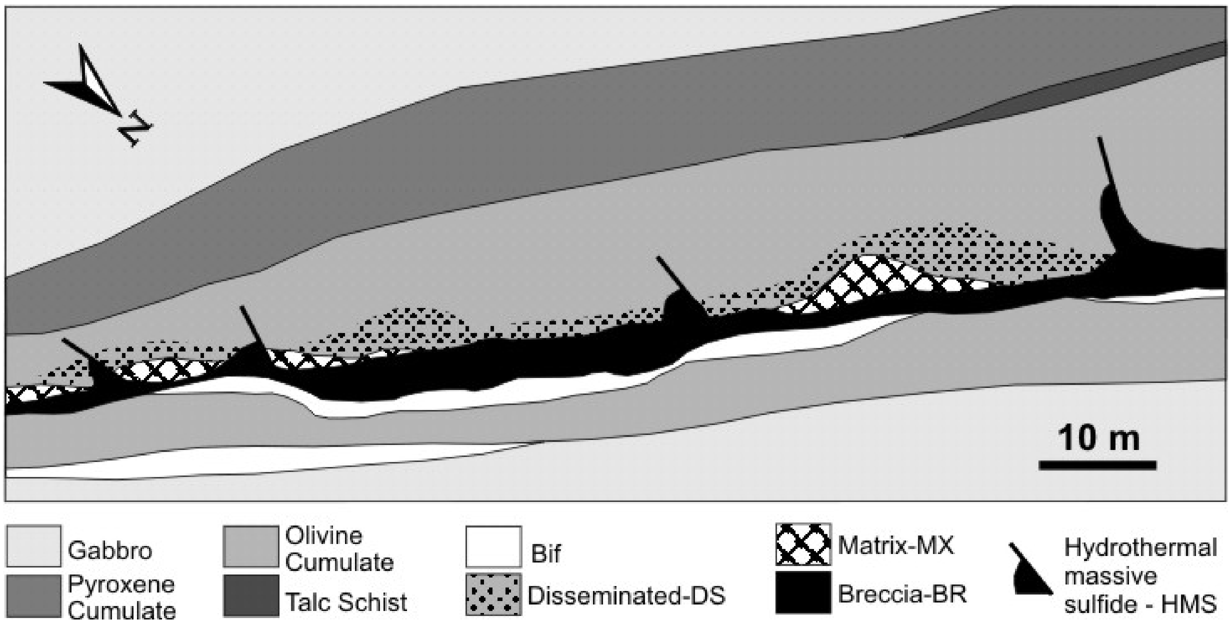

Fig. 8. Open pit 990 bench horizontal plan showing four offset bodies of HMS ore associated to oblique faults in the hanging wall olivine cumulate (serpentinite).

Contrasting to the other ore types the HMS can display zoning structures in the contact with wall rocks with different phases of Pn rich ore bordered by a massive Cp zone and with a massive magnetite contact halo. Talc, carbonate and chalcopyrite hydrothermal breccias are commonly associated with the HMS (Fig. 9a). This ore type show a very high nickel grade (8-14%Ni) when compared to the BR ore which usually displays grades between 3 and 5% Ni. It can exceed 90% wt% sulfides. It also shows an abnormal concentration of PGM achieving values of 5 g/t Pt and up to 40 g/t Pd. The Pn crystals are remarkably large where poikiloblastic decimetric crystals were recorded (Fig. 9b, c). The HMS ore shows a greenschist facies paragenesis and also uncommon minor element association for this type of deposit such as Ag, Mo, Bi. The typical grades for the HMS ore are: 9.10% Ni, 0.71% Cu, 1650 ppm Co, 28.3% S, 0.35 g/t Pt, 4.44 g/t Pd.

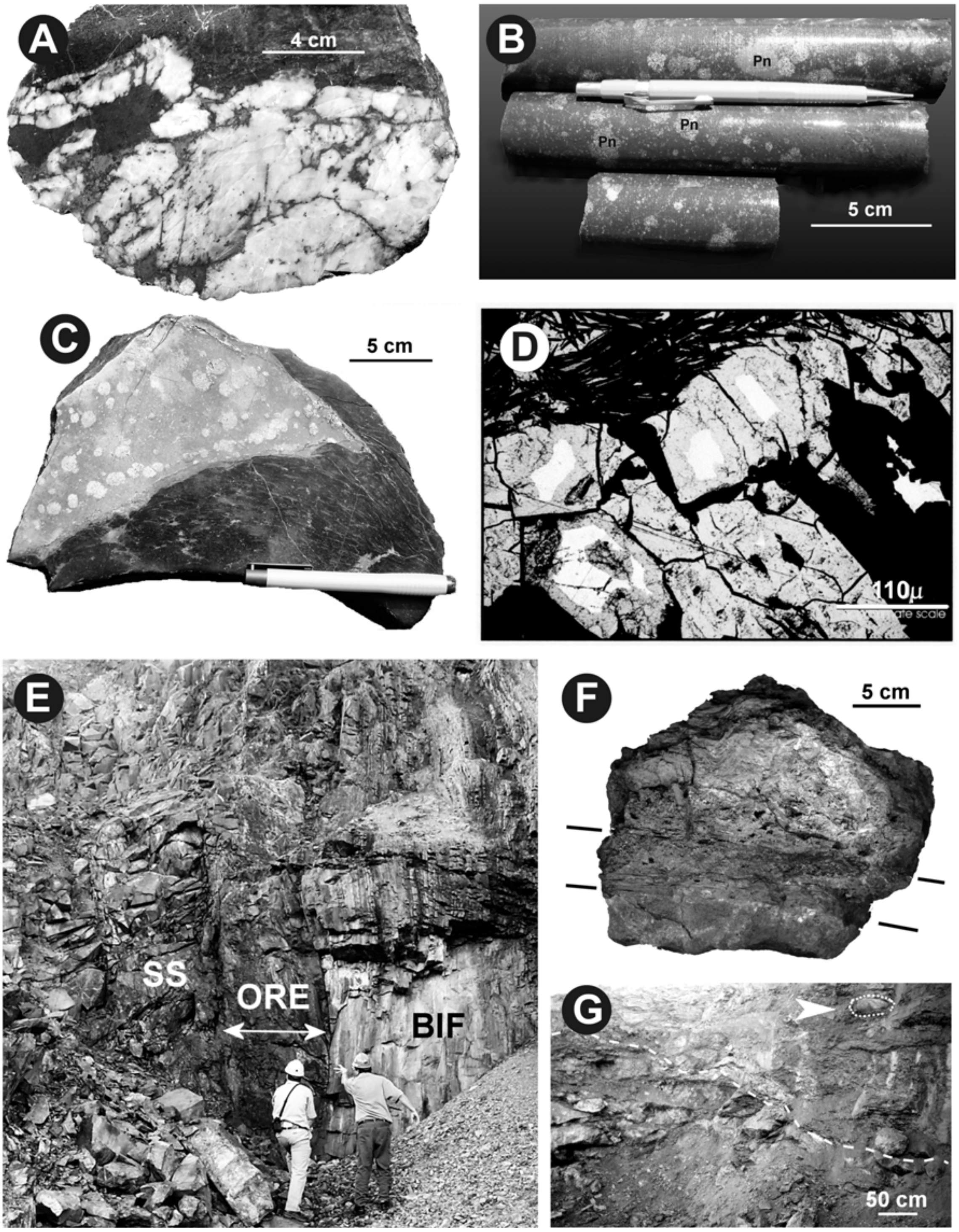

Fig. 9. Fortaleza de Minas HMS/ gossan ore types: **a** hydrothermal carbonate breccia with Chalcopyrite (Cp) in faults cutting hanging wall serpentinites associated with the hydrothermal massive sulfide (HMS). **b** coarse Pn crystals in cores from the hydrothermal massive sulphide (HMS). 870S sublevel /south area – underground mine. **c** hydrothermal massive sulfide (HMS) cutting disseminated ore in a cuspade structure. Coarse non foliated pentlandite (Pn) crystals in pale color. Very thin sulfide veinlets in a foliated sheared disseminated ore. **d** pentlandite crystal with strong cleavage almost totally replaced by violarite (grey). Pentlandite (white) still preserved in nuclei of cleaved blocks. Fe hydroxides (black) filling cleavage plans. Fibrous silicates also in black to the top. **e** violarite zone exposure in the north of the open pit mine showing partially weathered and fractured hangingwall serpentinite (SS) to the left and banded BIF to the right. To the top of the bench the violarite zone ore is capped by gossan.

Weathering profile

The Fortaleza de Minas deposit display a typical weathering profile, previously described by Imbernon, (1998); Oliveira et al., (1995 and 1998); Marchetto, (1990), and Carvalho et al. (1998, 1999), common to most massive sulfide nickel deposits (Blain & Andrew, 1977; Nickel et al, 1977; Nickel & Daniels, 1985; Thornber, 1975, 1976 and 1981), encompassing a 30m thick partially outcroping gossan followed by a 20m transition zone characterized by a violarite/bravoite zone above the fresh sulfide ore. The transition zone is herein defined on the basis of 25% of violarite concentration resulting from primary pentlandite substitution (Fig. 9d). A typical exposure of the transition zone is shown in figure 9e (1000N bench), which is represented by stained violarite zone developed on breccia ore. The gossan zone occurs on top of the transition zone. Figure 9f shows a hand sample from the gossan zone with distinctive sub-horizontal hard massive limonite vein, which represents reprecipitation of iron along sub-horizontal dilation fractures that cuts the friable gossan and weathered host walls. In the weathering process these hard iron oxide forms a typical gossan stone line over the deposit area which is responsible for a broad widespread Ni-Cu soil geochemical anomaly. The contact between the gossan and the sulfides (violarite zone) is quite irregular and often gradational with rounded blocks of matrix ore preserved within the gossan groundmass (Figs. 9g and 3). The weathered zone longitudinal profile shows a more uniform distribution for the gossan cap, which follows the topographic surface (fig. 10). The transition zone forms a more irregular boundary due to a more complex control depending on ore type and structures (faults, fractures). Continuous mapping and sampling of the gossan zone during the open pit mine stripping revealed a vertical and horizontal transition in metal grades. In the massive breccia ore the grade can drop from 4-6% Ni in the fresh ore to 0.5% Ni in the gossan.

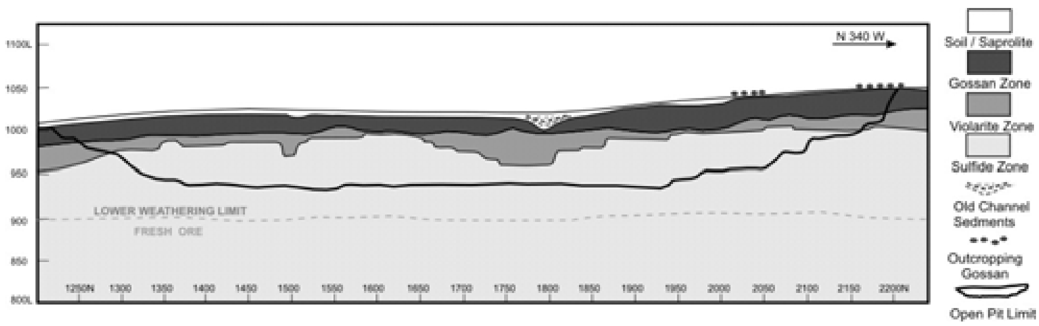

Fig. 10. Longitudinal weathering profile showing the oxidized gossan zone (30m) followed by the transition zone (Pyrite - violarite) (20m). The lower limit of the transition zone was initially defined after downdip subvertical drilling and later confirmed by bench mapping and sampling in the open pit mine. The transition between fresh sulfides and the violarite zone was defined by the cut of 20% of pentlandite converted to violarite on polished sections. Outcroping gossans in the northern area played an important role in the discovery of the deposit. An old river channel buried by lateritic soil was exposed in the pre-stripping of the open pit which caused locally almost complete erosion of the gossan zone.

The different ore types also display different weathering profiles, where the amount of sulfides in the primary ore is directly related the depth of the gossan profile (Fig. 11). The sulfide mineralogy of the primary ore, basically pyrrhotite, pentlandite and chalcopyrite, is replaced by pyrite-marcassite, violarite-bravoite and chalcopyrite-(covelite) in the transition zone, and finally, in the gossan zone, by goethite-pyrite.

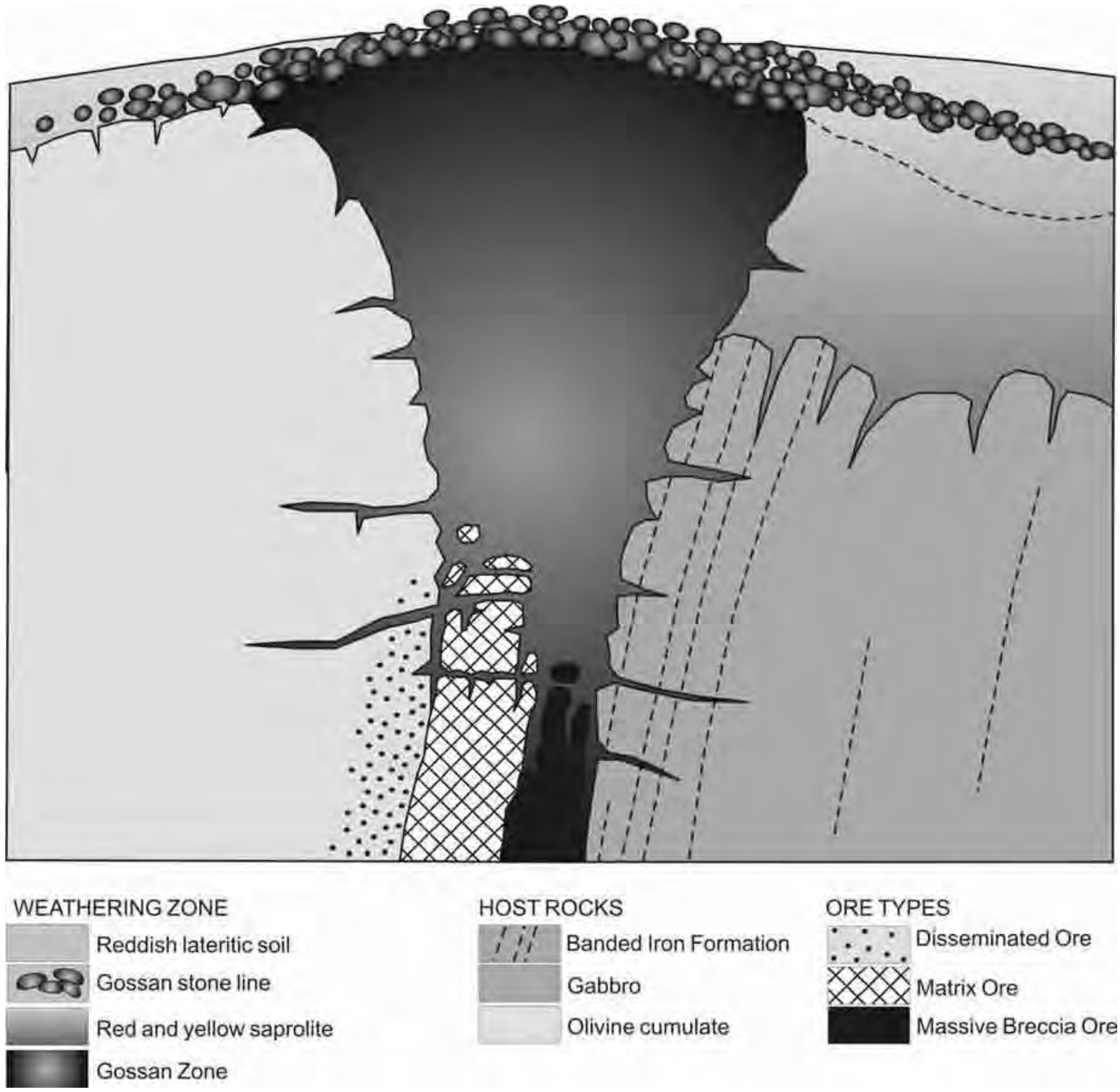

Fig. 11. Schematic vertical cross-section through the gossan zone based on open pit mine bench mapping. The matrix ore is more resistant to weathering and display a typical onion shell structure where nuclei of resistant violaritic matrix ore remains preserved within the gossan. The Breccia ore is more suitable for weathering and show a deeper gossan profile. The disseminated ore with only 15% sulfides does not develop a true gossan but shows instead a stained mottled rock.

Ore geochemistry

The major economic elements of the Fortaleza de Minas deposit are displayed in tables 2, 3, and 4.

Table 2. Mean analyses of the major ore types in the Fortaleza de Minas deposit.

	1 DS Hanging wall disseminated ore	2 MX Matrix ore (net textured ore)	3 BR Footwall high grade breccia ore	4 SC Footwall BIF hosted ore	5 SU Sheared talc low grade ore	6 ORE All ore types	7 MMH Hidrothermal massive sulfide ore
N_o of samples	652/146	542/146	2881/260	767/142	565/65	5407/759	23/05
Ni	0.95	3.40	4.14	1.00	1.23	2.93	9.10
Cu	0.25	0.63	0.56	0.35	0.22	0.47	0.71
Co	261	724	873	239	308	623	1650
S	2.70	13.24	16.01	4.41	5.06	11.41	28.32
Pt	0.13	0.53	0.42	0.11	0.23	0.31	0.35
Pd	0.24	0.74	0.69	0.20	0.32	0.49	4.44
Au	0.08	0.14	0.14	0.08	0.09	0.11	-
PGM+Au	0.45	1.41	1.25	0.39	0.64	0.91	4.79
Ni/Cu ratio	5.42	6.45	8.90	4.52	7.83	7.50	21.16
S/Ni ratio	2.89	3.93	3.86	4.37	3.99	3.85	3.24

Analytical methods: Ni, Cu, Co by Atomic Absorption with total digestion, S by LECO S determinator and Pt, Pd, Au by Fire Assay. Ni, Cu, S in %, Co in ppm and Pt, Pd, Au in g/t. Cutting assay values assummed for high outliers: Ni 7.60, Cu 2.00, Co 1620, S 30 except for the RR ore type (7). Number of samples refers to maximum assays available (Ni/Cu) and minimmum (Pt/Pd). Samples from surface drilling, underground drilling and underground face sampling.

Table 3. Mean analyses of the major rock types in the Fortaleza de Minas deposit.

	1 AT Gabbro	2 BK Pyroxenitic komatiitic basalts (upper sequence)	3 PI Pyroxene-Cumulate	4 KO Komatiites (peridotites) (upper sequence)	5 TT talc-schist (olivine-cumulate)	6 SS Serpentinites (olivine-cumulate)	7 BF Footwall banded iron formation	8 CG Black shales/ BIF (upper sequence)
N_o of samples	39	39	315	15	697	1160	2633	219
Ni	0.05	0.06	0.12	0.13	0.28	0.30	0.29	0.08
Cu	0.02	0.05	0.05	0.03	0.04	0.04	0.14	0.06
Co	76	107	106	147	140	153	104	156
S	0.50	1.60	0.37	1.20	0.81	0.60	2.07	4.08

Analytical methods: Ni, Cu, Co by Atomic Absorption with total digestion, S by LECO S determinator. Values in % except for Co (ppm).
Typical hosts to ore are: 3 (PI), 5 (TT), 6 (SS) and 7 (BF)

Table 4. Mean analyses of the major ore types in the Fortaleza de Minas deposit by domains.

	Embayment Domain				Remobilized Domain		
	DS Hanging wall disseminated ore	MX Matrix ore (net textured ore)	BR Footwall high grade breccia ore	SC Footwall BIF hosted ore	SU Sheared talc low grade ore	BR Footwall high grade breccia ore	SC Footwall BIF hosted ore
N_o of samples	500/66	378/63	1047/85	133/20	431/46	670/37	331/33
Ni	0.92	3.37	4.31	1.04	1.25	3.67	1.02
Cu	0.24	0.63	0.61	0.39	0.22	0.49	0.32
Co	259	743	916	248	311	781	252
S	2.63	13.38	16.64	4.37	5.35	14.37	4.49
Pt	0.13	0.64	0.43	0.13	0.24	0.32	0.15
Pd	0.24	0.80	0.70	0.25	0.31	0.49	0.22
Au	0.10	0.16	0.15	0.08	0.08	0.09	0.08
PGM+Au	0.47	1.60	1.28	0.46	0.63	0.90	0.45
Ni/Cu ratio	5.86	6.47	8.68	4.71	8.05	9.22	4.97
S/Ni ratio	2.90	3.92	3.90	4.29	4.19	3.87	4.39

Analytical methods: Ni, Cu, Co by Atomic Absorption with total digestion, S by LECO S determinator and Pt, Pd, Au by Fire Assay. Ni, Cu, S in %, Co in ppm and Pt, Pd, Au in g/t. Cutting assay values assummed for high outliers: Ni 7.60, Cu 2.00, Co 1620, S 30. Number of samples refers to maximum assays available (Ni/Cu) and minimmum (Pt/Pd). Samples from surface drilling, underground drilling and face sampling.

The sulfide mineralogy and the Po:Pn:Cp ratios are very uniform throughout the deposit with minor variations between the different ore types. Samples from the different high grade ore types were recalculated to 100% basis and the results are displayed in Table 5. Regardless the differences in the Fortaleza de Minas ore types the recalculated grades look very uniform. Comparing to other deposits the Fortaleza de Minas ore can be classified as a low tenor ore (<10%Ni) which reflects a low R factor. Chemical data from different mineral phases, achieved through ion microprobe survey are summarized in table 6 for pyrrhotite, pentlandite and chalcopyrite for the most typical ore types.

Table 5. Recalculated grades to 100% sulfide basis of the major high grade ore types in the Fortaleza de Minas deposit.

	2 MX Matrix ore (net textured ore)	3 BR1 Footwall high grade breccia ore	4 BR2 Footwall high grade breccia ore	7 MMH Hidrothermal massive sulfide ore
Ni	8.63	9.15	8.64	11.45
Cu	1.98	1.78	1.09	0.40
Co	0.17	0.18	0.18	0.26
S	37.40	37.30	37.50	37.20
Fe	90.00	68.70	81.20	56.00

Analytical methods: Ni, Cu, Co, Fe by Atomic Absorption with total digestion, S by LECO S determinator. Ni, Cu, Co, Fe and S in %.

Table 6. Chemical composition for the different ore types from the Fortaleza de Minas deposit, after more than 20 point scans for pyrrhotite, pentlandite and chalcopyrite.

	Breccia Ore	Matrix Ore	Disseminated Ore	BIF hosted Ore
(Po) -	**PYRRHOTITE**			
Fe	54.2 - 59.7	57.9 - 61.1	55.0 - 59.8	58.5 - 60.3
S	37.0 - 39.7	37. 9 - 39.3	37.2 - 39.4	37.4 - 38.9
Ni	0.32 - 1.60	0.22 - 1.01	0.37 - 0.76	0.20 - 0.25
Co	0.01 - 0.11	0.05 - 0.7	0.04 - 0.08	0.05 - 0.60
Co/Ni	0.11	0.26	0.13	0.65
(Pn) -	**PENTLANDITE**			
Fe	27.9 - 28.7	30.0 - 31.7	26.7 - 36.6	30.3 - 32.2
S	31.3 - 32.0	31.8 - 32.9	30.4 - 42.6	32.6 - 34.0
Ni	36.3 - 37.3	33.3 - 36.4	33.2 - 36.0	33.4 - 35.3
Co	0.81 - 0.91	0.8 - 0.95	0.79 - 1.30	0.83 - 0.86
Co/Ni	0.02	0.03	0.04	0.06
(Cp) -	**CHALCOPYRITE**			
Fe	29.2 - 30.3	30.5 - 33.4		30.4 - 30.8
S	33.0 - 33.9	32.9 - 33.8		32.3 - 34.2
Cu	33.37 - 34.2	30.4 - 33.4		32.5 - 33.0
Ni	0.02 - 0.06	0.02 - 0.06		0 - 0.03
Co	0.02 - 0.04	0.02 - 0.05		0.01 - 0.05
Co/Ni	0.85	1.18		-

The sampling dataset for both open pit and underground mines including bore hole and channel samples is displayed below for the major economic elements Cu, Co, Pt, Pd compared to Ni (Fig. 12). The chemical composition of the Fortaleza de Minas sulfide ore is compared to other major Ni-sulfide deposits plot. The Fortaleza Ni-sulfide deposit falls just at the border of the field for the major komatiite deposits field (Fig. 13).

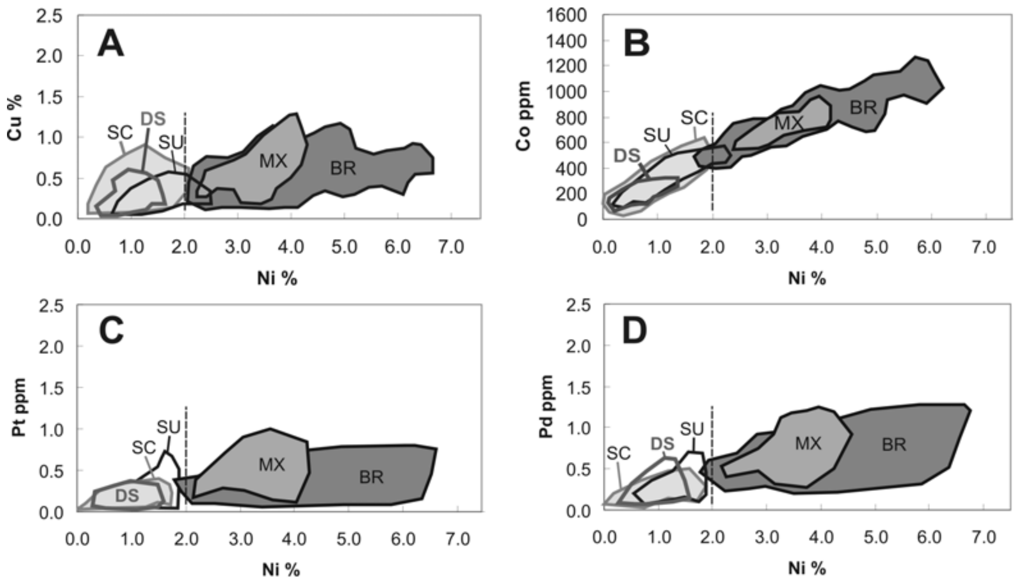

Fig. 12. Ore types scatter plots from the Fortaleza de Minas deposit core samples. **a** Cu shows a poor correlation with Ni probably due to remobilization of Cu during shearing. **b** Co shows a strong linear correlation with Ni. **c – d** Pt and Pd show a reasonable correlation with Ni. In all charts there is a clear boundary between low grade ore types (disseminated-DS, BIF hosted ore-SC, sheared ore-SU) and high grade ore types (matrix-MX, massive breccia ore-BR). The hydrothermal massive sulfide (HMS) has been omitted from this dataset. The boundary between low grade ores and high grade ores can be placed about 2% Ni.

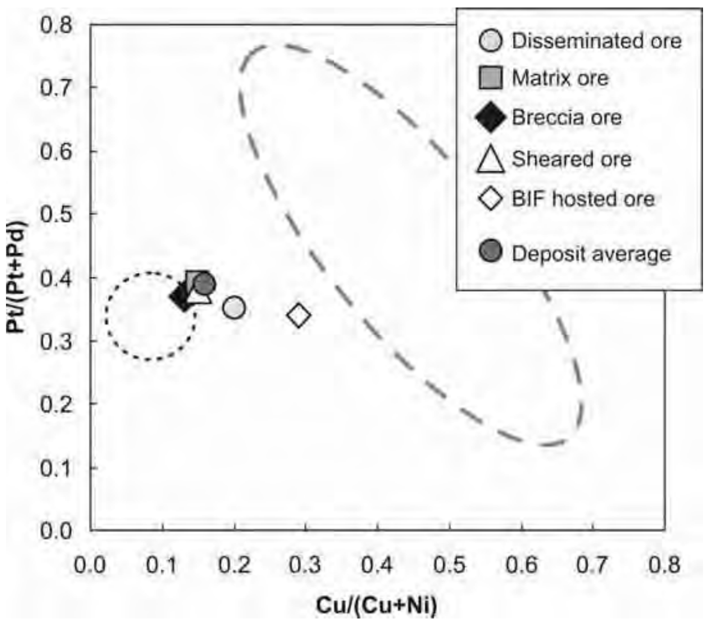

Fig. 13. Distribution of ore type samples average from the Fortaleza de Minas deposit. Doted dark circle – major komatiite deposits field, Grey hatched elipse – major gabbro related deposits field (after Naldrett, 81b). Symbols – average grades for the different ore types. Shift of Cu can be interpreted as effect of later remobilization related to shearing. No shift is observed in PGE.

Ore Distribution

The different ore types occur in an irregular pattern in the deposit. The different ore types layouts and their association give clues to the original distribution of the ore and also to it's genetic model. There is a strong correlation between disseminated and matrix ore types and they both occur within or close to the breccia sub-type (BR1). On the other hand the disseminated and sheared ore rarely occur together. Sheared ore (SU) is associated with BIF hosted ore and to the breccia ore sub-type (BR2). The vertical longitudinal section (Fig. 14) shows a schematic distribution of the different ore types and grades in the deposit suggesting trough structures where primary ore originally formed. There is a clear grade variation in the breccia ore in respect to the occurrence of troughs as suggested by the presence of disseminated and matrix ores. Figure 15 shows the nickel grade distribution along mapped and sampled sublevels from the underground mine. A clear drop in nickel grade is observed as the ore is remobilized from the trough zones until the breccia ore sub-type (BR2) gradually changes into the sheared ore.

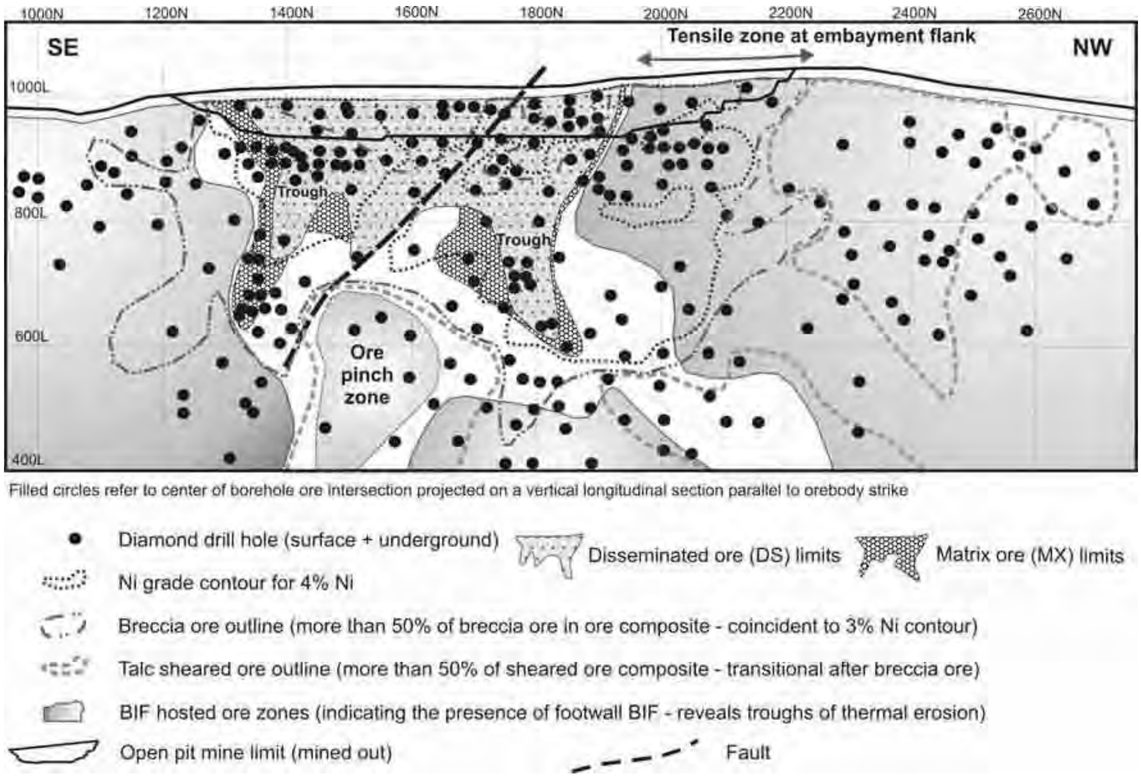

Fig. 14. Vertical longitudinal section showing broad embayment structure with troughs indicated by the presence of disseminated ore (dotted) and matrix ore (hatched) and the lack of BIF hosted ore (grey) indicating thermal erosion of BIF along major channels. Limits indicate contour of 4% Ni grades and 50% of breccia ore in the ore zone which corresponds to grade contour of 2% Ni. Thick line indicates presence of remobilized and sheared talc bearing ore (SU) indicating lateral thinning of mineralization along shear zone outside the central embayment. The outline of the shallow open pit is shown in black.

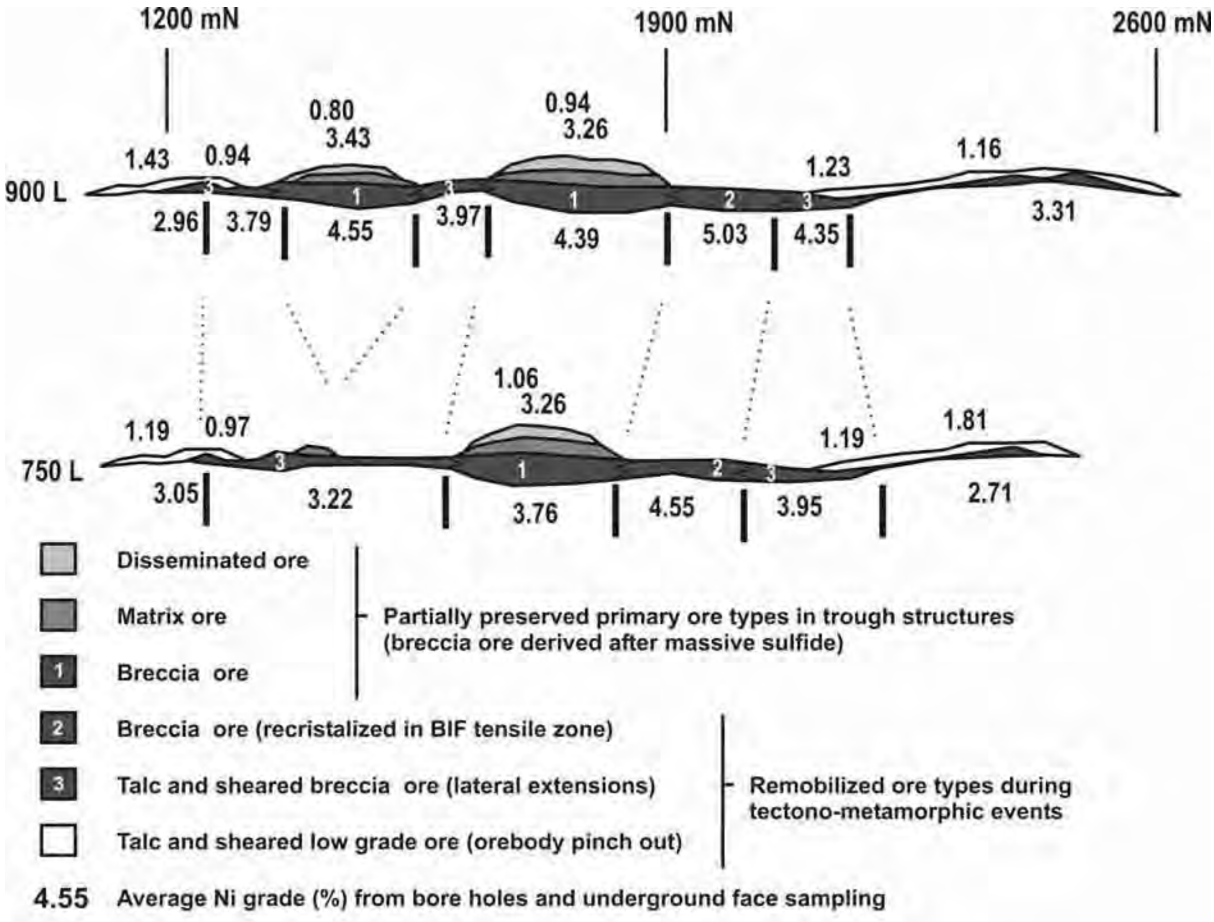

Fig. 15. Schematic horizontal distribution (not in scale) of disseminated ore, matrix or net textured ore, breccia ores and related sheared ore. Normal breccia ore (1) below trough structure associated to DS and MX ores. Sheared talc-bearing breccia ore (3) displays lower grades than (1) occurs laterally to troughs and gradually change into sheared low grade ore (SU) at orebody limits by continuous drop in sulfide content. A richer recristalized breccia ore (2) occurs at about 1900N local coordinate in a BIF tensile zone. Sublevel names 900L and 750L refer to true elevation above sea level.

Ore types evolution

The Fortaleza de Minas nickel sulfide mineralization was initially formed at the basal portion of a olivine-cumulate unit trapped in a lava channel or trough. The mineralization is similar to the Lesher and Keays, 2002 Type 1 classification. Ore settled as a basal massive sulfide followed by matrix ore and disseminated ore in a olivine-cumulate host. Folding and regional metamorphism, promoted recrystalization and remobilization of the ore destroying much of its primary texture. The gangue minerals in the ore reflect the host rock mineralogy with paragenesis compatible with the amphibolite facies for the major syn-tectonic metamorphic event assumed to be of paleoproterozoic age (circa 2Ga). This age is supported by a Rb/Sr isocron obtained after amphiboles from the mine footwall BIF. At the closure of the Transamazonian Cycle the host olivine-cumulate and both disseminated and matrix ore were completely serpentinized. During the Neoproterozoic Brasiliano Cycle a system of transcurrent faults affected the ore zone promoting stretching and shearing of the ore under brittle-ductile regime. Retrograde metamorphism affected the ore and wall rocks. High CO_2 fluid pressure were responsible for partial transformation of serpentinites into talc-carbonate schist. Evidences of retrograde metamorphism associated with strong shearing are present in the ore. Most of the talc observed in sheared ores is interpreted to have formed during the Brasiliano Cycle (900 – 520 Ma), where the major shear zones where active under greenschist facies metamorfic conditions achieving temperatures about 300^{o}C. At this time probably the breccia ore was remobilized along the serpentinite / BIF sheared contact forming the sheared breccia ore sub-type (BR2), and finally into the low grade sheared ore towards the deposit lateral extensions. A new ore type was fully formed during the Brasiliano Cycle, the hydrothermal massive sulfide (HMS) associated with carbonate breccias along late oblique faults that cuts the hanging wall. Due to field contact relationships it is assumed that the HMS ore is derived after the breccia ore as a hydrothermal remobilization which achieved ore grade as high as 14% Ni with high PGE nuggets up to 40 g/t Pd.

Origin of the Breccia ore

The breccia ore is the most continuous and widespread ore type in the deposit. Its current fabric is unquestionably tectonic showing evidences of several phases of shearing and recrystalization in both ductile and brittle regimes. However the high amount of wall-rock fragments and the dominance of footwall BIF fragments suggest that some of these fragments may have been incorporated into the massive sulfide by thermal erosion processes. It is very clear that in the trough zone defined by the presence of thick breccia, matrix and disseminated ores the footwall BIF is either absent or much thinner than normal.

It is reasonable to conclude that a considerable part of the footwall BIF in the embayment zone was taken by thermal erosion incorporating BIF fragments into the massive sulfide. Later tectonic events promoted more breciation at the interface between the brittle BIF and the easily remobilized massive sulfide. In bench exposures in the northern side of the open pit a thick “vein” of breccia ore was mapped as a shortcut into the footwall BIF leaving apart from the normal BIF / serpentinite contact zone. Smaller veins and stringers of massive sulfide where remobilized from the main breccia ore into fractures and faults breaking and incorporating new angular BIF fragments into the massive sulfide groundmass (Figs. 7e – 7g). Although fully injected into the footwall BIF for more than 50 meters, until it comes back to the normal BIF / serpentinite interface, the breccia ore also carried large fragments of matrix ore, and smaller fragments of serpentinite and eventually talc schist among the dominant BIF fragments. It is considered that the wide extension of the breccia ore outside the embayment zone is due to tectonic remobilization of sulfide along a contact shear zone under high temperature and high CO_2 fluid pressure. The breccia ore gradually changes to the breccia ore sub-type (BR2), with more talc schist fragments and less sulfides assuming a flaser mylonitic structure. At the deposit limits this talc bearing ore gives place to the low grade sheared ore with the same flaser mylonitic structure but with much lower grades until it becomes uneconomic (Fig. 15). Marginal sheared ore has been identified by drilling as far as 600m away from the embayment zone along the major contact shear zone.

Source of Sulfur

The footwall BIF can be quite thick outside the embayment zone. It displays a distinctive zoning from a thin oxide facies at the base (as the other lower BIFs) into a broad zone of silicate facies BIF with alternating layers of silica, actinolite and cummingtonite/ grunerite (Fernandes et al., 1998a and 1998b; Fernandes et al., 2004). At the top, in the contact zone with the ore it can display a discrete amount of exalative banded baren sulfide (Fig. 7f). However, the small amount of sulfides do not suport the footwall BIF as a sulfur supplier. It is considered then that the source of sulfur would be placed far upstream in the lava channel. In the southwestern limb of the syncline the footwall BIF oxide facies shows a lateral change to a graphite-bearing sulfide BIF. These graphite cherts or BIFs can display considerable amount of baren sulfide, dominantly pyrrhotite with subordinate chalcopyrite and minor sphalerite. Most of the komatiite hosted Type 1 deposits show indications of local contamination processes related to thermomechanical erosion of S-rich banded iron formations beneath lava channels (Lesher and Keays, 2002; Lesher and Arndt, 1995; Beresford, 2005; Naldrett, 2005). Indications of crustal contamination such as enrichment in light rare-earth elements (Fig. 16) can be found in many komatiite lava flowing conduits by thermomechanical erosion and assimilarion of banded iron formations. Extensive sulfide/ oxide bearing banded iron formations in the Fortaleza de Minas deposit area are interpreted as the major source for crustal contamination.

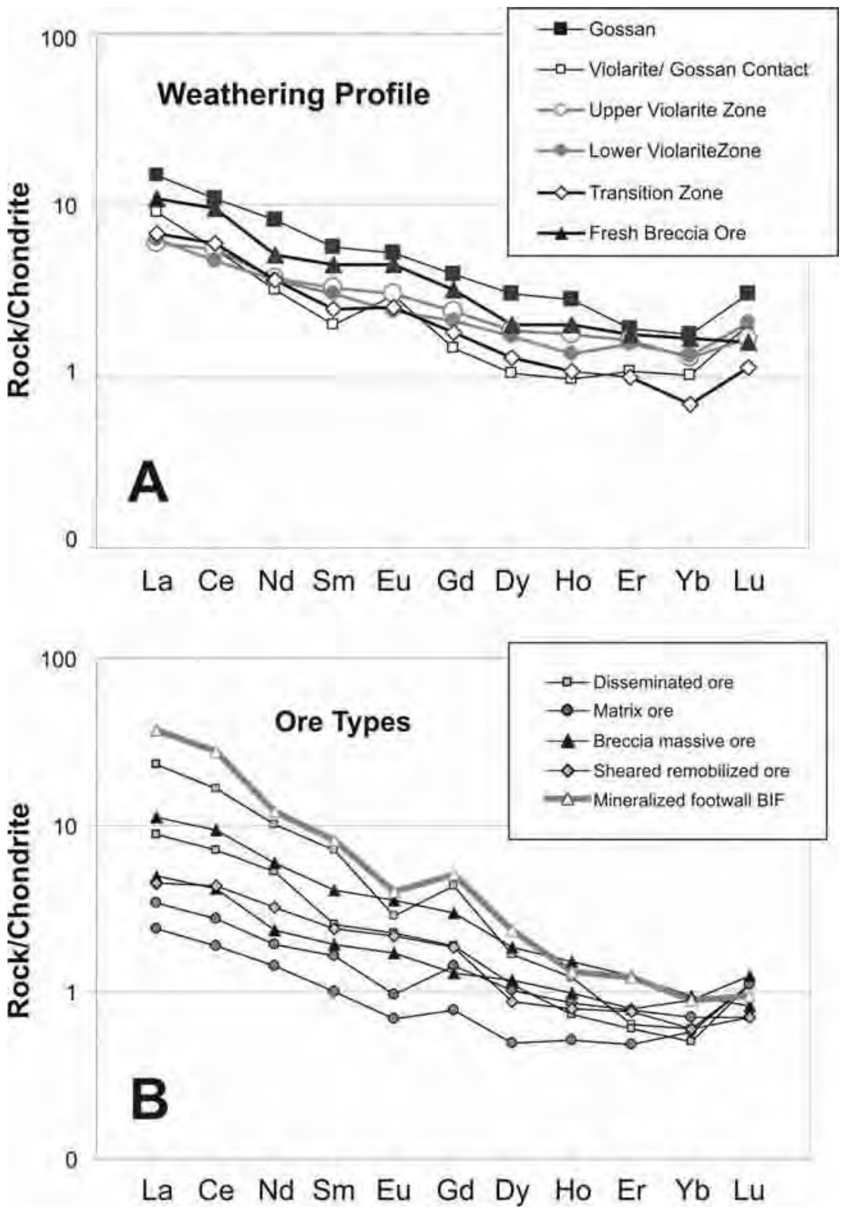

Fig. 16. REE plots for Fortaleza de Minas ore selected samples normalized to chondrite compositions (Mc Donough and Sun, 1995). **a** REE plot for the Fortaleza de Minas vertical weathering profile from gossan to fresh massive ore. **b** REE plot for the Fortaleza de Minas ore types and typical footwall banded iron formation.

Conclusions

The deposit is hosted by a basal olivine-cumulate (now serpentinte) from an upper flow unit of a thick and highly fractionated komatiite flow. The deposit has been highly deformed, sheared and metamorphosed since the lower proterozoic developing other remobilized ore types but still preserving some of it's primary cumulate textures and embayment structures. Disseminated, matrix and breccia massive sulfide are the major primary ore types similar to other Type 1 deposits. Average grades are 2.5%Ni, 0.4%Cu and 0.7g/t Pt,Pd,Au. It is a low tenor ore (9%Ni) with Ni:Cu ratio of 7.5 and S:Ni ratio of 3.85. A high grade hydrothermal massive sulfide ore type was formed during tectonic reactivation during the upper proterozoic Brasiliano Cycle (0.6Ga) with abnormal PGE nuggets.

The Fortaleza de Minas deposit is interpreted as a komatiite hosted Type 1 deposit formed by thermomechanical erosion of sulfide-bearing banded iron formations within an open embayment structure and ponded lava lake volcanic facies environment.

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Tectonics and Mineralization of the Komatiite-Hosted Ni-Cu-(PGE) Fortaleza de Minas Deposit, Minas Gerais, Brazil

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Abstract

The granite-greenstone terrain of the southwestern Minas Gerais was affected by the sinistral Campo do Meio Strike-Slip System, having acquired a regional structure of anastomosed sigmoids. One NW-trending sigmoid at south of Fortaleza de Minas is a transtensive segment where the Ni-Co-Cu sulfide mine covered in this paper is located. The sigmoid inner structure involves several more discrete brittle-ductile shear zones of P, R, R’ and Y types and T fractures, as well as younger strike-slip and normal brittle shear zones, all of which related to the Campo do Meio System. The shear zones controlled sulfide deformation, remobilization and reconcentration, more actively in the breccia ore and sheared types, and less actively in matrix and disseminated ores. Primary basal massive sulfides concentrations, changing gradually at the top to matrix ore, and this to disseminated ore still preserve the original zoning of the deposit. The footwall banded iron formation hosted-ore was entirely formed by tectonic-metamorphic processes.

Introduction

The first economically significant massive sulfide deposit of Ni-Cu in Brazil was discovered in 1983 at the southwest of the State of Minas Gerais (Fig. 1), the Fortaleza de Minas deposit (formerly named O`Toole). It is a medium size deposit of about 6 Mt of ore with an average grade of 2.5 % Ni, 0.4 % Cu, 0.05 % Co and 0.7 g/t PGM. Mining was started by Mineração Serra da Fortaleza (Rio Tinto Group) in 1998 and the deposit should be depleted by mid 2007.

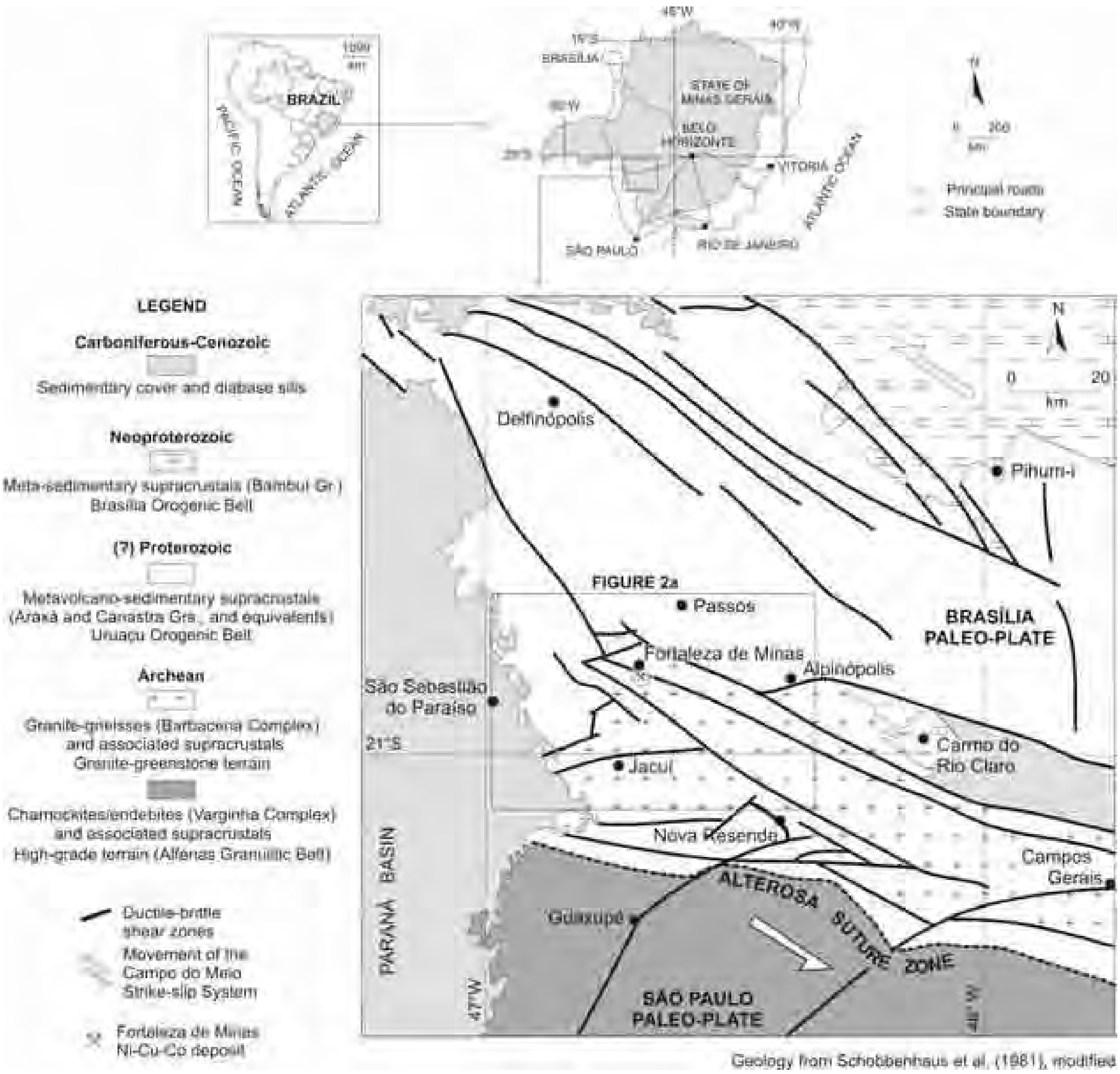

Fig 1. Location map of the Fortaleza de Minas Ni-Cu-Co deposit and litho-structural framework of southwestern Minas Gerais region.

The deposit was firstly described by Brenner et al. (1990). It is associated to a volcano-sedimentary sequence which is part of the Morro do Ferro Greenstone Belt in the granite-greenstone terrain of the southwest of Minas Gerais (Teixeira and Danni, 1979a,b). When compared to other similar deposits described in worldwide literature, significant similarities can be noted of geological context, embedding lithotypes, mineralization, chemistry of host rocks, volcanogenic aspects, ore types and geological evolution (Marston et al., 1981; Naldrett and Campbell, 1982; Hutchinson et al. 1982; Marston, 1984; Hill et al., 1995; Barnes et al., 1995; Riganti and Wilson, 1995; Perring et al., 1995). It has been acknowledged that the geometric configuration of the orebody reflects a tectonic remobilization and reconcentration of ore overprinted on a recognizable primary mineralization setting (Brenner et al., 1990). This is demonstrated by detailed litho-structural surveys carried out on land surface and in a 650 m long exploratory drift, as well as new assays of borehole samples. Results are explained in this article.

Regional Geology

The regional geology is summarized in Fig. 1. The Paleozoic-Mesozoic sedimentary cover and associated Mesozoic diabase sills from the Paraná Basin are shown in the western side. The pelites and limestones in the north are related to the Bambuí Group; they represent the filling of a Neoproterozoic basin which was inverted, with shearing and metamorphism of greenschist facies during the Brasiliano Cycle (0.6-0.5 Ga), as a part of the Brasília Belt. In addition to these units, a volcano-sedimentary sequence, an older granite-gneissic complex and a greenstone belt are present in the region, as follows:

The metavolcano-sedimentary sequence of Araxá and Canastra groups are represented by micaschists, quartzites, metagraywackes, paragneisses and secondly by metalimestones, calc-silicate rocks, amphibolites and metaultramafic rocks, the latest interpreted as ophiolites. The two units were not fully detailed and are referred to herein as Araxá/Canastra. They experienced greenschist to amphibolite facies metamorphism, with isogrades inversion, and were displaced together by thrust zones overlying against the older complex, which is now exposed in the core of an deeply eroded anticlinorial structure (Zanardo, 1992; Morales, 1993; Zanardo et al., 1996). Their age has been considered as Neoproterozoic, related to a basin filling and inversion during the Brasiliano Cycle (900 - 520 Ma), (Trouw and Pankhurst, 1993; Soares et al., 1994).

The oldest units are represented by the Varginha and Barbacena Complexes both including remnants of metavolcano-sedimentary supracrustals. The Varginha Complex is made up of tonalitic to granitic gneisses metamorphosed in the granulite facies and retrometamorphosed in medium to low grades. The associated supracrustals are paragneisses, kinzigites, quartzites, micaschists, marbles, calc-silicate rocks, magnetite-bearing BIFs, amphibolites and metaultramafic rocks, and were described as Caconde Group (Zanardo, 1992). The Varginha Complex represents the high-grade terrain of the Alfenas Granulitic Belt (Hasui et al., 1993). The Barbacena Complex gathers (1) more or less migmatized monzogranitic to granodioritic gneisses, (2) banded, augen and laminated biotite and/or hornblende gneisses, and (3) sparse bodies of orthoamphibolitic rocks, like amphibolites, amphibole schists and amphibole gneisses (Hasui et al., 1993). Metamorphism of high amphibolite facies and retrometamorphism occurred. The associated supracrustals are essentially metaultramafic and metamafic rocks, BIFs, schists and varying quartzites, deemed to be portions of a greenstone belt. The older units display a complex structural pattern and its understanding has been sought since early '60s (Ebert, 1968; Hasui and Oliveira, 1984). Most recent geological and geophysical studies show that the general structural framework corresponds to a joining zone of two crustal blocks, named Brasília and São Paulo, which represent two paleo-plates separated by the Alterosa Suture Zone (Fig. 1); the Araxá/ Canastra sequence is interpreted as deposited in a passive margin basin of the Brasília block (Hasui et al., 1993; Ebert and Hasui, 1998).

The collisional processes have developed a thrust system, which was affected by a late or subsequent strike-slip belt, the prevailing conditions varying from ductile to brittle, under temperatures of amphibolite facies/kyanite zone, having attained anatexis, decreasing to that of low greenschist facies (Zanardo, 1992; Morales, 1993). In the thrust system, there was segmentation and transport of the units to form an assemblage of alloctonous, and anastomosing, lentiform or sigmoidal masses. Foliation of several kinds (layering, compositional banding, schistosity, gneissosity, mylonitic foliation), mineral and stretching lineations, countless shear zones and shear bands, and folds of different styles and directions, are the most significant features observed in the area. Movement is connected to the subduction nearly southwestward of the Brasilia paleo-plate under the São Paulo paleo-plate, and lifting of the upper block crust base, represented by the Alfenas Granulitic Belt. The strike-slip system, known as Campo do Meio, is a series of sinistral NW-trending strike-slip zones, responsible for the sigmoid-shaped domains observed from regional to microscopic scale in all lithotypes (Morales, 1993). A number of lens-shaped bodies of metavolcanic and metasedimentary rocks of two assemblages can be distinguished (Fig. 2a).

The northernmost bodies in the Fortaleza de Minas-Alpinópolis region represent parts of the Morro do Ferro Greenstone Belt, which, together with the Barbacena Complex, configure a granite-greenstone terrain of Archean age. Sulfide mineralization and ultramafic flows appear in this greenstone belt, the latter with thicknesses of some hundred meters and even more, displaying spinifex textures and predominant komatiitic chemistry, in addition to BIFs of oxide, sulfide, silicate facies, and graphitic cherts (Teixeira et al., 1987; Brenner et al., 1990; Carvalho, 1990; Carvalho et al., 1996). Metamorphism was of amphibolite facies. Fig. 2b shows a detail of the area where the Fortaleza de Minas deposit is located.

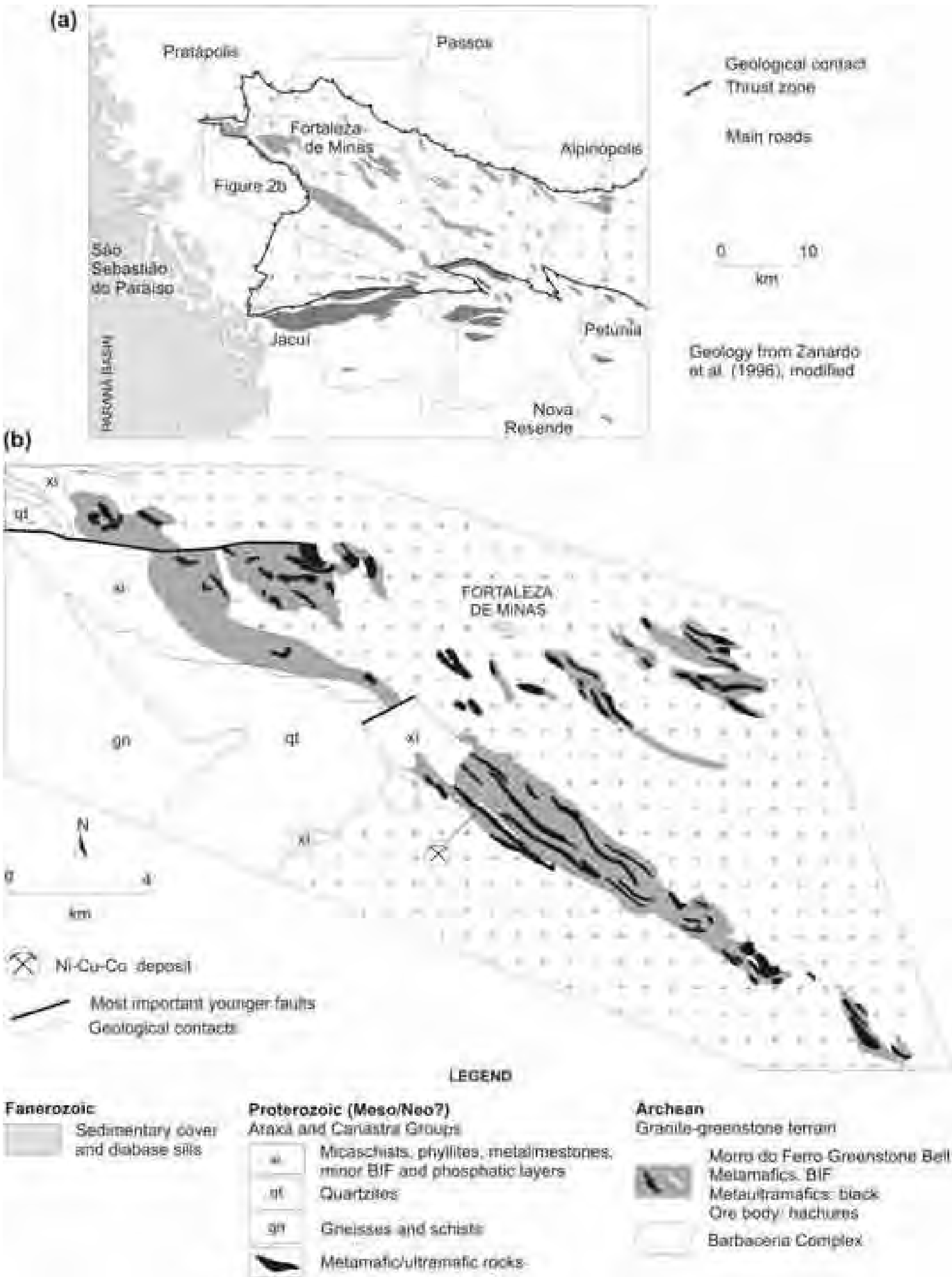

Fig 2. Geological map of Fortaleza de Minas area.

The assemblage of the Jacuí-Petúnia-Nova Resende region is related to the Araxá/Canastra groups, and display mafic-ultramafic rocks interpreted as ophiolitic, associated to quartzites and schists. Several uneconomic bodies of asbestos and podiform chromite are present, and also alluvial gold old workings (Carvalho, 1990; Zanardo, 1992; Zanardo et al., 1996). In some places, in special in the Jacuí region, the thickness of flows can be seen, as well as intermingled meta-sediments, metamorphism of amphibolite facies, chemistry of mafic-ultramafic rocks and metallogenetic patterns different from those which can be noticed in the northernmost bodies.

Local Geology

The Fortaleza de Minas deposit is located near the homonymous village (Fig. 2b). It is over 1,700 m long, varying from 2 to l5 m in thickness, and known depths of more than 700 m, displaying a sinuous tabular form with dips varying from vertical to 70° SW. Fig. 3 shows a NW-SE cross-section to illustrate the general stratigraphy and structure deduced by field data and supported by exploration drills. The ore host rocks form the O`Toole Sequence and comprises three stratigraphic units referred to as Lower, Intermediary and Upper (Brenner et al., 1990).

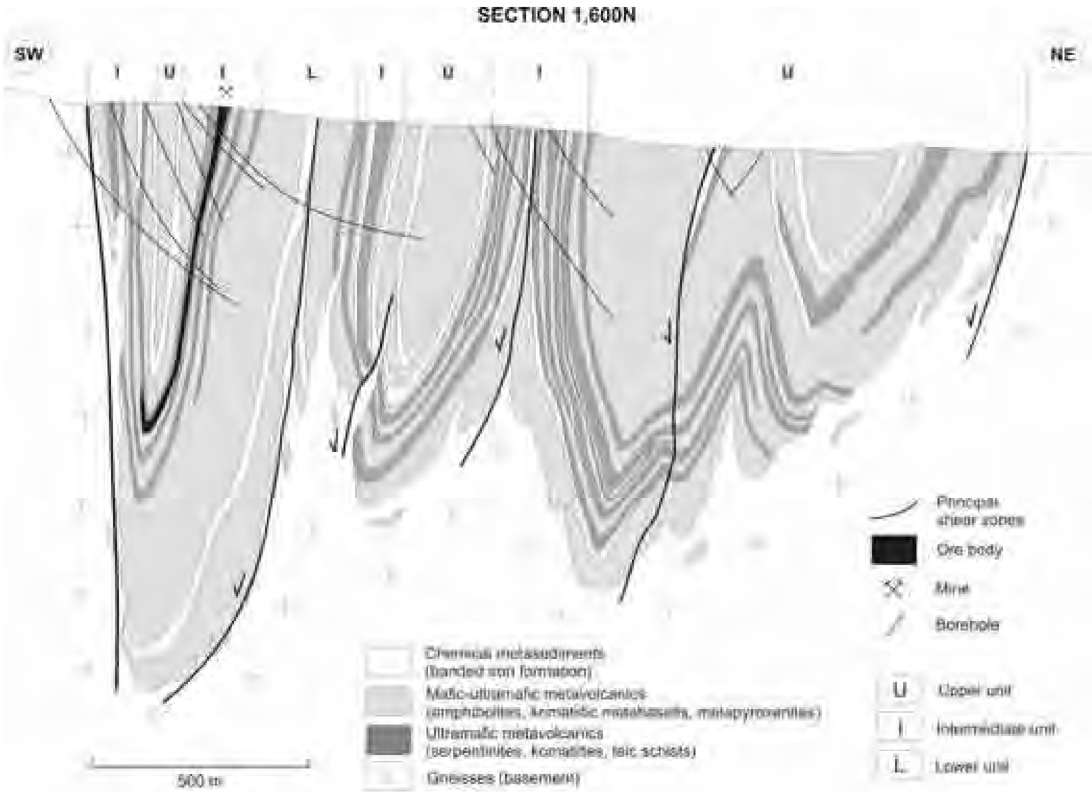

Fig 3. Litho-structural SW-NE cross-section interpreted after drilling and gravimetric profiles.

The Upper and Lower units show several similarities. These start as basalt flows of komatiitic composition, containing restricted tholeitic basalt insertions and sulfide-bearing basaltic metatuffs, closely associated to sulfide graphitic metacherts. Rarely flows show a spinifex texture and the top of the lower unit is marked by BIF of oxide facies. The Intermediate Unit, informally known as the O'Toole Sequence, consists of four differentiated ultramafic volcanic flows. Cyclicity of volcanic processes is well individualized thanks to the presence of a BIF at the top of each one. All flows begin with serpentinites after olivine cumulates at the base, followed by clinopyroxenite with high Ca contents, low contents of Al and horizons of orthocumulate texture; the pyroxenite grade up to metagabbros (amphibolites) in the upper portion, which are on their turn covered by BIF a few centimeters up to 20 m thick. The upper cycle, informally known as the O'Toole Mineralized Cycle, which is more uniform and persistent on the sides, hosts in its base portion, the Fortaleza de Minas massive sulfide deposit. The ore body, at the footwall, shows a basal contact with the preceding BIF cycle, and is covered by massive serpentinite (average thickness of 13 m), which are followed by clinopyroxenite (up to l5 m thick), subsequently by amphibolite, representing the thickest unit of such cycle (thickness of approximately 20 m), and lastly by a BIF (about 12 m thick), as shown on Fig. 4. The contacts between ore and hosts and among the different ore types are predominantly sheared. Recently the Inermediate Unit described in Brenner et al., 1990 has been interpreted as thick higly fractionated flows formed in a lava lake distal environment (Brenner and Carvalho, 2006).

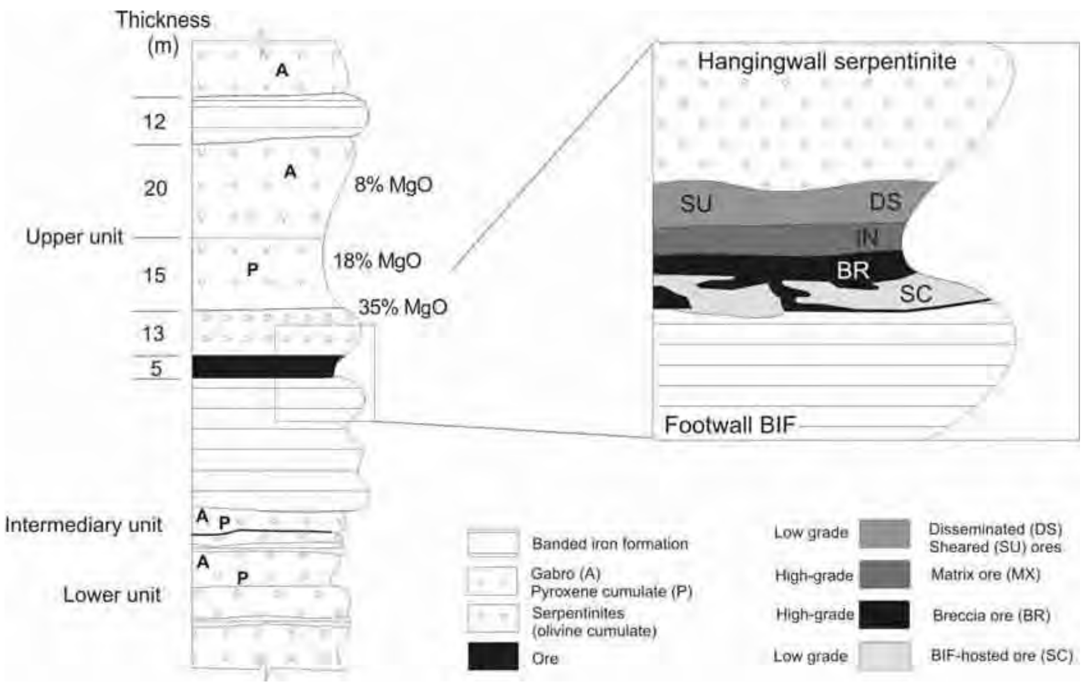

Fig 4. Schematic stratigraphic section of the Fortaleza de Minas deposit. After Brenner et al. (1990), with modifications. Not to scale.

Ore Types

Four main ore types are identified from hanging wall to footwall: disseminated, matrix, breccia and BIF-hosted ore. They can be distinguished by their sulfide content and grades, host rock and gangue mineralogy and by textural and structural features. The fine grain disseminated sulfides that occur in the serpentinite host in the upper limit of the mineralized zone form the disseminated ore. It is composed of 5 to 7% sulfides, 8 to 10% magnetite and 85% silicate gangue, the silicate gangue being dominantly antigorite with minor talc, tremolite and chlorite. Photo 1 (Plate 1) displays fine grain sulfide dissemination in an antigorite matrix with local concentrations of sulfide along the foliation and P, X, R and T type discontinuities. Laterally, along sheared contact zones, this ore type becomes strongly deformed, giving rise to a sub-type called sheared ore (Photo 2, Plate 1).

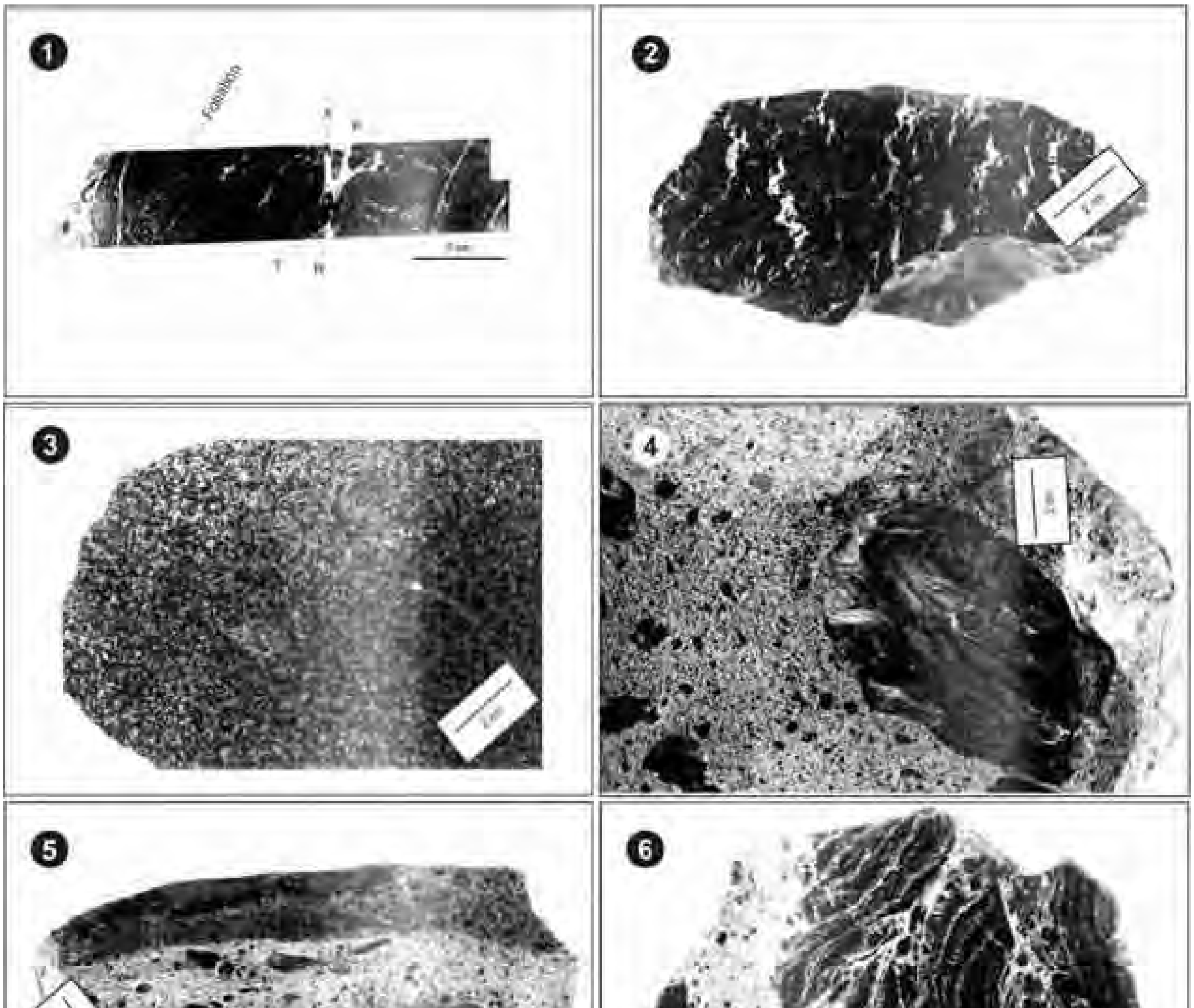

PLATE 1. Mesoscopic features of the Fortaleza de Minas ore types. **Photo 1 -** Disseminated ore with remobilized sulfides concentrated along the mylonitic foliation and in late P, X, R and T fractures. **Photo 2 -** Sheared variety of the disseminated ore with sulfides concentrated along fractures and deformed. **Photo 3 -** Matrix ore with sulfides displayed in the interstices between the serpentinitic minerals. **Photo 4 -** Massive breccia ore with BIF fragments. The biggest fragment presents a fold and some fractures filled by sulfides. **Photo 5 -** Breccia ore in a shear zone displaying host rock fragments in a sulfide matrix along a discontinuity of type Y. The fragments are oriented in the central portion and show no orientation at the borders indicating sulfide flow, interpretation supported by thin and continuous layers of pentlandite. **Photo 6 -** Typical framework of the BIF-hosted ore with sulfides being controlled by discontinuities of several types. Note fine grain sulfides following banding and breccia ore veinlet cutting the ore. With increasing deformation the almond-like pieces of BIF are broken apart and assimilated by the breccia ore.

The matrix ore is characterized by a sulfides and oxides matrix involving serpentine pseudomorphs of cumulus olivine. The original cumulus olivines were fully replaced by antigorite. The typical ore composition includes 30% sulfides, and 10% magnetite in a serpentine groundmass. Photo 3 (Plate 1) shows interstitial sulfides in an antigorite groundmass. This ore type is also known as net textured ore.

The breccia ore is a tectonic breccia with a massive sulfide matrix and lithic fragments of varied proportions and sizes of BIF, serpentinite and talc schist. Its matrix is made up of 60 to 70% sulfides, 10% oxides and 10 to 20% silicates. They represent the highest grade ore in the deposit. Photo 4 (Plate 1) displays a typical breccia ore with a BIF fragment with internal folding and small faults from a former deformation. Photo 5 (Plate 1) shows breccia ore with rock fragments in a sulfide matrix.

The BIF-hosted ore corresponds to sulfide concentrations along bands and discontinuities in the footwall BIF, commonly in contact with the breccia ore. It has a variable composition, normally 65 to 90% silicate gangue, 5 to 15% sulfides and 5 to 20% magnetite. Photo 6 (Plate 1) shows sulfides along discontinuities and intergranular spaces in the BIF-hosted ore.
According to the Ni grade and total sulfide content, ore types can be grouped into high grade ore (> 2% Ni), represented by matrix and breccia ore types, and low grade ore (< 2% Ni), represented by disseminated, sheared and BIF hosted ore types. Mineralogical studies indicated three main mineral phases: the sulfides, the oxides, and the silicates. Pyrrhotite, pentlandite and chalcopyrite dominate the sulfide phase. The oxide phase is largely magnetite, locally Cr-bearing, and subordinate Ti-magnetite, Mg-ferrite, ilmenite and Fe-chromite. The silicate gangue comprises a Mg-rich and a Fe-rich types. The Mg-rich gangue is, in decreasing order, serpentine (antigorite), tremolite, actinolite, clinochlore, magnesite and dolomite. It occurs dominantly in disseminated, matrix and breccia ore types. The Fe-rich gangue is represented by amphiboles, such as cummingtonite, Fe-actinolite, typically in the BIF hosted ore and in the BIF fragments from the breccia ore. In addition to the major ore minerals, there occurs on an accessory basis a wide variety of minerals of the cobaltite group (cobaltite-gersdorffite series) included in pyrrhotite, pentlandite and magnetite, nickel telluride (melonite) and bismuth, and traces of platinum group minerals (PGM) included in magnetite and pyrrhotite. Sphalerite, galena, tetradimite, nicolite and more scarcely valerite-maaknawite also appear as accessories.

The surface alteration processes, acting on the orebody, generated an assembly of supergenous minerals, represented by the general development of violarite at the expenses of pentlandite and pyrrhotite, and specifically in the location by the formation of pyrite and marcasite from pyrrhotite. Closer to the surface, the ore changes to a mass of limonite/goethite with a cellular texture and other mineral residue characteristically generated as a product of weathering, constituting a typical gossan. Fig. 5 presents the map of the deposit (5a) and a detail of the northwestern third (5b). The different ore types can be individualized in the form of lenticular bodies of varying sizes, irregularly distributed along the deposit. The disseminated and matrix ore types are restricted to the central portion of the deposit between sections 1,300N and 1,900N and above level 800 m in the area identified as embayment. They occur typically above the basal breccia ore, and the disseminated ore is, most of the times, in contact with the hanging wall serpentinite. Local shearing, however, may affect the original distribution by inter-layering the ore types or by truncating one or more of them. Broad pinch-and-swell and necking structures are also common where the overall ore width may vary from 1 to 13 m. These ore width variations occur very rapidly along strike and down dip an eggbox pattern. In this central area the BIF-hosted ore is often limited or absent. However, to the north of 1,900N and to the south of 1,300N the BIF hosted ore is well distributed and occurs typically associated with sheared ultramafic ore and breccia ore.

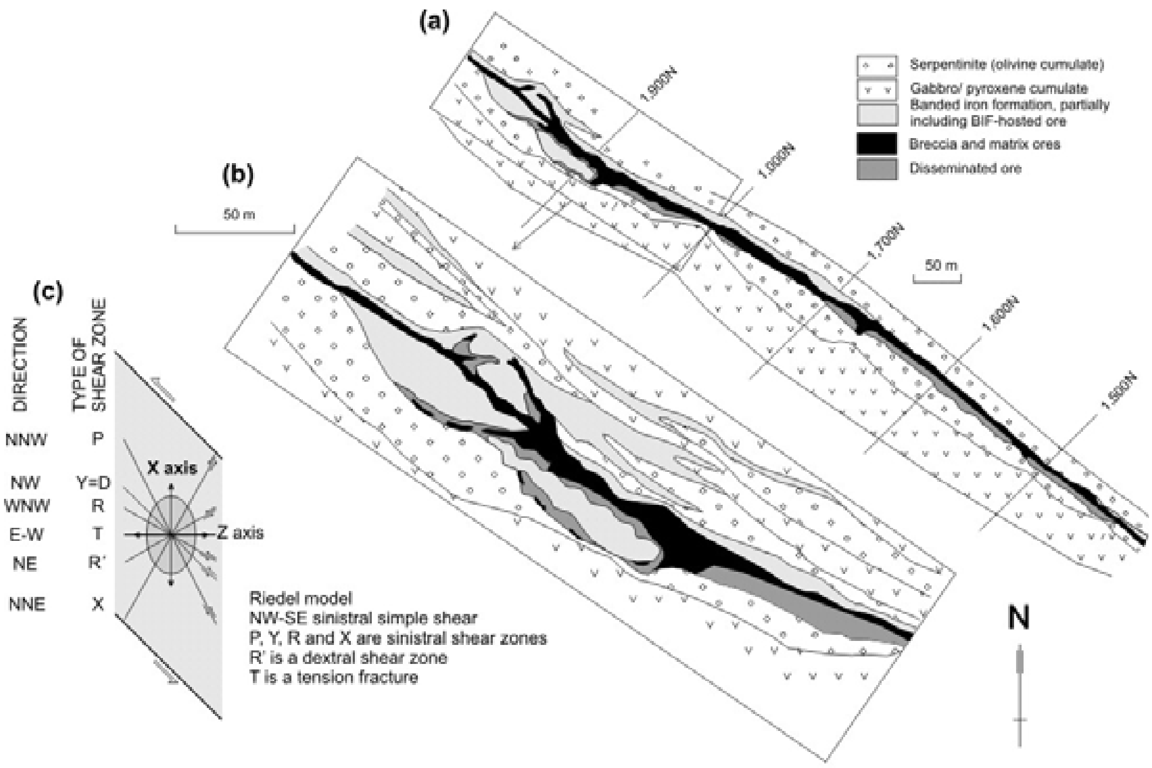

Fig 5. Simplified geological plan view of the central portion of the Fortaleza the Minas deposit after underground mapping. General view (a) and detail of the northwest portion (b). Riedel model for the area indicating the shear zones and tension fractures (c).

The breccia ore is well spread over almost the entire deposit. It forms the basal ore type associated with matrix and disseminated ores in the central zone of the deposit or lays within BIF-hosted and sheared ores in the lateral extensions and at depth. This spatial placement of the different ore types and the distribution of their host rocks indicates the presence of a central primary embayment-like structure outlined by the association disseminated/matrix/breccia ores and a broader zone of remobilized ore types represented by the association BIF-hosted/sheared/breccia ores (Fig. 6). Both ore width and metal content decreases from the central embayment zone away, laterally and at depth. The exploratory drift was developed along the northern side of the embayment zone until its limits with the remobilized zone to the north, from section 1,650N to 2,015N covering different ore types associations and tectonic environments.

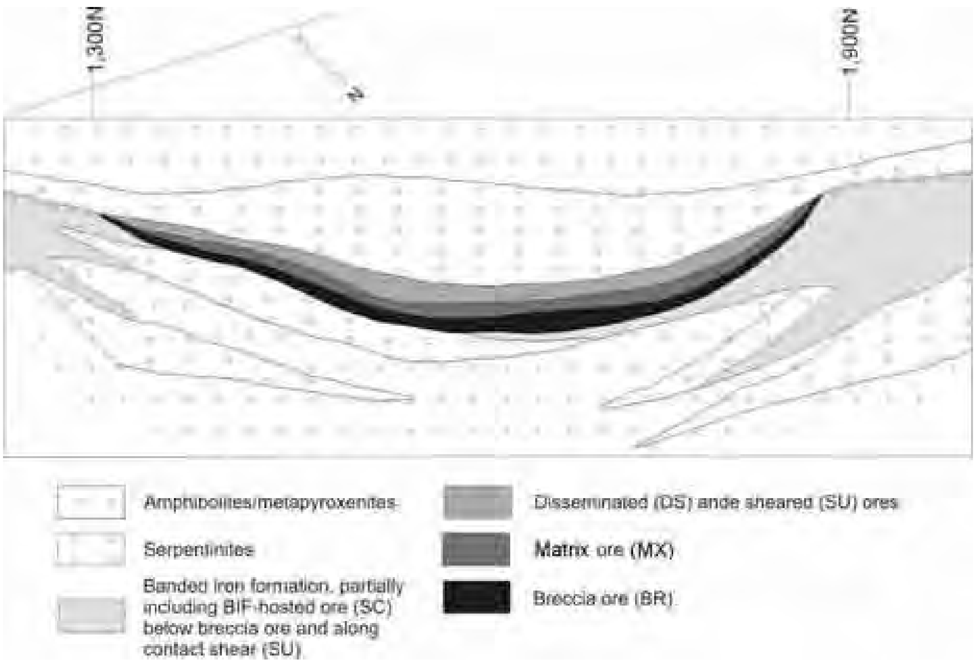

Fig 6. Sketch of the embayment structure and main primary ore types. Note paucity of chemical sediments (BIF) in the embayment domain. Scale only for reference.

The word embayment is used here in a broad sense referring to the central thick and rich zone were primary ore types were identified. It differs from the typical embayment structures of the Western Australian volcanogenic Ni deposits in a few aspects, as follows: (1) the absence of steep structures like faults in the lateral limits of the embayment; (2) the presence of Ni ore, although weaker, outside the embayment limits; (3) the lack of a clear elongated shape like the structures in the Kambalda area (Stone, 2005; Beresford, 2005). These differences could be at least partially explained by the intense deformation and shearing that took place in the Fortaleza deposit. However, it could also indicate that the Fortaleza deposit is in some way different from the classic Australian komatiite-hosted volcanogenic Type 1 deposits (Hill and Gole, 1990; Hill, 2001; Lesher and Keays, 2002). The komatiite-hosted Type 1 deposits refer to the original therminology volcanic peridotite associated deposits (VPA) in opposition to the intrusive dunite associated deposits (IDA) (Marston et al., 1981; Marston, 1984), later reviewed as Type 2 deposits. Type 1 deposits are characterized by accummulations at the base of komatiite lava flows of massive and matrix or net-textured ores with 40-60wt% of sulfides as a matrix to original olivines. Type 2 deposits are large low grade sulfide disseminations commonly formed in the core of thick olivine cumulate undifferentiated sills. The Ni/Cu ratio from Fortaleza is about 6:1 which places it in between the typical Type 1 deposits (Ni/Cu > 20:1) and the intrusive gabbroic type deposits (Ni/Cu < 3:1). Another indication for the embayment structure is given by the paucity of footwall sulfidic sediments (BIF) in the embayment area (Fig. 6) and the distribution of the S/Ni ratio in the ore. The S/Ni ratio is typically 3.5:1 or 4.0:1 in the central embayment zone and gradually increases to 6:1 and higher as we move laterally and also downwards (down dip and along strike) from the embayment zone.

DEPOSIT AND HOST ROCKS STRUCTURES

Larger Structures

The metavolcano-sedimentary pile of the Morro do Ferro Greenstone Belt forms an assembly of wedge-shaped bodies imbedded in rocks of the Barbacena Complex. Such bodies with general NW-SE trend are delimited by sinistral brittle-ductile strike-slip shear zones. In the deposit area there appears one such feature (Fig. 2). The supracrustals are bounded by a principal strike-slip shear zone at southwest and another one in the northeastern side (Fig. 3); the last one and several inner secondary shear zones have slip with dip components, to which is related the tilting of wedge-shaped blocks towards southwest and the distribution of the stratigraphic units in the section. The general framework is a negative flower structure, a transtensional feature related to the Campo do Meio Strike-Slip System.

The sketch of Fig. 5c is the Riedel model for a left-hand NW-SE simple shear recognized in regional scale (Fig. 1), indicating the direction of the several types of shear zones (P, Y or D, R, X and R’) and tension fracture (T). Host rocks and parts of the ore body are broken up into other smaller bodies through several smaller strike-slip zones, so that the structure is marked by anastomosed pattern of juxtaposed lentiform portions, which is reflected in the sinuous tracings of the several lithotypes and ore, and may be observed from large to microscopic scales (Santos 1996).

In addition to the shear zone of the southern border, of general direction N45W and high dip towards southwest, such smaller strike-slip zones have general directions around NNW-SSE, WNW-ESE, NW-SE and NE-SW, and high-angle dips, which correspond respectively to P, R, Y e R' in the Riedel model. Kinematic indicators show that displacements were dextral for R' zones and sinistral for the others, consistent with the overall sinistral movement of the Campo do Meio Strike-Slip System.

The ore shows a mylonitic foliation, as a rule parallel to the schistosity, layering and compositional banding of the lithotypes present therein. This foliation has a preferred direction about N47W/sub-vertical (Fig. 7a), with anastomosed fabric around smaller lenticular bodies. To this foliation are associated mineral and stretching lineations defined by the direction and elongation of amphibole, quartz, magnetite e sulfide, with general N47W/sub-horizontal orientation (Fig. 7b). A stretching lineation around N30E/85SW can also be observed (close to the center of the Fig. 7b stereogram), and which is parallel to axis Y of the finite deformation ellipsoid; it is interpreted as a structure generated during the earlier thrust movement and rotated by the later strike-slip displacement.

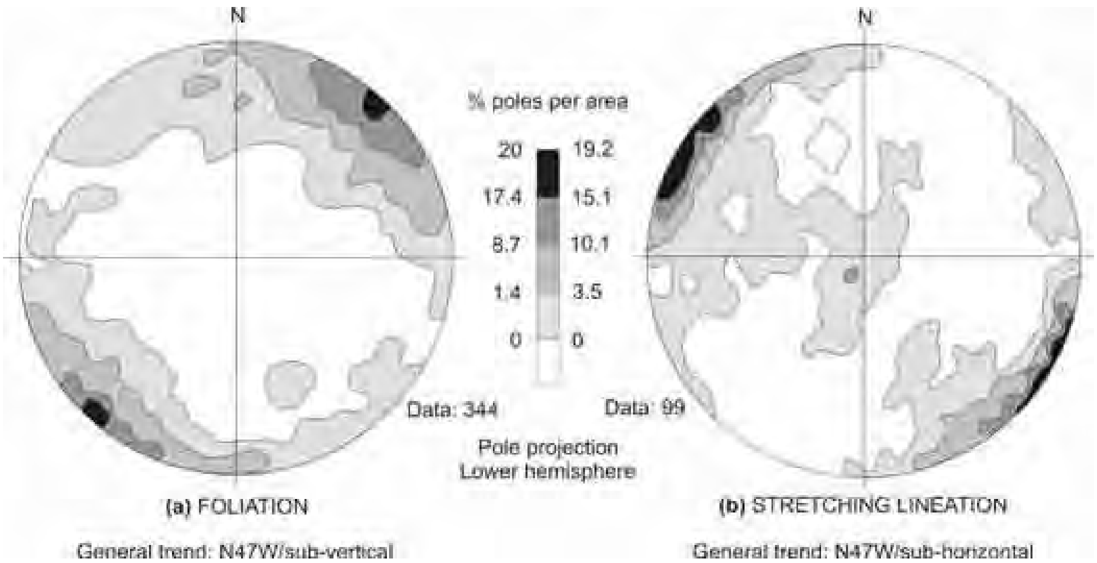

Fig 7. Stereograms of the foliation (a) and stretching lineation (b) in the mine area.

Folds are not rare in the area. Those of the intrafolial type may be better noticed in the BIFs, displaying sizes ranging from millimeters to centimeters, styles from closed to isoclinal, axial planes parallel to the mylonitic foliation and axis parallel to the stretching lineation. Drag folds are common in the exploration drift, both on the ore and also in the host rocks. In addition to these features, crenulations and kink bands also appear, following in one or more directions in the schistified portions of hosts. Besides these brittle-ductile deformation features, another important assembly of structures generated in a last brittle regime can also be seen, represented by faults and joints.

Faults are noticeable features, marked by cataclastic rocks and slickensides, continuous for 2 to 3 m and in directions NW-SE, WNW-ESE, NE-SW e NNE-SSW, predominantly of strike-slip type and sub-vertical. To these are associated remobilized sulfides, particularly pyrrhotite and chalcopyrite, with a frequent presence of carbonates, forming sigmoids and filling tension gashes. There are also normal faults with direction WNW-ESE and subordinately NW-SE, frequently filled with chrysolite, carbonate, pyrite or limonite. Fault surfaces were preferably nucleated along the existent shear zones.

Several crossed joint sets are present in the deposit area, particularly with NW-SE, WNW-ESE, NE-SW and NNE-SSW directions. The NW-SE and WNW-ESE sets are mainly responsible for water percolation and supergenic alteration of the deposit. This two joint sets, along with NNE-SSW faults, are coincident with the Y, R and R´ Riedel directions determined for the area. All such features may be attributed to the same tectonic system which originated the Campo do Meio Strike-Slip Belt, which allows to consider that the strike-slip movement event began under amphibolite facies temperature conditions and progressively went on until reaching the stage of brittle behavior.

Smaller Structures

The shear zones and faults have deeply affected the original mineralization, by introducing new structures, remobilization, transformations and reconcentration of ore, in a transtensive context, that is to say, tectonic and metamorphic processes were important in the conformation of the deposit. The different ore types are greatly affected by brittle-ductile shear zones P, Y, R e R'. T surfaces have also developed in more competent lithotypes. The several types of surfaces do not appear separately, but show overlaying and interactions which may be rather complex, as is normal in deformation by non-coaxial shear. Simpler situations of two sets of surfaces successively developed can be better seen on disseminated ore, where sulfides tend to be arranged according to an anastomosed structure, mainly defined by surfaces R e P (Photomicrography 1, Plate 2). In the remnants of serpentinites one can clearly identify structures of the S-C type, defined by large and sigmoidal serpentines (S) and by planes and overlaying brittle-ductile shear zones (C). More complex situations result from the intervention of more than two types de planes: structures developed by surfaces R, intersected by other surfaces P and subsequently by R’ zones, stand out since the last two delineate a nearly orthogonal reticular structure (Photomicrography 2, Plate 2). In these events, features of the S-C-type tend to be destroyed.

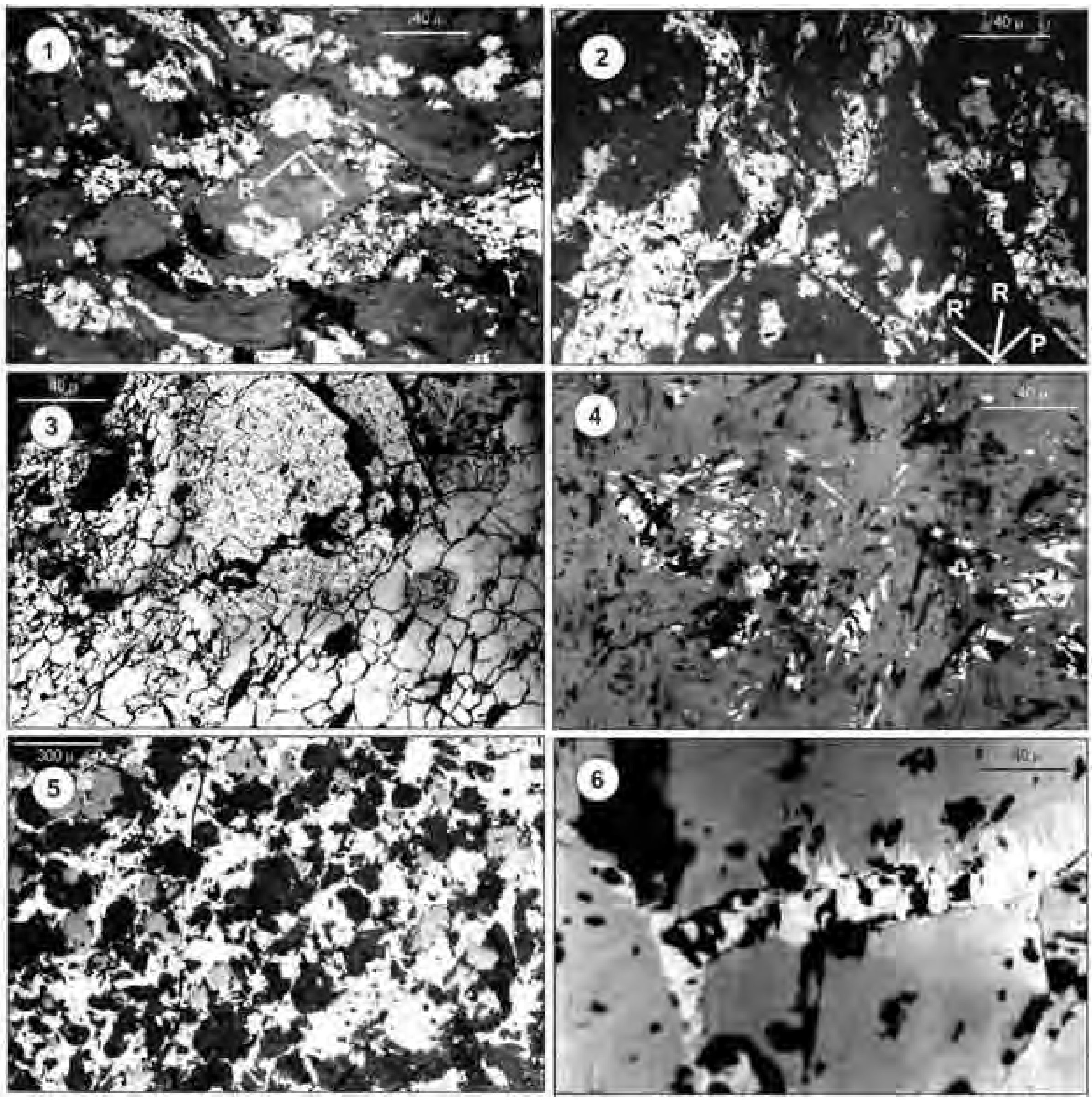

PLATE 2. Microscopic features of the Fortaleza de Minas ore types. **Photomicrography 1** - Matrix ore displaying sulfides concentration in the shear planes and intersections (R and P). As deformation increases the anatomosed fabric takes place. **Photomicrography 2** - Disseminated ore showing complex orthogonal reticular structure possibly formed by the influence of R’ shear zones over pre-existing structures of R and P types. **Photomicrography 3** - Breccia ore displaying block textured pentlandites and subordinately incipient lenticular shapes. **Photomicrography 4** - Flake-like and intergrowth textures displayed by the disseminated ore. **Photomicrography 5** - Matrix ore showing pyrrhotite and pentlandite surrounding and individualizing serpentine grains, possibly derived after olivines. **Photomicrography 6** - Typical polycrystalline pyrrhotite where the pentlandite is present as small aggregates that are developed along the contacts and triple junctions of pyrrhotite crystals.

Along surfaces there occurred a general recrystallization of antigorite which shows intergrowth with other pre-existing serpentines. Inside some lenses one can notice recrystallization of the serpentine along planes perpendicular to the stretching lineation, with the development of an intergrowth texture of sulfide and magnetite, suggesting that this texture occurs in portions less damaged by shear. As a rule, sulfides and oxides have also suffered from recrystallization, with an increase in granulation. Sulfides are represented predominantly by pyrrhotite displaying intergrowth with flake-like crystals of antigorite well developed and secondarily with magnetite. Pyrrhotite masses show evidence of mobility, whereas the pentlandite aggregates, with a less ductile behavior, acquire lenticular shapes (Photomicrography 3, Plate 2).

Disseminated Ore

Dissemination occurs under the form of intergrowth textures of silicate+sulfide, silicate+sulfide+magnetite, or silicate+magnetite, preferably oriented along brittle-ductile shear planes. Silicate in the intergrowth textures is predominantly serpentine, but may also occur as carbonate e chlorite (Photomicrography 4, Plate 2). Two types de microstructures are present, orthogonal reticular and anastomosed, the first predominating. In the sheared ore, the orthogonal reticular pattern tends to give way to the anastomosed oriented according to the major foliation and transitional features are rather common. Late right or left-lateral faults and some veins filled with chalcopyrite and/or magnetite and/or pyrrhotite and recrystallized carbonate are relatively common. Pyrrhotite forms lenses oriented parallel to foliation, migrating in the direction of these faults and veins. Lenses occur in an aggregate manner, with pyrrhotite showing a polygonal texture resulting from annealing, with intergranular pentlandite (locally altered to bravoite-violarite), sometimes sphalerite, and also by chalcopyrite. The disseminated ore behaved in a stiffer manner toward deformation, due to its lesser quantity of sulfides, presenting only an inner rearrangement of the latter at a microscopic level and without the evidence of deformation noticed in massive breccia ore.

Matrix Ore

Although displaying a geological and mineralogical evolution similar to the disseminated ore, the matrix ore behaved in a more ductile manner toward regional deformation. Such behavior is due to the greater proportion of the sulfide and oxide phases, which originally surrounded individual olivine cumulate crystals (forsterite), magnetite and chromite. Continuous movement along the shear zones promoted extensive recrystallization and mineralogical and textural changes in the ore. Thereby sulfides, specially pyrrhotite, pentlandite and chalcopyrite form chained arrangements, intergranular to antigorite, Fe-chromite and magnetite, which represent respectively the original olivine, chromite and magnetite (Photomicrography 5, Plate 2). Recrystallizations are noticed particularly in pentlandite, which forms coarse grain lentiform aggregates parallel to the mylonitic formation. Pyrrhotite occurs in polycrystalline aggregates with polygonal contacts due to annealing; pyrrhotite, contrary to pentlandite, had a more mobile behavior, adjusting among silicate and oxide minerals. Antigorite, iron-chromite and magnetite also as a rule present lenticular forms and textures of intergrowth with sulfides. These features occur controlled by zones R or P and, locally, Y. The orthogonal reticular pattern is visible only in lenticularised antigorite masses, which show a stiffer behavior toward deformation. In addition to the lenticular aspect, antigorite also displays sigmoidal forms at places saved from intense deformation. Small concentrations of sulfides, magnetite and Fe-chromite intergrow with antigorite, occur in the inner shear planes of such lenses, subdividing it into smaller lenses. In some places one can note predominance, stronger persistence and continuity of the R shear zones as compared to P, or vice-versa. In all shear zones R, P and Y, which control the matrix ore, small quantities of talc and carbonates (magnesite) occur, exhibiting strong deformation (mylonitic and schlieren type structures). Late ore occurs filling extension fractures T, generally consisting only of chalcopyrite and sporadically pyrrhotite in the central region and chalcopyrite (later on) or magnetite and chalcopyrite at the ends. Chalcopyrite is frequently presented as millerite along the cleavage planes and fractures, or as small-embedded grains; it shows gemination, orthogonal spear-shaped flakes in between, and also recrystallization forming a polycrystalline mass consisting of polygonal sub-grains. Pyrrhotite in these veins frequently occurs as polygonal sub-grains, in general associated with pentlandite also as polygonal sub-grains, and likewise with exsolutions of a flame pentlandite, partially altered to bravoite-violarite. Traces of cobaltite can be noticed, particularly included in magnetite. Frequent sulfide inclusions are present in magnetites. Sphalerite occurs in small quantities included in magnetite or as exsolution flakes in pentlandite.

Breccia Ore

As happens with the other types, the massive breccia is presented metamorphosed, deformed, recrystallized, and with silicate-sulfide, oxide-sulfide and silicate-oxide intergrowth textures, always controlled by shear zones, in a manner similar to what is seen in the richer portions of matrix ore. Ratios between the limits of sulfide, silicate and oxide grains are more varied, reflecting the nature of inclusions and/or lithic fragments present in it. Such fragments are mineralogically heterogeneous and derivate, in varying proportions, from ultramafic rocks and from BIFs, both metamorphosed and tectonized. Normally they show ductile and brittle deformation prior to their engulfing by massive sulfide (Photo 4, Plate 1). As a rule, pre-existing fractures in these clasts are filled by chalcopyrite, pyrrhotite and secondarily by pentlandite, which represent remobilization processes subsequent to the formation and deformation of the major ore which occurs as the matrix for the clasts. However, they also show evidences of recrystallization and deformation. Mineralogically, inclusions consist of serpentines, chlorites, various types of amphibole of the tremolite/actinolite/iron-actinolite and cummingtonite/grünerite series, and fine elongated aggregates of talc and chlorite. The sulfide phase (pyrrhotite, pentlandite) occurring as a matrix presents intense recrystallization, constituting crystalline aggregates with polygonal arrangements. Intergrowth textures of sulfides with antigorite, magnetite and iron-chromite are common and similar to those occurring in matrix ore. Pyrrhotites in particular host outer granular exsolutions of pentlandite, developed in the interface with the silicate phases, acquiring larger sizes at contact points and triple seams of polycrystal aggregates (Photomicrography 6, Plate 2). More rarely there occur small quantities of pentlandites, developed as exsolution bodies in the shape of a flame within pyrrhotites. Both such types of exsolution are recrystallized and are common features in this type of ore. These features exhibited by the massive breccia ore, like all others, indicate the operation of successive tectonic events upon a pre-existing monosulfide solid solution and its derivates. Such modifications are particularly outstanding at places where the brittle-ductile shear zones R, P and Y, as well as the extension zones T, have enabled ore remobilization and reconcentration. Millimetric and centimetric size lenticular fragments of serpentinites and BIF, lodged and oriented by sulfide flows in Y shear zones, laterally grade toward regions where the flow was less intense and as a result fragments are less oriented (Photo 6, Plate 1). Such features show that the sulfide remobilization at first penetrated in the host walls controlled by structures R and P, which progressively have engulfing and tearing out the almond-shaped fragments from the host, which then become a part of the ore body. At places, where these fragments are incorporated by Y shear zones, they are presented disperses and/or oriented parallel to mylonitic foliation. In lenses new subordinate penetrations of sulfides, predominantly chalcopyrite and pyrrhotite, can occur along the inner foliation, zones R and P, and subordinately from fractures; such sulfides also present recrystallizations, and seem to be associated to the last deforming event which operated upon the deposit. In those areas showing more active remobilization processes, one can notice in microscopic and mesoscopic scale, narrow and continuous parallel beds of recrystallized pentlandite, of a more brittle behavior than pyrrhotite. It can also be noticed in serpentinite fragments the presence of pressure shadows of the σ and δ types filled by pyrrhotite, chalcopyrite and pentlandite. Magnetite, Fe-chromite and antigorite, occurring as small anastomosed grains inside the sulfide matrix and inside serpentinitic lenses, progressively migrate toward the shear planes. When present inside Y zone, magnetite and iron-chromite are drawn. Platinoids occur as small inclusions in magnetite and pyrrhotite. It is relatively frequent the presence of extensional fractures and microscopic recrystallized carbonate veins (magnetite and Fe-dolomite), with elongated sub-grains and wavy extinction, having associated sulfides and magnetite; such fractures and veins show that they have been affected by a left- or right-lateral strike-slip movement. This carbonate is encompassed by the sulfide mass in some places.

BIF-hosted Ore

This ore type, of local occurrence, in the embayment area, genetically differs from the magmatic disseminated, matrix and massive breccia ores. In this case, mineralization takes place by filling cracks, fractures, faults and other structures existing in BIFs (oxide, silicate, sulfide facies) that are in contact with massive breccia ore in the footwall (Photomicrography 5, Plate 2). This is a mineralization process whose origin is related to metamorphic and tectonic processes that have provoked and controlled mobilization of pre-existing sulfides (magmatic) on the basis of ultramafic flows for the BIF, their current hosts. Mineralogical associations which constitute this ore, except for the silicate association introduced by the BIF, are strictly the same which constitute the other ore already described herein, with a predomination of pyrrhotite, pentlandite, chalcopyrite, magnetite, Fe-chromite etc. The new silicate phase is mainly formed by amphiboles, such as cummingtonite and/or Fe-actinolite, in addition to quartz, and more locally carbonate, Fe-pyrosmalite and chlorite. Despite occurring late, it can be noticed in the ore complex intergrowth textures among sulfides, oxides and silicates, a general recrystallization of sulfides and quartz, evidencing that it same have suffered at least partially a tectonic and metamorphic evolution similar to that of magmatic ore. The major structural control in the formation of this ore is related to shear zones R, P and Y, which serve as main conduct for sulfide mobilization. Such deformation, visible in all observation scales, led to the formation of varying size lenses of a BIF, which on its turn may be subdivided into smaller lenses. Depending on the continuity of this process and the proximity of massive breccia ore, these lenses have been incorporated and absorbed by this ore, or were replaced, in part or fully *in situ*. Sulfide ore, in particular concentrated along the tension gashes, spaces between boudins and along faults, display to be strongly recrystallized, intergrowth textures and polygonal textures of pentlandite exsolution in pyrrhotite, similar to that described above in disseminated, matrix and breccia ore.

Tectono-metamorphic evolution of the deposit

Despite the transformations suffered by the Fortaleza de Minas deposit and its host, the mineral paragenesis by pyrrhotite-pentlandite-chalcopyrite and magnetite, present all around the massive breccia, matrix and disseminated ore, constitutes a strong evidence indicating that the formation of same is connected to ultramafic lava fractionating processes. Furthermore, textural and phase relations among such sulfides, in conformity with modern genetic models, e.g., the billiard-ball model (Naldret, 1973; Naldrett and Campbell, 1982; Lesher et al., 1984; Lesher and Stone, 1996; Naldrett, 2005), prove that they represent solidification products from a monosulfide solid solution (MSS), subsequently modified by metamorphism and deformation. These tectonic processes recorded on the ore and its hosts due to the presence of shear zone, mylonitisation, cataclasis, recrystallization and textural modifications, indicate the evolution history of the deposit, affecting the primary embayment structure proposed by Brenner et al. (1990), schematically presented in Fig. 6. The first transformations could perhaps be related to the brittle-ductile thrust in the beginning of the collisional process; however, despite deformation and metamorphism having taken place under thermal conditions of amphibolite facies, no mineral transformations nor changes in the primary stratigraphic disposition of the deposit was not identified. This difficulty is due to the marked operation of the Campo do Meio Strike-Slip System, which later on superimposed the collisional process. Strike-slip displacements imposed a near verticalization of lithotypes and the deposit, as well as the now noted transformations, which took place under temperatures consistent with the greenschist and lower facies. In addition to one of the larger shear zones, in the deposit can be seen several smaller zones of varying orientations, besides all kinds of discontinuities, features which have developed in succession and involved repeated sulfide remobilization and mineralogical alterations.

Conclusions

Collisional processes in southwestern Minas Gerais have developed an extensive thrust system, upon which later on the Campo do Meio Strike-Slip System superimposed, which imposed upon the region a structure of varying size wedge-shaped bodies, including to the Morro do Ferro Greenstone Belt. The belt located to the south of Fortaleza de Minas, which hosts the Ni-Cu-Co deposit, has a general orientation around NW-SE, is delimited by an anticlockwise strike-slip shear zone at the southwestern border, and has a rather complex inner structure, involving several other shear zones with slip having significant dip component in a transtension context, and minor brittle-ductile shear zones of types P, R, Y e R', as well as discontinuities of type T. These structures are related to the sinistral Campo do Meio Transcurrent System. The thermal conditions of this tectonic event were of the greenschist facies, going down to lower levels, where the rocks acquired a brittle behavior. Some subsequent strike-slip and normal faults are also observed.

Anastomosed geometry of the brittle-ductile shear zone can be noticed as from the scale of host masses and the several ore types (breccia, matrix, disseminated and BIF hosted ore), down to microscopic lenses of mineral grains. It is admitted that primary sulfides, of magmatic origin, should already have been settled as masses of massive type at the base, and gradually and transitionally passed on to matrix and from this to disseminated at the top. Upon this assembly processes of strong deformation, remobilization and reconcentration have operated, controlled by the shear zones and faults. Remobilization on the breccia ore and locally on the more sheared terms was more active than on the matrix and disseminated ore, having generated the banded iron formation ore, although the original zoning was maintained.

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The Fortaleza de Minas Deposit: An Example of Komatiite-Hosted Ni-Cu-(PGE) Deposit in Highly Fractionated Ponded Flows

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Abstract

The Fortaleza de Minas nickel sulfide deposit (formerly known as O`Toole) is hosted by a highly fractioned thick flow within komatiitic sheet flows of the Guariroba-Peroba segment of the archean Morro do Ferro Greenstone Belt. The fractionated flow has been affected by high grade metamorphism, folding and intense shearing destroying almost completely its primary volcanic textures. Whole rock chemistry indicates a komatiitic composition although no spinifex texture has been found so far. Each individual flow unit is fractionated into a basal olivine-cumulate, a pyroxene-cumulate zone and an upper gabbro zone. The upper flow unit hosts a Type 1 nickel sulfide mineralization. This flow shows similarity with other fractionated thick flows (e.g. Fred’s flow from Munro, Township) and contrasts with the majority of komatiite related nickel sulfide deposits hosts; normally a thick and channelized ortho-cumulate flow laterally capped with spinifex textured thin flows. The volcanic environment for the Fortaleza de Minas fractionated flow is interpreted as a distal lava lake ponded facies. The Ni deposit host is characterized by a high Cr x Ni signature which contrasts with the common low Cr x Ni mineralized channelized flows from the majority of Type 1 deposits.

Introduction

Since the start up of the mine a great ammount of new data became available regarding the volcanic host rocks of the Fortaleza de Minas (formerly O`Toole) deposit (Brenner et al. 1990). The highly fractionated flow that host the nickel mineralization was strongly affected by metamorphism and intense deformation resulting in almost complete obliteration of primary volcanic textures. The original volcanic rock types were completely transformed during metamorphic events but their major chemical composition is considered to be roughly preserved and still valid for characterization of its original composition. The mineralogical and petrochemical characteristics of the deposit komatiitic host flow is discussed herein and compared to the barren komatiitic flows from the Morro do Ferro greenstone belt in the Guariroba-Peroba segment. The fractionated flow shows a distinctive mineralogical and chemical composition when compared to the majority of the komatiite related nickel sulfide deposits. For the discussions on komatiite lithologies the igneous terminology is adopted and the term meta- is assumed.

Geological setting

The regional geology of the deposit area was described in Brenner et al (1990), Teixeira et al (1987) and Marchetto et al (1984) and has been reviewed more recently (Zanardo et al, 1996; Zanardo, 1992 and Morales, 1993). The archean Morro do Ferro greenstone belt (Teixeira & Danni, 1979) occurs at the southern limit of the archean Paramirim craton along a EW trending block of granite-greenstone terrain cut by a system of sinistral transcurrent shear zones (Fig. 1). Sm/Nd isotopic results from the Ni deposit host flow revealed an isochron age of 2.86 ± 65 Ga for the cristalization of the lavas (Pimentel & Ferreira Filho, 2002). Migmatites from the same area have a Rb/Sr isochron age of 2.92 ± 0.11 Ga (Schrank and Silva, 1993). These ages are compatible to the Piumhi greenstone belt (ca. 2.9 – 3.1 Ga), (Machado and Schrank, 1989). The granite-greenstone terrain is limited in the South by the archean Alfenas granulite belt and to the North by Proterozoic supracrustal sediments. In the Guariroba-Peroba segment, where the Ni deposit is located (Fig. 2), a thick pile of komatiites and komatiitic basalts occur with subordinate horizons of banded iron formation. The SW margin of this greenstone segment is interpreted as the lower portion of the belt which hosts the fractionated flows and related Ni sulfide deposit, and the upper portion being represented by the thick chemical-detritical sediments at the NE margin of the belt in the Peroba area (Fig. 2). The SW margin of this segment is characterized by strong airborne magnetic anomalies reflecting the higher proportion of komatiites and olivine-cumulates. The Ni deposit is associated with a large and strong magnetic anomaly (Fig. 2b).

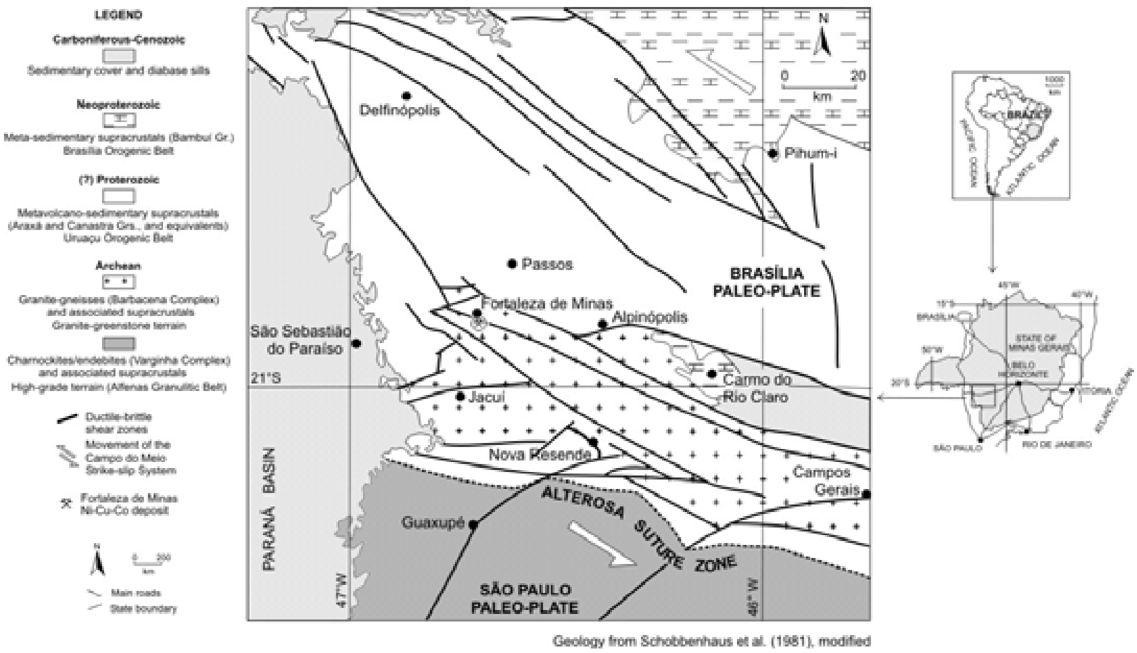

Fig. 1. Regional geology of the granite-greenstone terrain in the Fortaleza de Minas area.

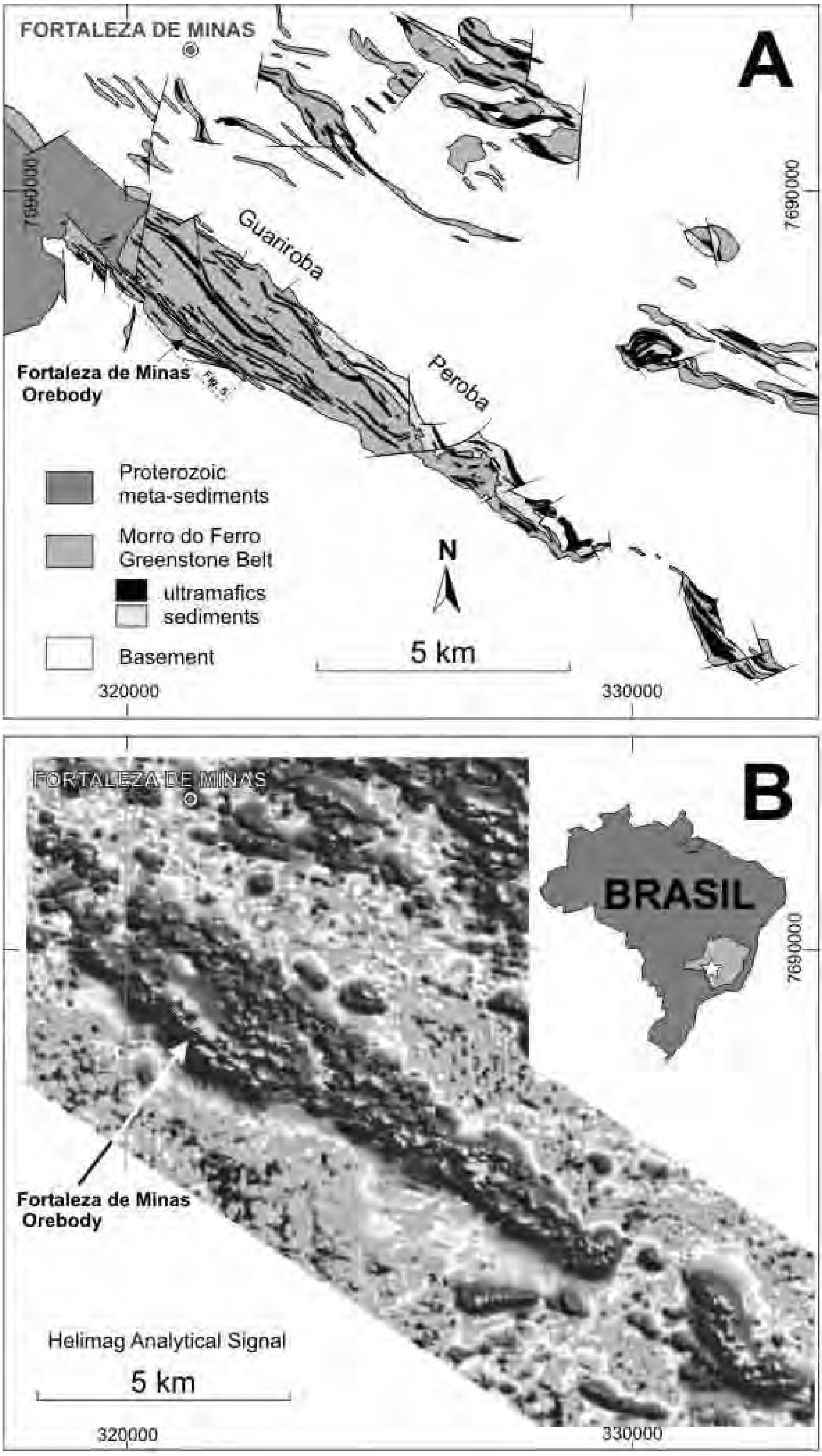

Fig. 2. Local geology. **a** the Guariroba – Peroba segment of the Morro do Ferro greenstone belt with highlighted komatiites and olivine cumulates. The Fortaleza de Minas deposit lies at the SW border of the greenstone belt south of Fortaleza de Minas village. **b** analyctical signal contour map of the Guariroba - Peroba segment highlighting the Fortaleza de Minas orebody. A strong airmag anomaly is associated with the olivine cumulates (serpentinites) that host the Ni-Fe sulfide mineralization.

The major event of folding and regional metamorphism is assumed to be occurred during the paleoproterozoic Transamazonian Orogeny (2.16 – 2.0 Ga). Metamorphism achieved high amphibolite facies in the deposit area, where temperatures higher than 650 ^{o}C are indicated by amphibole paragenesis from the deposit footwall BIF (Fernandes, 1998). In the Alpinópolis area, to the northeast, Szabó, (1996), reports temperatures for peak metamorphism between 720 to 780 ^{o}C and pressures between 3 to 6 kbar. Amphiboles from the footwall banded iron formation indicated an Ar/Ar cooling age of ca. 2.0 Ga (Fernandes, 1998). By the closure of the peak metamorfism the olivine-cumulates were fully converted to massive serpentinites. Olivine pseudomorphs are the only indication of original olivines. Original chromites were transformed into Cr-magnetite. Despite the high metamorphic grade and the intense shearing observed in the area, primary cumulate textures have been observed in drill cores and underground exposures, mostly in pyroxene-cumulate rocks. Outside the deposit area, where shearing was less intense, spinifex textures, flow breccia and nodular peridotite can be seen in scattered outcrops (Brenner et al, 1990). The region was later affected by intense transcurrent shearing during the Brasiliano Cycle (900 –520 Ma) with reactivation of major regional faults. Retrograde metamorphism with temperature not higher than 300^{o}C associated with intense ductile-brittle shearing promoted partial transformation of serpentinites into talc-carbonate schists with high CO_2 fluid pressure. Fractionated gabbros from the deposit area were converted into actinolite-albite-epidote schist or fels. Undeformed post-tectonic gabbro and diabase dykes were fully retrograded to greenschist paragenesis in the Brasiliano Cycle without loosing their original magmatic textures (Fig. 3a). These basic dykes are common in the region and are assumed to be of mesoproterozoic age. Similar basic dykes, in the São João del Rei area, have a Sm/Nd model age of 1.7-1.3 Ga, which dates the beginning of the Brasiliano neoproterozoic sedimentation (Heilbron et al, 2004).

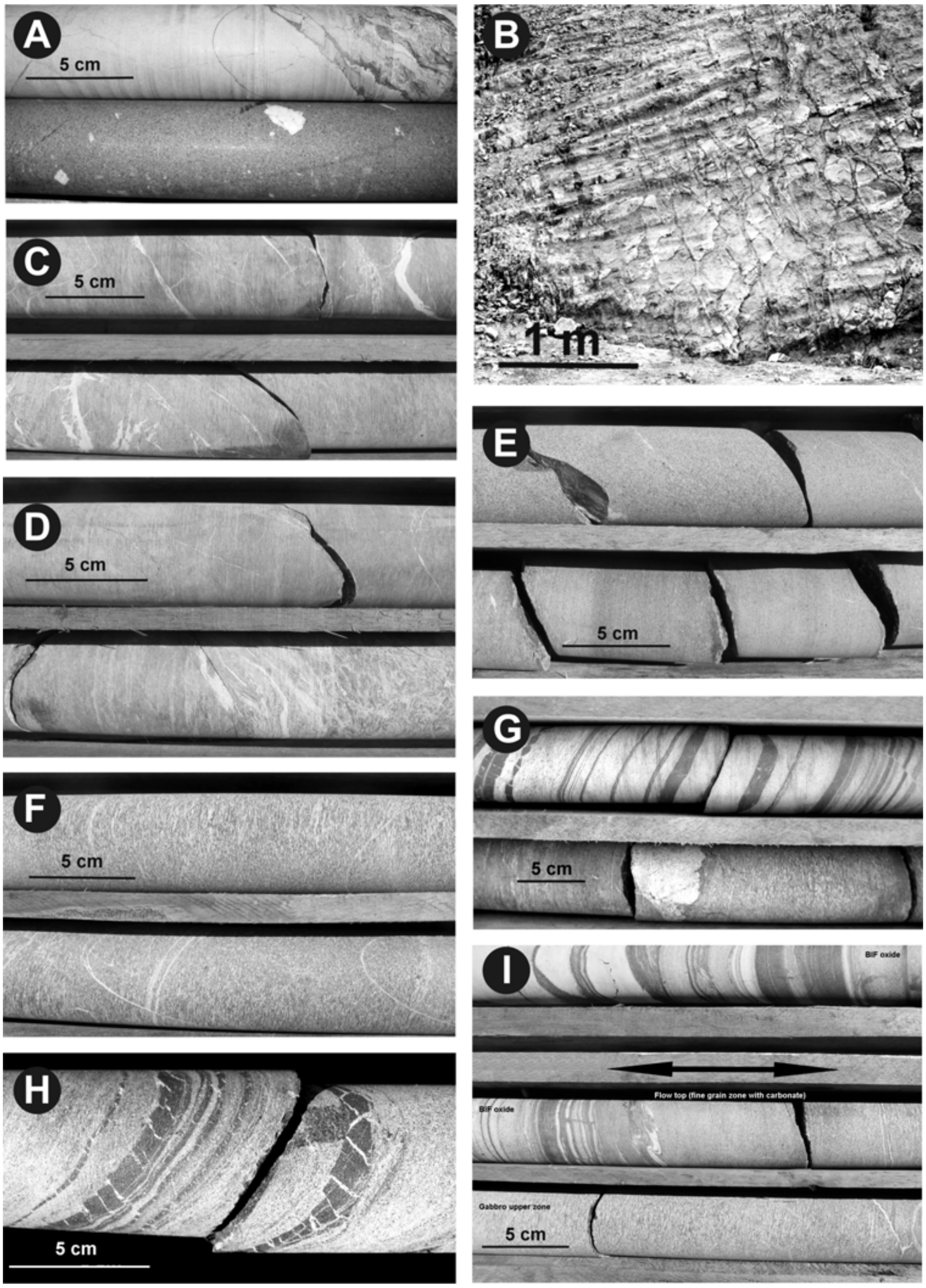

Fig. 3. Rocks types from the Fortaleza de Minas greenstone belt. **a** non deformed cores from proterozoic diabase dyke showing well preserved porphiritic texture in the dyke core (bottom) and afanitic texture at dyke border in contact with tuffaceous sulfidic sediments (top). Despite the well preserved textures the rock is fully retrograded to albite – chlorite green-schist paragenesis. **b** deformed pillow lavas in the Guariroba basalts flows. Outcrop north of the Fortaleza de Minas deposit on plant site. **c** massive serpentinite core with typical carbonate veining (dolomite) representing metamorphosed olivine ortho cumulate. **d** contact between massive serpentinite and foliated talc schist (lighter color). **e** chlorite tremolite schist representing the intermediate pyroxene cumulate zone, at the top fine grained Ca rich-pyroxene cumulus with ad-cumulate to ortho-cumulate textures. **f** core samples of the upper gabbro (AT) now represented by amphibolites. **g** oxide facies banded iron formation are a good marker to separate flow units, although thin they can be very continuos along strike and down dip. **h** oxide facies BIF with thick magnetite bands in a tremolitic groundmass. Note carbonate filling tension gashes in broken magnetite layers. **i** possible flow top of pyroxenitic composition. Fine grain zone, sometimes very fine grained and commonly with carbonate veinlets near upper BIF contact. Spinifex texture had never been observed in the upper zone of fractionated flows.

Komatiitic flows in the deposit area

Brenner et al (1990) identified four cycles or flow units comprising serpentinite - clino-pyroxenite - gabbro separated by usually thin banded iron formation horizons. These flow units defined the intermediate sequence or O'Toole sequence, which lies in a thight syncline between a lower and an upper sequence represented by komatiite and komatiitic basalt flows with interbedded horizons of graphitic meta-chert, BIF and cherty-tuffs (black shales). The nickel deposit is hosted by the uppermost cycle or flow unit from the intermediate sequence (fig. 4). The upper and lower sequences represent the dominant units in the Guariroba-Peroba area. The intermediate sequence is currently interpreted as a thick highly fractionated flow where the individual cycles represent individual flow units separated by thin BIF. (fig. 5). The flow units are commonly 50 to 100m thick, except when intensely sheared, and several km long, being laterally truncated by shear zones in contact with granitic basement (fig. 6). Although intensely sheared, folded and laterally truncated the Fortaleza de Minas fractionated flow displays a minimum unfolded length of about 7km long by 2km wide with an average width of 150m.

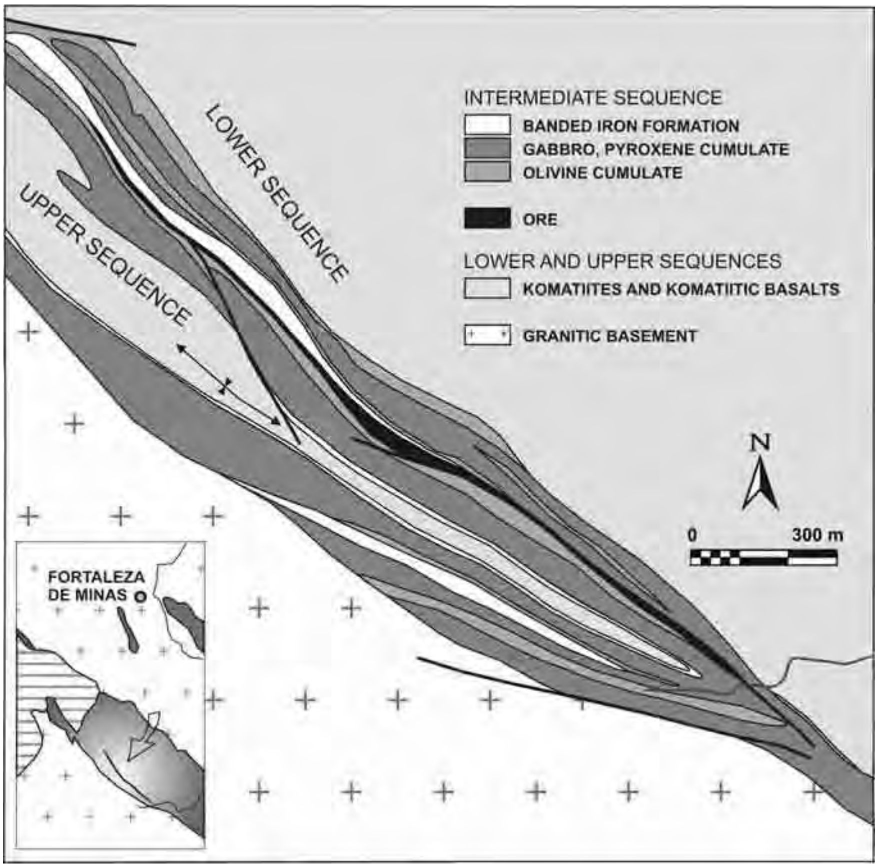

Fig. 4. Geology of the Fortaleza de Minas deposit (modifiyed after Brenner et al., 1990).

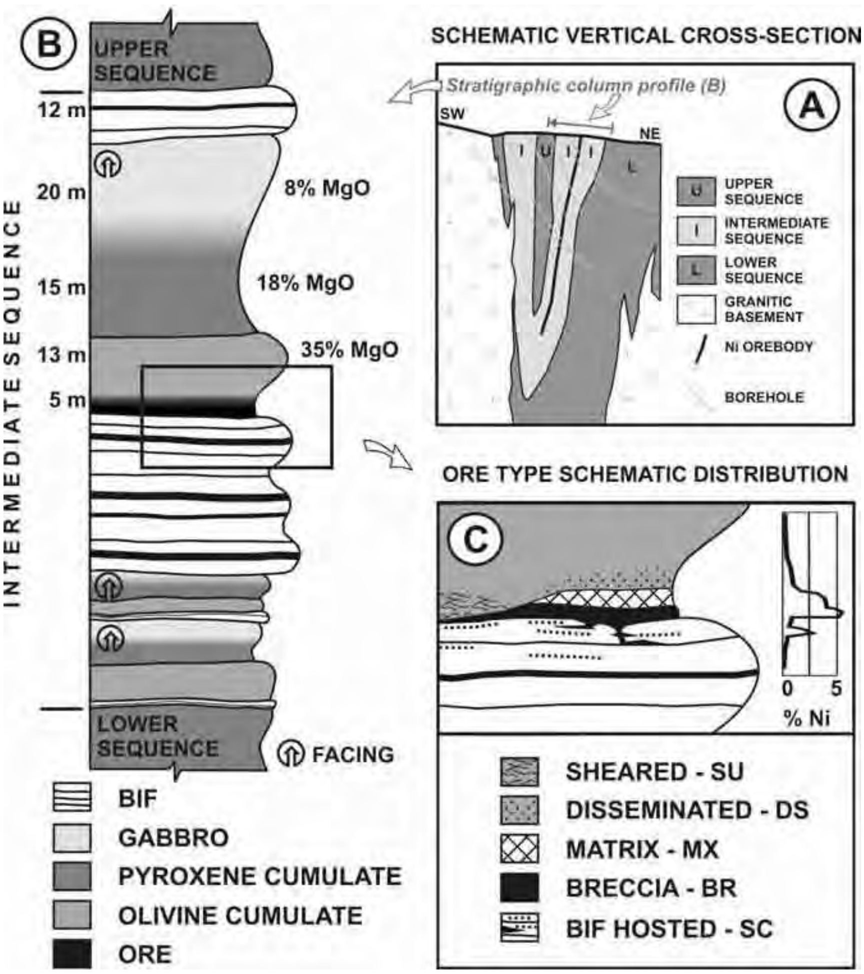

Fig. 5. Schematic stratigraphic column showing the fractionated flow units and related Ni ore.

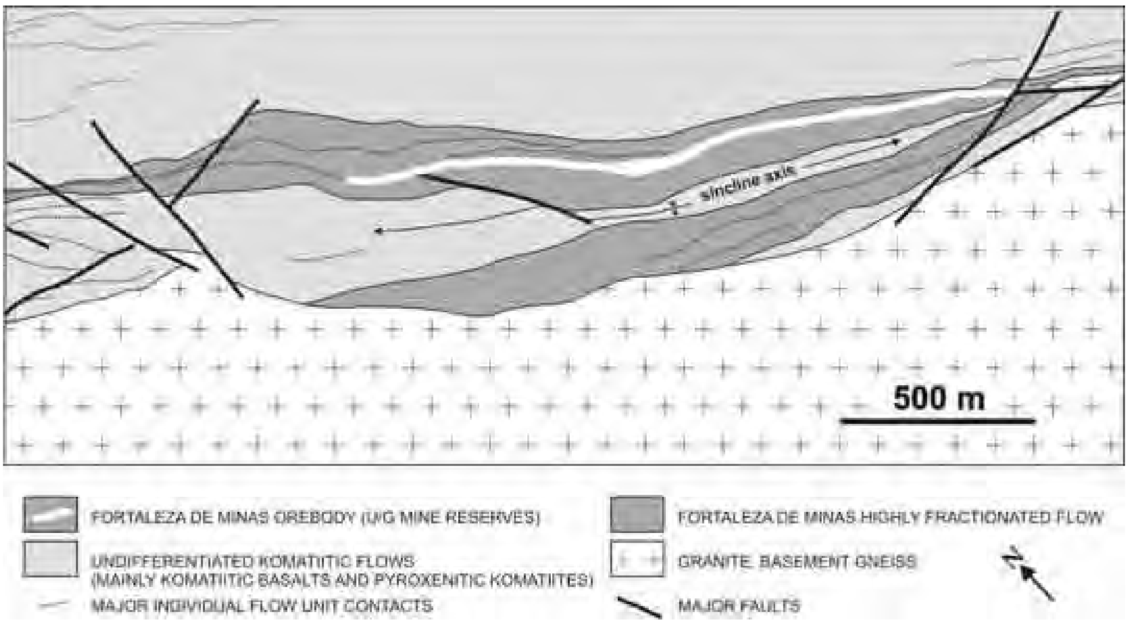

Fig. 6. Distribution of the Fortaleza de Minas highly fractionated flow within undifferentiated barren komatiitic flows of the Morro do Ferro greenstone belt in the Guariroba area. The Fortaleza de Minas orebody is shown in white. Thin lines represent major individual flow unit boundaries commonly marked by thin horizons of chemical sediments (sulfide and oxide banded iron formations).

The Guariroba – Peroba komatiitic flows

The komatiites from the Guariroba-Peroba segment are dominantly fine grained rocks exhibiting foliated textures and subordinate massive textures where volcanic textures such as spinifex, pillow lavas and flow tops, were mostly destroyed by metamorphism and shearing. They range from chlorite-tremolite schists and chlorite-talc/serpentine-tremolite schist to massive serpentinites and talc schists from ortho-cumulates. Metamorphic or magmatic olivines are extremely rare in the cumulates. Most of the komatiites of peridotitic and olivine-peridotite composition are now chlorite-carbonate-talc schists. The komatiitic basalts are represented by chlorite-actinolite schists, chlorite-tremolite schists and plagioclase-actinolite schists where most of the plagioclase is now replaced by epidote and carbonate. Common BIF assemblages are quartz-cummingtonite-actinolite-(magnetite) and cummingtonite-tremolite-magnetite. These assemblages indicate a progressive amphibolite metamorfic facies with superimposed retrograde greenschist facies paragenesis. Primary volcanic textures such as spinifex and pillow lavas are locally preserved (Fig. 3b).

Mineralogy of the thick fractionated flow

The Fortaleza de Minas deposit host flow has fractionated into three distinct rock types: a basal olivine-cumulate zone (SS/TT), an intermediate pyroxene cumulate zone (PI) and an upper gabbroic zone (AT) (fig. 5). The gradational change from the pyroxene cumulate to gabbro is marked by the appearence of porfiritic plagioclase building up to a medium massive gabbroic texture. The pyroxene cumulate zone is normally quite massive, (except for highly sheared zones in the lower flows) and often display one to two internal sub-zones of preserved adcumulate to meso-cumulate texture. The lower olivine cumulate zone has a massive texture and has been fully serpentinized and partially talcified. It is interpreted to correspond to an ortho-cumulate based on its MgO content (33–38%) but also by preserved ortho-cumulate texture from the matrix ore. The contact with the upper pyroxene cumulate zone is sharp and commonly slightly sheared but continuous gradational contact has been also observed in a few bore holes. The metamorphic mineralogical composition of the different fractionated zones is shown in Table 1.

Table 1. Metamorphic mineralogical composition of the fractionated flow.

FRACTIONATED FLOW ZONE	PROTOLITE	LITOTYPE	COMMON PARAGENESES	MINERAL COMPOSITION
AT	gabbro	amphibolite	act - epd - (crb) - (spn) act - epd - plg - (crb) - (spn)	70-85 wt% act
PI	Pyroxene-cumulate	tremolite chlorite schist	trm - chl - (crb) - (mgt) act - chl - (prx) - (mgt) prx - trm - chl - mgt - (crb)	75-90 wt% trm/act
SS	Olivine-cumulate	serpentinite	ant - crb - mgt ant - crb - tlc - mgt ant - mgt - (tlc) - (crb) - (chl)	50-90 wt% ant 10-15 wt% mgt
TT	Sheared olivine-cumulate	talc-schist	tlc - crb - chl - (mgt) crb - tlc - chl - mgt tlc - crb - chl - mgt - (trm)	30-60 wt% tlc 20-50% crb 10-15 wt% chl
	KEY:	ant - antigorite prx - pyroxene trm - tremolite act - actinolite	hbl - hornblend chl - chlorite tlc - talc plg - plagioclase	epd -epidote crb - carbonate mgt - magnetite spn - sphene

The olivine-cumulate zone is represented by massive serpentinites (SS) with 50-90 wt% antigorite and 10-15 w% magnetite displaying typical mesh texture (Fig. 3c). Particularly in sheared or pinching zones the massive serpentinite can be replaced by chlorite – carbonate - talc schists (TT) with talc ranging from 30-60 wt%, carbonate (dolomite) from 20-50 wt% and chlorite from 5-20 wt% (Fig. 3d). Like in the serpentinites magnetite ranges between 10-15 wt%. Intermediate members between TT and SS are found in transition zones. The intermediate pyroxene-cumulate zone (PI) is dominantly represented by massive and poorly foliated chlorite-tremolite-actinolite schist or fels where tremolite-actinolite normally range from 75-90 wt% (Fig. 3e). Tremolite is much more common but actinolite and hornblend may be present. Pyroxene occurs as coarse crystals (augite – diopside) or as pseudomorphs being replaced by tremolite and hornblend. This zone displays one to two internal sub-zones of meso-cumulate to ad-cumulate textures with coarse augite – diposide cumulus within a hornblend tremolite fine grain matrix with magnetite. Rare plagioclase and talc may be found in this zone. Petrographic evidences indicate processes of mineral transformation as follows: Pyroxene > hornblende > actinolite-tremolite > chlorite. The upper gabbro zone (AT) is represented by medium grain massive anfibolites where actinolite is dominant (75-85 wt%) followed by plagioclase and/or epidote – carbonate (Fig. 3f). The original andesine has been almost completely transformed into albite + epidote + carbonate. Due to the metamorphic and shearing processes typical flow tops can no longer be identified. However in the upper contact with the chemical sediments, typically oxide facies banded iron formation (Figs. 3g, h), a zone of fine to very fine grained actinolite-tremolite schist is observed in many places and are also commonly associated with carbonate veinlets or stringers. These features are interpreted as possible metamorphic equivalents to flow tops (Fig. 3i).

Petrochemical characteristics of the komatiitic flows

The komatiitic lavas in the Guariroba-Peroba greenstone segment are represented by typical komatiites (18-25 wt% MgO) with subordinate cumulates (34 wt% MgO) and komatiitic basalts (10-15 wt% MgO). They show a differentiation trend similar to other archean komatiitic flows (Fig. 7a, b). Some samples display local drift to the CaO side as shown in figure 7a. Due to the high amphibolite facies metamorphism, intense weathering, deformation and shearing, volcanic textures such as spinifex, pillow lavas and flow tops are normally absent. With the escavations for the construction of the Ni plant site several exposures of spinifex texture and pillow lava were shown north of the nickel deposit (Fig. 3b). However, the outcrops are scarse and preclude any reconstruction of the entire flow structure. Most borehole cores show recristalized fine to medium grained foliated rocks. The fractionated deposit rocks have a distinctive massive texture and, regardless the intense drilling carried out in the mine area, they do not show spinifex textures. Chemical data show a marked switch towards the CaO side in the MgO-CaO-Al_2O_3 ternary diagram with a bended differentiation trend (Fig. 7a). The Fortaleza de Minas trend is similar to the Barbeton trend (Viljoen et al, 1982; Viljoen and Viljoen, 1982), rather than the Western Australian komatiites behaviour (Lesher and Keays, 2002; Hill, 2001).

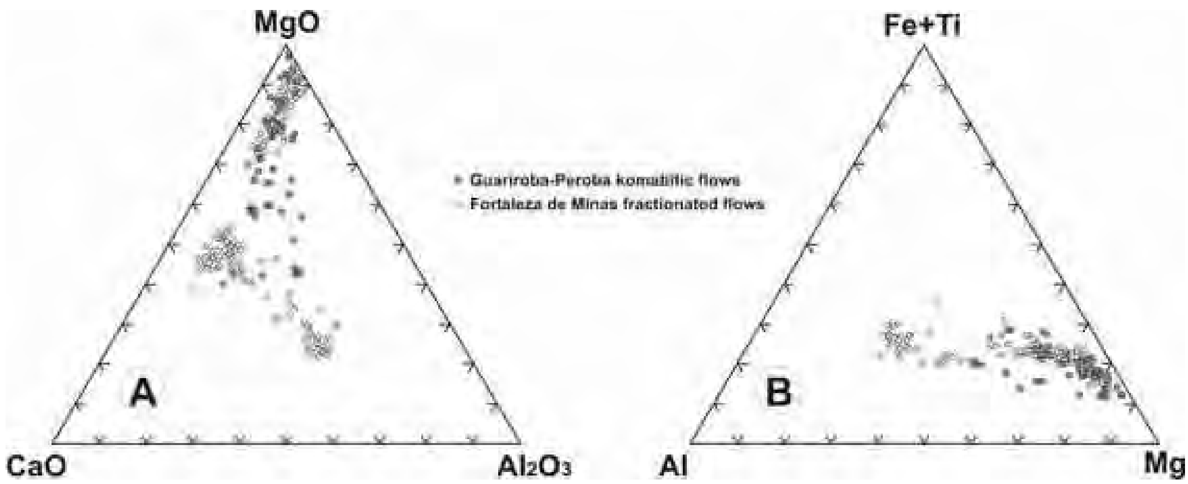

Fig. 7. Petrochemical data from the Fortaleza de Minas greenstone belt flows. **a** MgO-CaO-Al2O3 ternary diagram (left side) for komatiitic flow from the Guariroba- Peroba segment. Komatiites and komatiitic basalts in dark squares with typical vertical fractionating trend. The Fortaleza de Minas highly fractionated flow (open circles) shows a strong drift to the Ca side with a bended trend. **b** Jensen cation plot (right side) for the same dataset. Open circles showing data from the Fortaleza de Minas fractionated flow and dark squares for the komatiitic flows in the Guariroba – Peroba segment.

Whole rock composition of major rock types from the Guariroba-Peroba segment is shown in Table 2. Whole rock composition of major rock types from the thick fractionated flow is shown in Table 3. The olivine-cumulate zones from the lower individual flow units are listed apart from the upper mineralized flow unit and this is also split into trough and flank environment. The olivine-cumulate zone from the trough environment shows higher MgO values and also higher Ni, Cr, Cu, Co values. Only non mineralized samples were used (S<0.30 wt%). Table 4 display olivine-cumulates for different individual flow units in both limbs of the syncline structure. The dataset summarized on these tables are displayed as scatter-plots on figure 8 highlighting the fractionation trend for the fractionated flow. SiO_2 and Al_2O_3 show a typical negative correlation with MgO.

Table 2. Mean analyses of the major rock types in the Guariroba-Peroba segment.

	1 **AT** Basaltic Komatiites	**2** **BK** Pyroxenitic komatiites	**3** **KO/TT** Komatiites (peridotites)	**4** **KO** Komatiites (peridotites) SW limb of Mine Syncline	**5** **SS/TT** serpentinites and talc-schist (olivine peridotites, cumulates)
N° of samples	2	5	8	4	34
SiO_2	50.30	50.25	48.58	48.78	44.73
TiO2	0.71	0.59	0.44	0.66	0.35
Al_2O_3	5.40	10.34	6.74	4.88	2.93
Fe_2O_3	13.48	12.02	12.78	14.18	14.00
MnO	0.23	0.19	0.21	0.20	0.20
MgO	13.27	15.00	21.65	20.29	32.48
CaO	13.37	9.66	8.88	9.86	4.37
Na_2O	1.57	1.04	0.30	0.40	0.08
K_2O	0.12	0.14	0.05	0.29	0.03
P_2O_5	0.07	0.08	0.05	0.04	0.03
Total	98.52	99.31	99.68	99.58	99.20
Ni	61	248	425	304	1323
Cr	1200	1719	1863	1550	1706
Cu	113	111	166	149	99
Co	15	35	49	33	97
Zn	20	52	60	32	113

Analytical methods: Major element data by X-ray fluorescence reported on a dry basis with total iron as ferric iron. Ni, Cu, Cr, Co, Zn by multi-acid digestion/ICP.

Major elements in % (recalculated 100% volatile free). Ni, Cr, Cu, Co, Zn in ppm.

Table 3. Mean analyses of the major rock types in the Fortaleza de Minas thick fractionated flow.

	1 **AT** **Gabbro Zone** Mineralized Fractionated Flow	**2** **PI** Pyroxene-cumulate Mineralized Fractionated Flow	**3** **SS/TT** Serpentinite, talc schist - Olivine-Cumulate Mine area, lower flows	**4** **SS/TT** Serpentinite, talc schist - Olivine-Cumulate Mineralized flow, flank environment	**5** **SS/TT** Serpentinite, talc schist - Olivine-Cumulate Mineralized flow, trough environment
N° of samples	38	70	22	73	21
SiO2	51.27	49.43	43.53	41.46	39.93
TiO2	0.87	0.63	0.39	0.37	0.36
Al2O3	13.06	4.62	2.84	2.81	2.65
Fe2O3	11.99	12.12	15.11	16.42	15.95
MnO	0.17	0.20	0.21	0.20	0.24
MgO	9.05	17.14	33.05	34.33	36.52
CaO	9.98	14.46	3.82	3.23	2.83
Na2O	2.45	0.36	0.08	0.08	0.06
K2O	0.31	0.05	0.01	0.01	0.01
P2O5	0.10	0.06	0.04	0.04	0.03
Total	99.25	99.07	99.08	98.95	98.58
Ni	64	243	1279	1780	1962
Cr	413	2243	3891	5530	5665
Cu	65	204	87	202	300
Co	19	29	81	120	129
Zn	27	28	54	72	93

Analytical methods: Major element data by X-ray fluorescence reported on a dry basis with total iron as ferric iron. Ni, Cu, Cr, Co, Zn by multi-acid digestion/ICP.

Major elements in % (recalculated 100% volatile free). Ni, Cr, Cu, Co, Zn in ppm.

Table 4. Mean analyses of the olivine-cumulate rocks in the Fortaleza de Minas deposit syncline.

	1 **SS/TT** **Gabbro Zone** Mineralized Fractionated Flow	**2** **SS/TT** Pyroxene-cumulate Mineralized Fractionated Flow	**3** **SS/TT** Serpentinite, talc schist - Olivine-Cumulate Mine area, lower flows	**4** **SS/TT** Serpentinite, talc schist - Olivine-Cumulate Mineralized flow, flank environment	**5** **SS/TT** Serpentinite, talc schist - Olivine-Cumulate Mineralized flow, trough environment
N° of samples	38	70	22	73	21
SiO2	51.27	49.43	43.53	41.46	39.93
TiO2	0.87	0.63	0.39	0.37	0.36
Al2O3	13.06	4.62	2.84	2.81	2.65
Fe2O3	11.99	12.12	15.11	16.42	15.95
MnO	0.17	0.20	0.21	0.20	0.24
MgO	9.05	17.14	33.05	34.33	36.52
CaO	9.98	14.46	3.82	3.23	2.83
Na2O	2.45	0.36	0.08	0.08	0.06
K2O	0.31	0.05	0.01	0.01	0.01
P2O5	0.10	0.06	0.04	0.04	0.03
Total	99.25	99.07	99.08	98.95	98.58
Ni	64	243	1279	1780	1962
Cr	413	2243	3891	5530	5665
Cu	65	204	87	202	300
Co	19	29	81	120	129
Zn	27	28	54	72	93

Analytical methods: Major element data by X-ray fluorescence reported on a dry basis with total iron as ferric iron. Ni, Cu, Cr, Co, Zn by multi-acid digestion/ICP.

Major elements in % (recalculated 100% volatile free). Ni, Cr, Cu, Co, Zn in ppm.

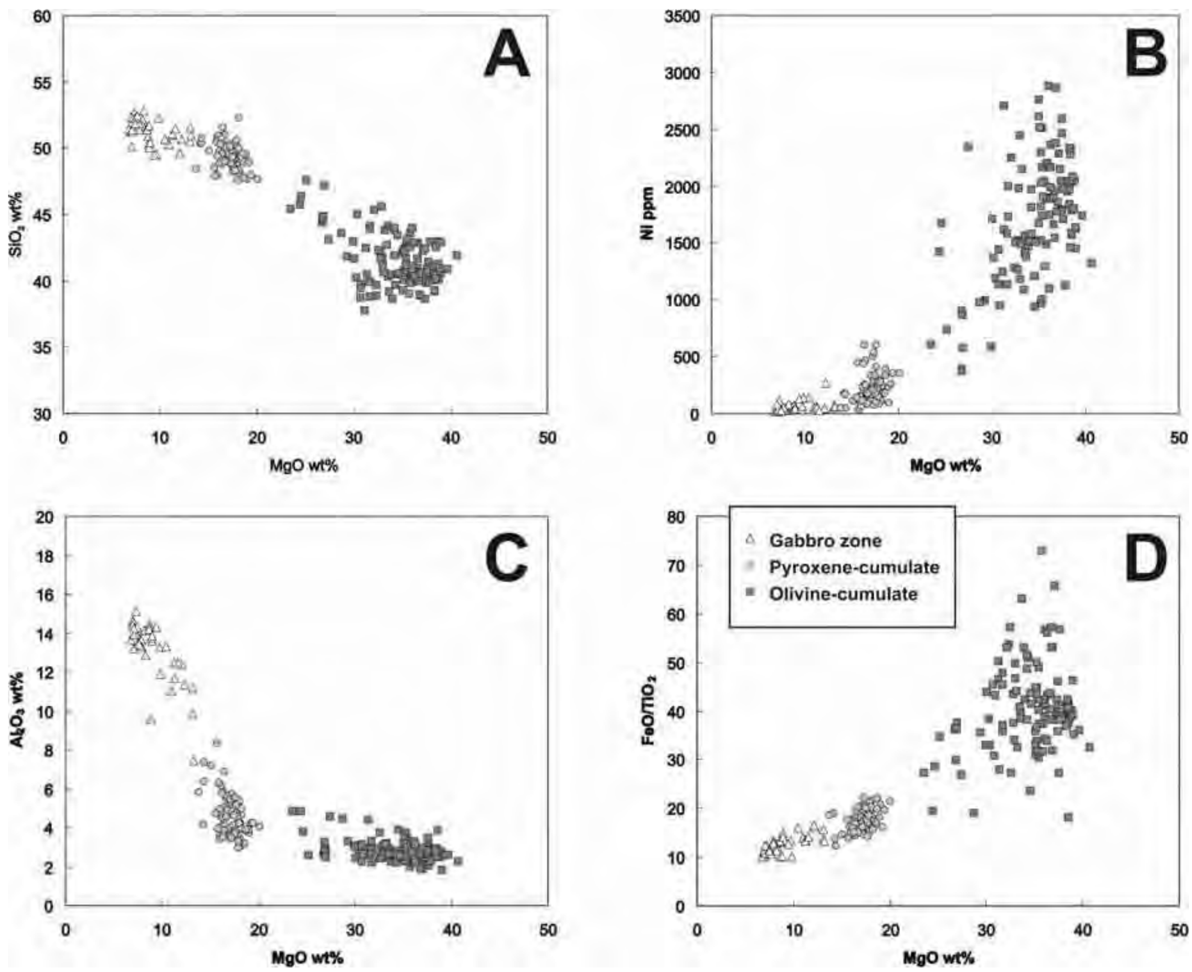

Fig. 8. Fractionation trends for the Fortaleza de Minas highly fractionated flow.

The fractionated flow gabbro zone may plot partially out of the original limit between komatiitic and tholeitic basalts as defined by Jensen (1976) for the Jensen cation plot. Viljoen et al (1982) proposed a revision of Jensen limits for the Barbeton komatiites (Fig, 9). The data fits better to the limits proposed by Viljoen as it moves towards the field of tholeitic high Mg basalts. The proposed limit for komatiites and komatiitic basalts falls within the pyroxene-cumulate zone. The observed boundaries for the fractionated flow is shown as a dotted line. The higher dispersion of the data for the gabbro zone can be related to modifications of original composition during metamorphism. However, for the olivine-cumulate zone - where processes of retrograde metamorphism with high CO_2 pressure formed talc-carbonate rocks after serpentinites derived from primary olivine-cumulates - the dispersion of the data is considered to be negletable even considering the high amount of volatiles in the serpentinite (SS) and talc-carbonate schist (TT) (average 11% (SS) and 13% (TT), maximum 21% (SS) and 23% (TT)).

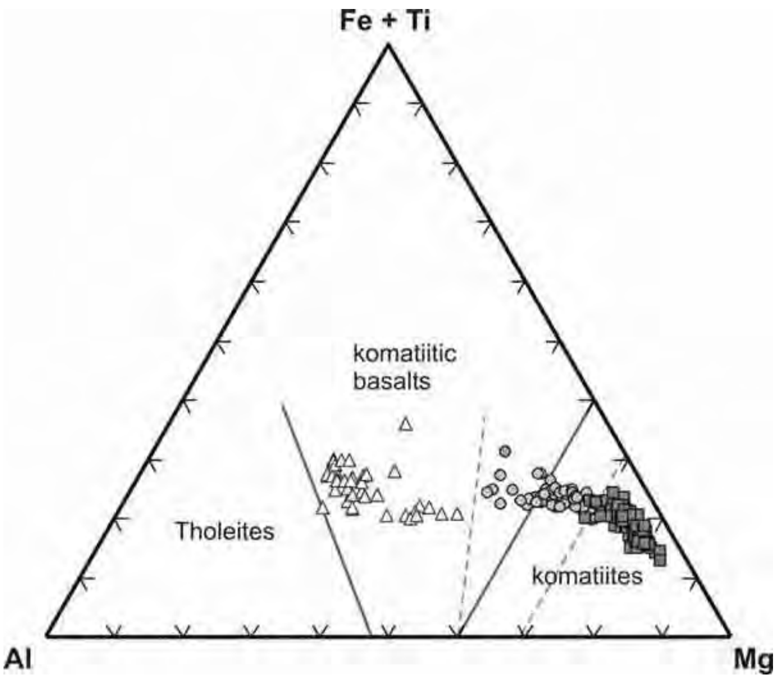

Fig. 9. Jensen cation plot of Fortaleza de Minas fractionated flow. Gabbro (triangles), pyroxene-cumulate (circles) and olivine-cumulate (squares). Solid lines after Viljoen (1982) revision of original Jensen limits for Barbeton greenstone flows. Dotted lines represent natural breaks for Fortaleza de Minas flow fractioning.

Due to metamorphism and shearing no olivine and cromite were preserved. The olivine cumulates have been completely transformed into serpentinites and talc carbonate rocks. The estimation of the original bulk composition was inferred from the proportions and average MgO contents of each fractionated zone of the flow. From a comprehensive borehole database the weighted average bulk MgO content was estimated, ranging between 18 and 23 wt% MgO (Appendix 1).

Geological model for volcanogenic komatiitic related Ni - Fe sulfide deposits

The most accepted model today for this type of mineralization is well documented in many recent papers (Lesher and Keays, 2002; Lesher, 1989; Hill, 2001; Hill et al, 2004; Barnes et al, 2004; and Nadrett, 2005) and is related to assimilation of sulfides by thermal erosion processes in channelized komatiite flows. The different volcanic environment show distinctive features as function of the proximity to the feeder area for the lava flows. Lesher and Keays (2002) and Hill (2001) classified the komatiite related sulfide deposits into different types regarding their volcanic setting. The Fortaleza de Minas deposit shows characteristics of a Type 1 mineralization of distal facies with a shallow thermal erosion trough in a thick highly fractionated flow. The major characteristics of Type 1 deposits described in Lesher and Keays (2002) are the presence of a basal massive sulfide followed by matrix and disseminated ores in an ortho-cumulate thick zone associated with a trough or channel formed by thermal erosion (fig. 10).

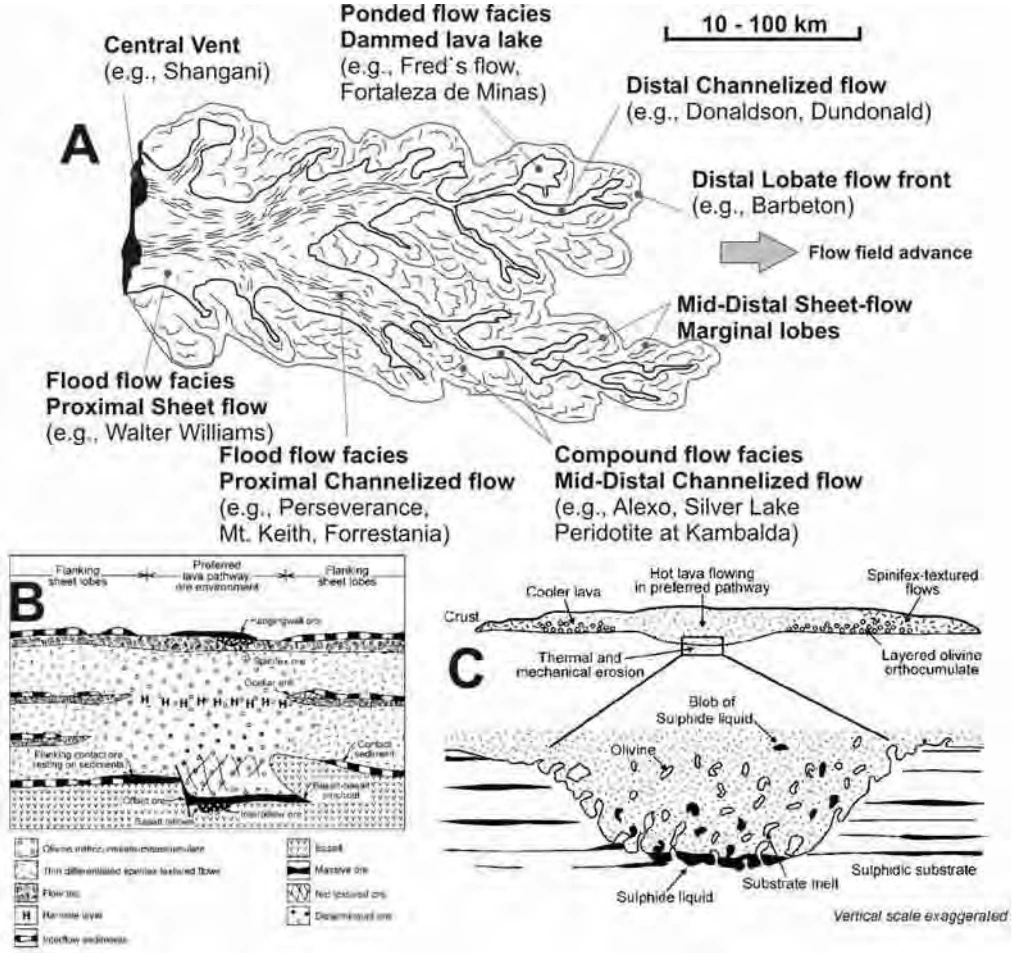

Fig. 10. Komatiite volcanic facies. **a** diagram showing a typical komatiitic flow field with facies and related deposits after Hill, 2001 and Lesher and Keays 2002. **b** diagramatic cross-section showing Type 1 sulfide mineralization of the Silver Lake Member of the Kambalda Komatiite Formation after Cowden and Roberts 1990 in Hill 2001. **c** schematic cross-section illustrating the formation of Type 1 Ni deposit through thermal-mechanical erosion of sulfidic sediments after Hill 2001.

Most of the Type 1 deposit flows show indications of local contamination processes related to thermomechanical erosion of Sulfur-rich rocks beneath lava channels (Lesher and Keays, 2002; Lesher and Arndt, 1995). Indications of crustal contamination such as enrichment in light rare-earth elements (Fig. 11) can be found in many komatiite lava flowing conduits by thermomechanical erosion and assimilation of felsic tuffs and banded iron formations. Extensive sulfide/ oxide bearing banded iron formations in the Fortaleza de Minas deposit area are interpreted as the major source for crustal contamination. Sulfur isotopes and S/Se ratios (Choudhuri et al., 1997) and Re-Os isotopes (Correia et al., 2001) from the Fortaleza de Minas deposit show similar values from other komatiite hosted type 1 deposits. Although the above mentioned authors argued against thermomechanical erosion, we agree with Lesher & Keays, (2002) that the best interpretation of the S and S/Se variations in Type 1 deposits is in favour of assimilation of crustal metasedimentary rocks. S/Se ratios (4810-17540) from the Fortaleza de Minas ores are higher than the mantle value and, like other Type 1 ores, are consistent with the interpretation that most of the S in the ores has been derived from assimilation of sulfidic sediments (Lesher & Keays, 2002). The high Os initial ratio and γOs values in the Fortaleza de Minas ores is interpreted herein as related to crustal assimilation and not to metamorphic and remobilization processes as suggested by Correia et al., (2001). Lesher and Keays, (2002) pointed out that the observed Os isotopic compositions can be attributed to variations in the R factor, resulting from mixing of highly radiogenic crustally-derived Os with less radiogenic mantled-derived Os.

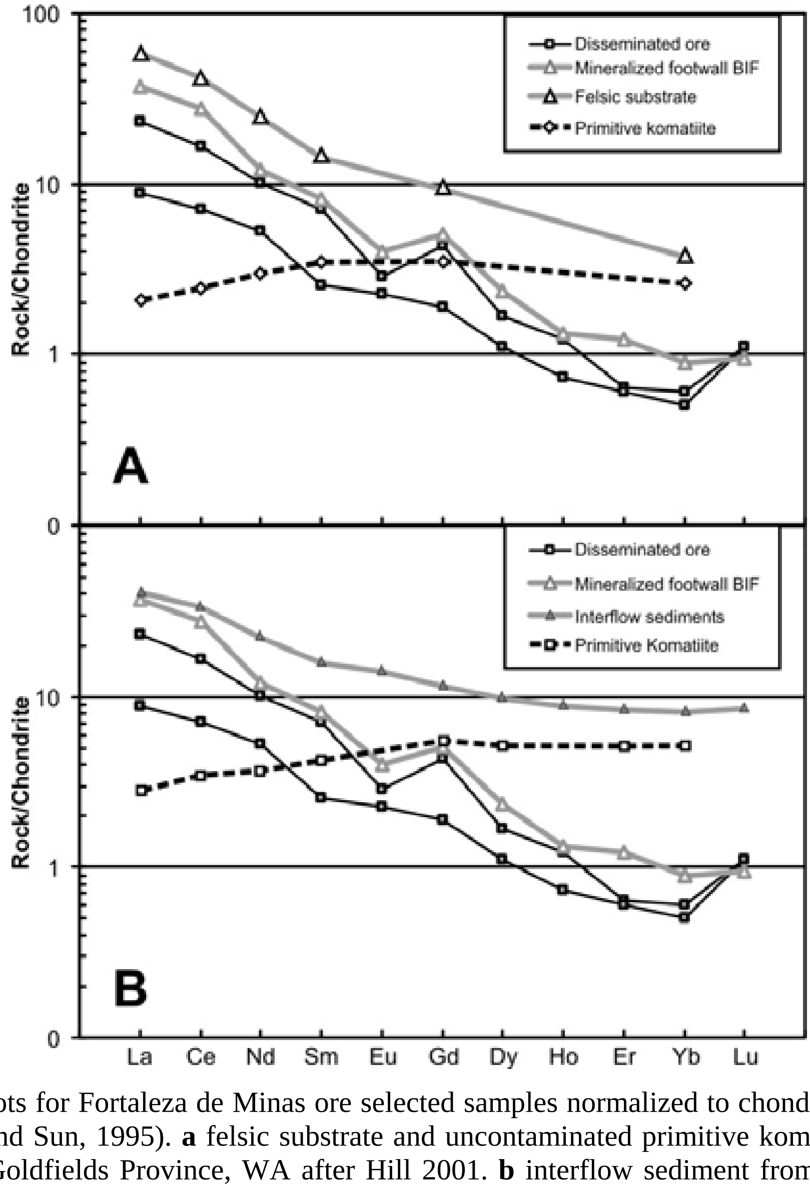

Fig. 11. REE plots for Fortaleza de Minas ore selected samples normalized to chondrite compositions (Mc Donough and Sun, 1995). **a** felsic substrate and uncontaminated primitive komatiite from Black Swan, Eastern Goldfields Province, WA after Hill 2001. **b** interflow sediment from Kambalda, WA after Lesher and Arndt 1995 and primitive komatiite after Barnes et al. 2004.

Hill et all, (1995) proposed a classification of komatiite flow faciology based on the degree of internal differentiation, proportion of cumulate material and characteristic thickness of flow units. The “Thick fractionated flow units” are up to 150 m thick and several km wide and are characterized by in situ differentiation of ponded komatiite lava containing pyroxenitic and gabbroic cumulates in lava lakes. Commonly the lower part of these units are occupied by homogeneous olivine orthocumulates and meso cumulates assumed to be formed during an early flow-trough stage in a lava channel, which subsequently became dammed up. A typical example of this type of flow being Fred`s flow at Munro Township (Arndt et al., 1973). The Fortaleza de Minas highly fractionated flow units has similar thickness and widths (fig. 6) and also similar fractionation products – olivine-orthocumulate, pyroxene-cumulate and gabbro - and is considered to be formed in a ponded lava lake facies environment similar to Munro Fred’s flow (fig. 10). Figure 12 shows a schematic cross-sections illustrating the volcanic structures and lithologies of type 1 (Fig. 12a) and type 2 (Fig. 12b) deposits, after Hill, (2001), and the schematic diagram proposed for the Fortaleza de Minas ponded type 1 mineralization (Fig. 12c).

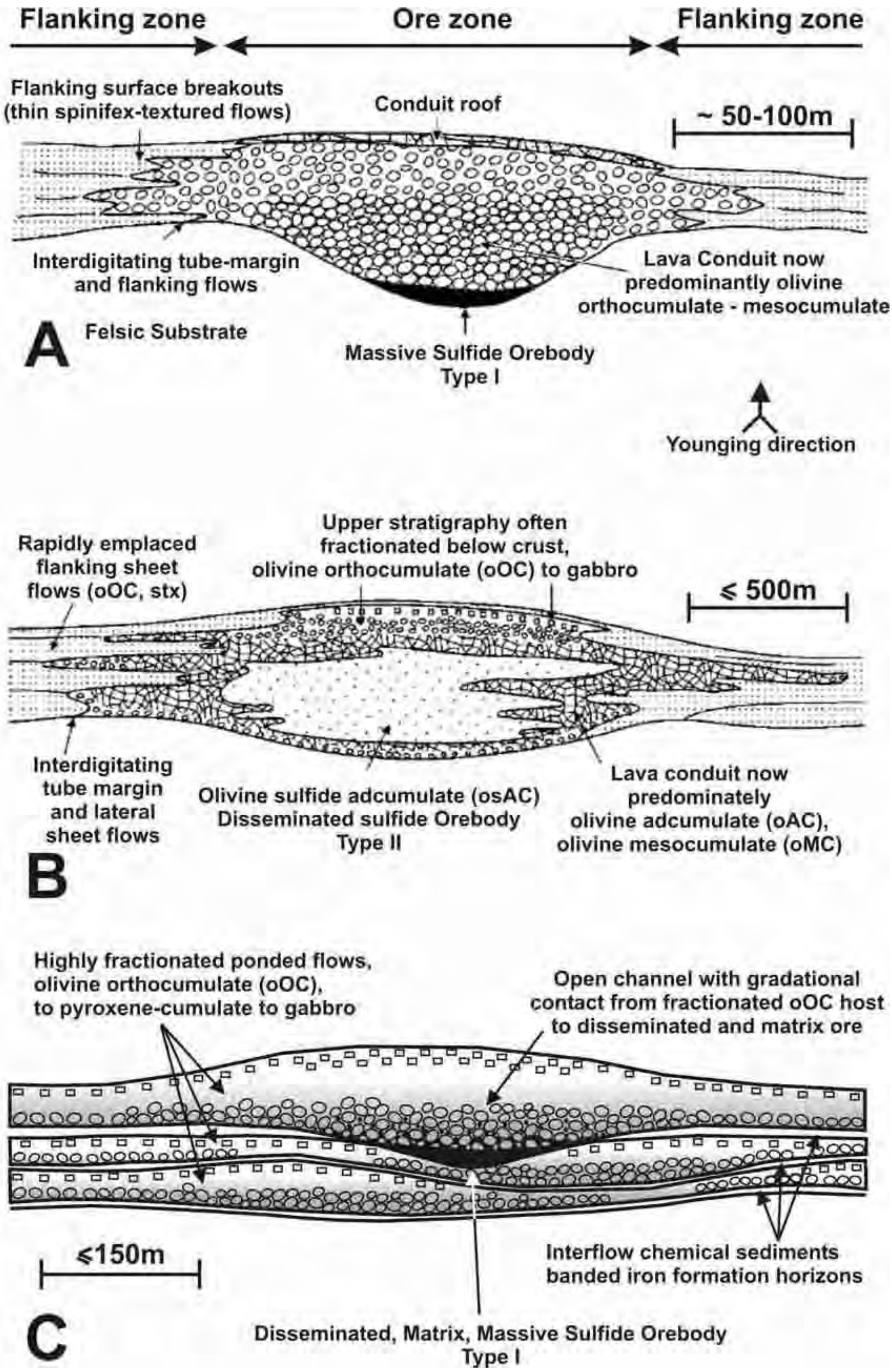

Fig. 12. Schematic cross-sections showing volcanic structure, and lithological associations for komatiite hosted deposits. **a** Type 1 mineralization, after Hill, 2001. **b** Type 2 mineralization, after Hill, 2001. **c** Fortaleza de Minas Type 1 ponded facies mineralization.

Interflow sediments faciology

The Guariroba-Peroba greenstone segment has a distinct zonation of chemical sediments. In the NE margin of the Peroba area a thick pile of chemical sediments with minor contribution of detritic sediments is interpreted to represent the upper sequence of this greenstone segment, which is estimated to be 200m thick. They are typically banded cherts and hematite bearing banded iron formation with thin komatiitic inter-sediment flows. In the central portion of the Guariroba-Peroba segment the komatiites and komatiitic basalt flows are often separated by thin cherty black shale horizons, banded cherty graphitic meta-tuffs and sulfide facies banded iron formations. Laterally they gradually merge to oxide facies magnetite bearing BIFs. Pyrrhotite is the dominant sulfide followed by chalcopyrite, sphalerite and arsenopyrite. The same carbonaceous banded iron formation and tuffs also occur in the SW portion of the segment as interflow sediments in the upper and lower sequences from Brenner et al, (1990). The Fortaleza de Minas fractionated flow (formerly intermediate sequence) has distinctive oxide and silicate facies BIF horizons within the individual fractionated flow units. The lower flow units are separated by thin (0.5 to 5m) horizons of oxide facies with a tremolitic/ actinolitic groundmass finelly or coarsely banded with magnetite layers where free silica is absent or rare (Figs. 3h and 5). The interflow sediment horizon that separates the ore bearing upper flow unit to the lower ones is abnormally thick (up to 50m) and starts with a silica rich oxide facies BIF (with fine magnetite bands) evolving to a silicate facies with banded cummingtonite, actinolite and silica displaying banded disseminated sulfides towards the top. The width of this horizon becomes very narrow and eventually discontinues in the central part of both openpit and underground mines along a steep plunge and has been interpreted as due to thermal erosion processes along a lava flow channel (Fig. 12c). In the SW limb of the Fortaleza de Minas Syncline some of the lower BIF horizons show gradational contacts to graphitic banded iron formations and cherty-tuffs indicating a change to deeper water environment. The facies distribution suggests a shallow water environment for the fractionated flow changing laterally to deeper water environment.

Embayment and Trough structures

Similarly to other komatiite volcanic Type 1 Nickel deposits (Lesher and Keays, 2002; Hill, 2001; Beresford, 2005) the Fortaleza de Minas deposit is also related to trough or embayment structures. Evidences for such structures are:

- The presence of high MgO ortho-cummulates (B zone) and the absence of spinifex zones (A). (Not applicable for the Fortaleza de Minas highly fractionated flow).
- Presence of cumulate and massive textures in highly fractionated flows.
- Lateral changes to thinner sequences with spinifex textures.
- Evidences of thermal erosion (lack of footwall BIF).
- Presence of massive, matrix and disseminated ores in these troughs. (Massive ore has been recristalized and remobilized as breccia ore prograding the trough limits at Fortaleza de Minas).

Although the deposit has been affected by intense folding and shearing indications of trough structures can still be recognized. Figures 13 and 14 show trough structures with primary disseminated and matrix ores associated with thinning of the footwall BIF interpreted as caused by thermal erosion. The intense shear associated with the sinistral transcurrent faults that affected the deposit and the greenstone belt segment as a whole promoted a strong flattening of the rocks in the mine area where the flattening effect seems to have been much more intense than the horizontal displacement along the ore contact fault (Rosas, 2003; Brenner et al, 2006 – in press). Figure 15 shows the 900m sublevel where up to five individual flow units can be outlined. The deposit is hosted by the upper V flow unit. Despite the strong shearing, the trough zone is clearly defined by the presence of disseminated and matrix ore types and the sudden pinch of the footwall BIF. Figure 16a show the 990m bench from the open pit mine and a simplified reconstruction of the overall shape of the embayment structure in the central portion of the deposit prior to deformation by shortening the 990m bench plan view by 7 times (Fig. 16b). The trough is indicated by both the thinning and lack of the footwall BIF and the presence of disseminated and matrix ores.

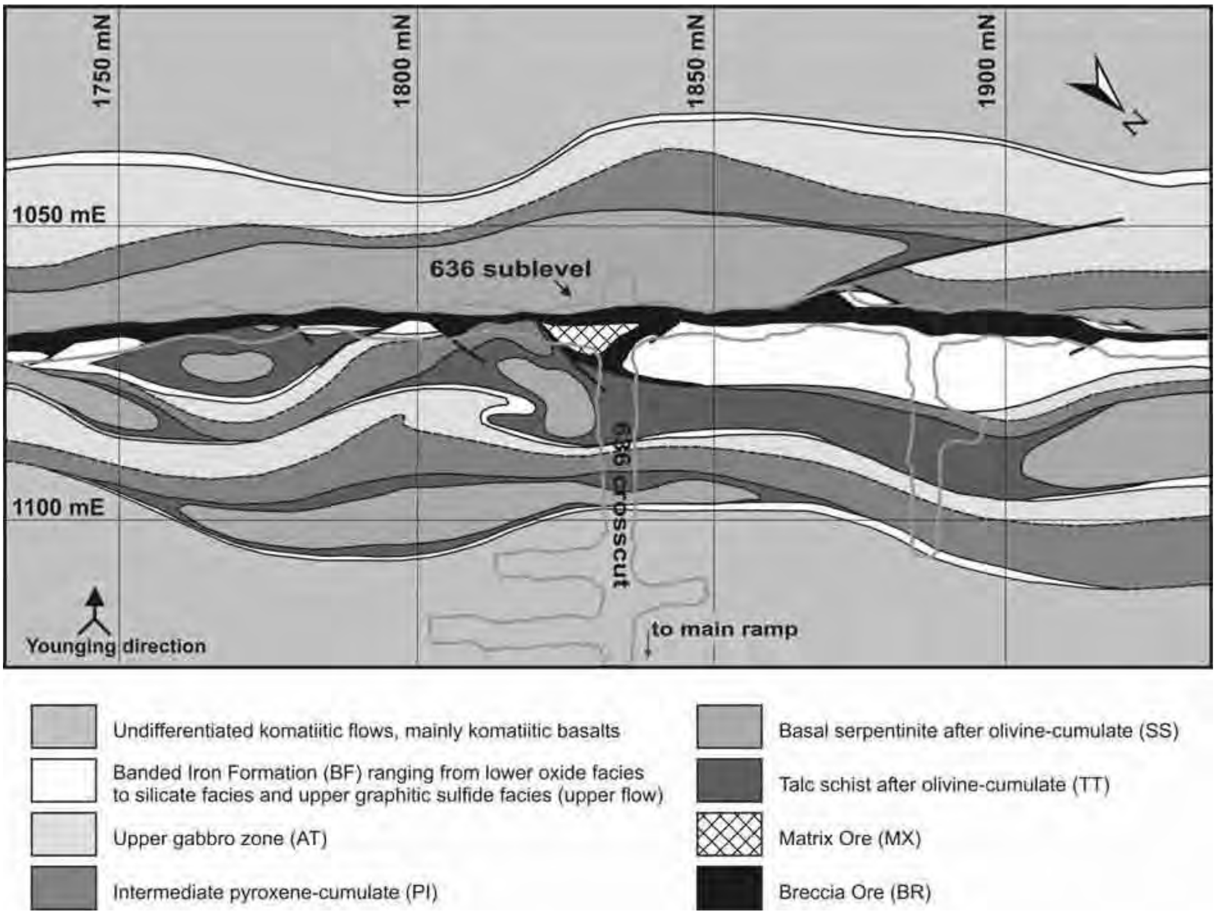

Fig. 13. Plan view of 636 sublevel showing the termination of the central trough at depth. Widespread distribution of Breccia ore (BR) and restrict occurrence of primary Matrix ore (MX) associated with rapid thinning of footwall BIF (BF). Four highly fractionated flows can be identified facing upwards and separated by thin but continuous horizons of Banded Iron Formation with clear facies change from oxide (BFo) to silicate (BFs) and graphitic sulfide facies (BFg) indicating change from shallow to deep water environment to the top. Each flow has a distinctive olivine-cumulate basal zone (now represented by serpentinite – SS and talc schist – TT), followed by an intermediate pyroxene-cumulate (PI) and an upper gabbro zone (AT). Concentrated shearing in the footwall side of the ore zone has promoted pinching and stretching of the olivine-cumulates in the footwall flows followed by incomplete talcification of serpentinites leaving remaining nuclei in the thicker zones.

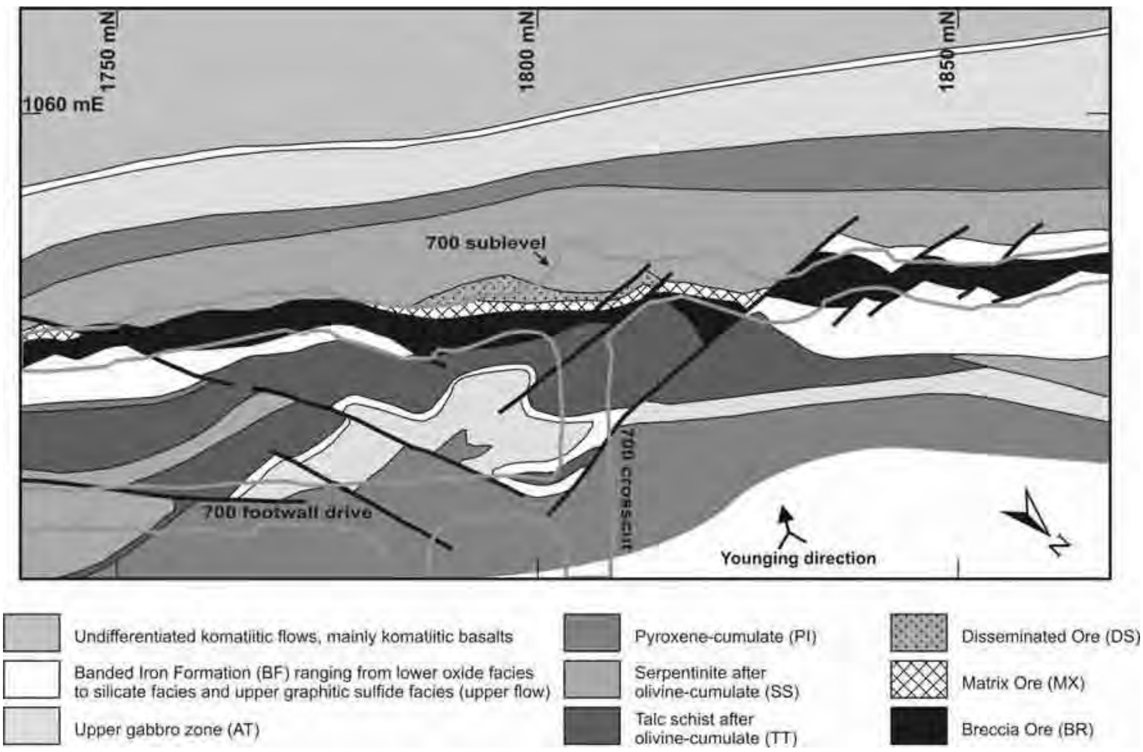

Fig. 14. 700 sublevel plan showing trough structure with Disseminated (DS), Matrix (MX) and Breccia (BR) ores and thermal erosion of the footwall BIF. Matrix and disseminated ores are truncated by fault to North. Breccia ore at North of fault is remobilized into footwall BIF with recrystalized texture and higher grades. Thin marginal sheared ore (SU) at the serpentinite/ BIF contact in the North and thin BIF hosted ore in BR / BIF contacts not represented due to scale.

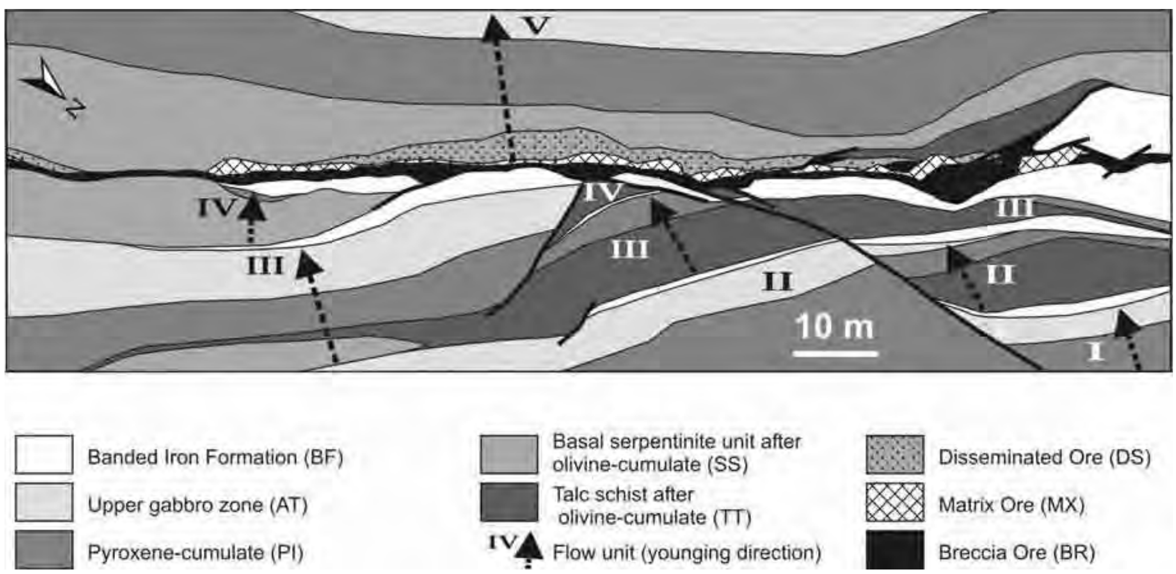

Fig. 15. 900 sublevel plan. Major shear zone along Breccia ore (BR). Up to five highly fractionated flow units are identified by roman numbers I to V. Central trough is marked by DS, MX and BR ore and sudden thinning of footwall BIF (right side). Shearing inside the ore zone resulted in pinch and swell and boudinage structures in the brittle matrix ore (MX) and remobilization and recrystalization of the breccia ore (BR) along the shear zone.

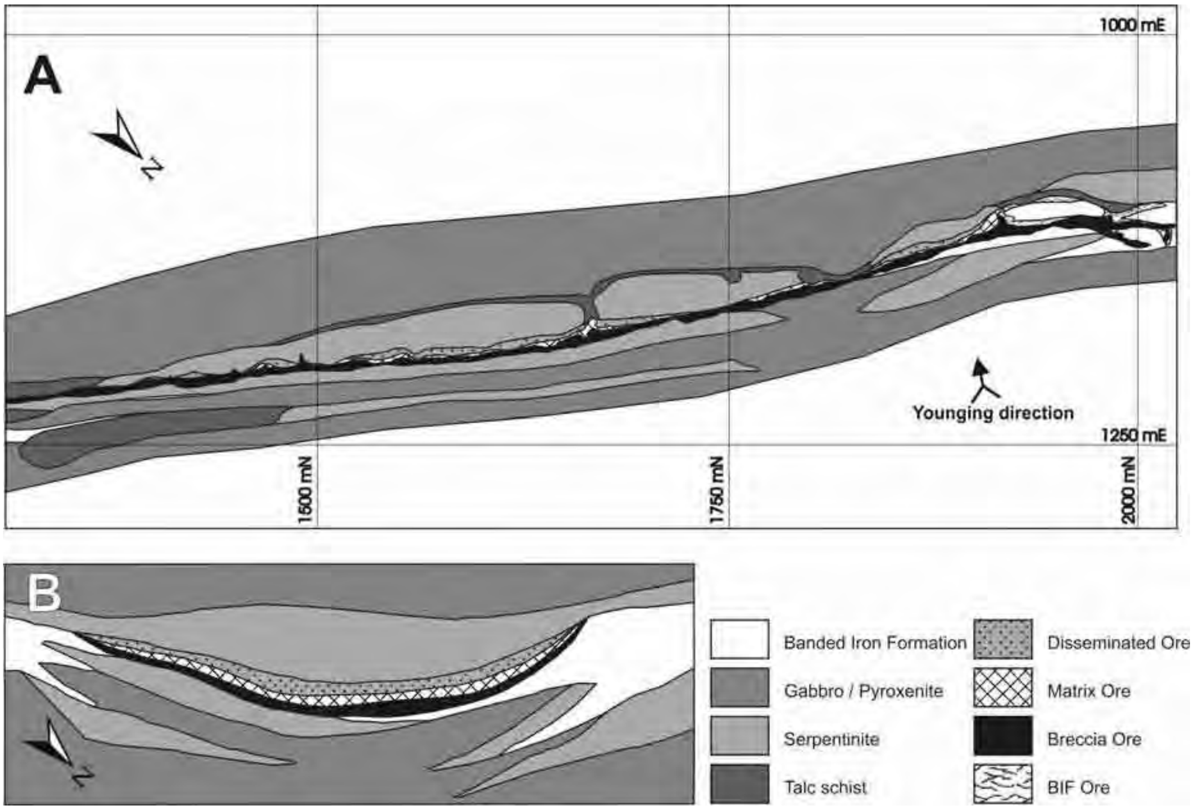

Fig. 16. Simplifiyed geology from the central part of the 990 bench plan from the open pit mine. **a** the broad shallow embayment zone is marked by disseminated ore, matrix ore and breccia ore. Pinching out of footwall BIF is clear in the right side where the trough disseminated and matrix ores give place to remobilized breccia ore and BIF hosted ore. The hanging wall olivine-cumulate (serpentinite and talc schist) shows a well defined pinch and swell structure with talcification associated to the pinch zones. Pyroxene-cumulate (intermediate) and gabbro zones (top) are not separated. **b** simplified reconstruction of the 990 bench with 7x vertical exaggeration to highlight the broad embayment structure marked by primary disseminated and matrix ores and thermal erosion of footwall BIF. The olivine-cumulate zone (serpentinites) is also locally thicker over the embayment, although this could be also caused by large scale pinch and swell along the major shear zone.

A vertical longitudinal section including both open pit and underground mine also reveals clearly the trough structure where two interpreted separate troughs open apart at depth (Fig. 17). The troughs are revealed by the outlines of both disseminated and matrix ores and also, indirectly, by the lack of remobilized ore in the footwall BIF as a consequence of thermal erosion of the banded iron formation. The trough structures also coincide with higher ore widths and higher average Ni grades. Major displacements are tentatively interpreted as resulting from primary faults that could have controlled the trough structures and consequently the ore distribution. It is difficult to confirm that these structures were not settled much later during folding and shearing, however, minor faults and shears observed at underground exposures do not seem to relate to these major structures.

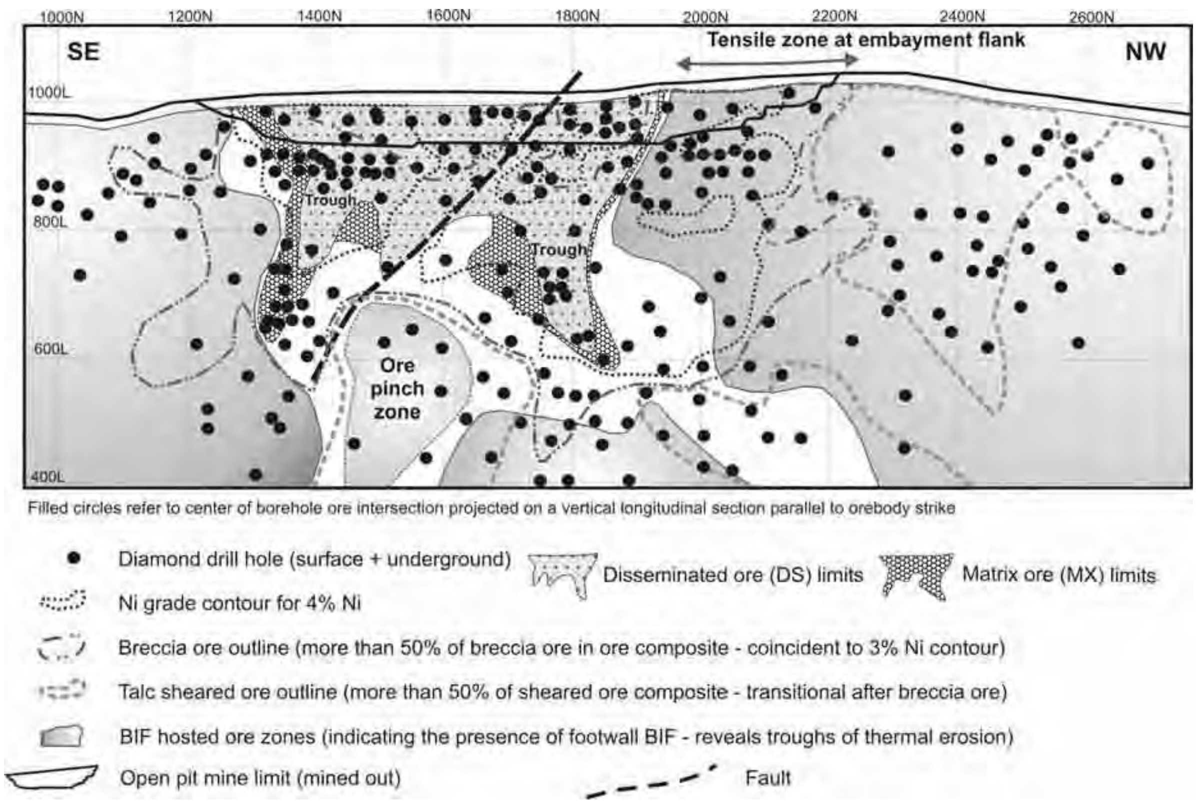

Fig. 17. Vertical longitudinal section showing broad embayment structure with troughs indicated by the presence of disseminated ore and matrix ore and the lack of BIF hosted ore (grey) indicating thermal erosion of BIF along major channels. Limits indicate contour of 4% Ni grades and 50% of breccia ore in the ore zone which corresponds to a contour of 2% Ni. Light gray thick line indicates presence of remobilized and sheared talc bearing ore (SU) indicating lateral thinning of mineralization along shear zone outside the central embayment. The outline of the shallow open pit is shown in black.

Geochemical signature as a genetic indicator

A strong effort has been focused in finding geochemical indicators to determinate between mineralized komatiites sequences from barren sequences. Barnes & Brand (1999) looked at komatiites Ni and Cr data from a compreensive literature review. Although roughly 75 percent of the data fall in a low Cr low Ni cluster of less than 4.000 ppm, -the “olivine-liquid field”-, they observed that barren and mineralized komatiite sequences show contrasting trends on plots of Cr versus Ni (Fig. 18). A high Ni low Cr ‘mineralized field` composed of sulfide bearing samples, with low Cr values, is strongly associated with lava pathways. Channelized and related thin flows are systematically depleted in cromite as channelized flow environments are dominated by more primitive magmas usually not saturated in cromite. Ponded flow facies rocks from lava lakes tipically contain cumulus chromite resulting from crystal segregation during fractionation in evolved liquids saturated in chromite. A high Cr low Ni ‘barren field` is largely made up of samples from highly fractionated lava lakes. The strong association of the barren and mineralized fields to volcanic facies indicated that ponded sheet flow and lava lake sequences would be of low potential for economic Ni deposits in contrast with the more prospective sequences from channelized flow facies (Hill, 2001, Barnes & Brand, 1999).

The Fortaleza de Minas mineralized flow has a typical high Cr ‘lava lake` signature. Even the higher Ni samples, towards the disseminated ore type, have high Cr values (Fig. 18b). The Guariroba – Peroba komatiite barren sheet flow samples fall mostly in the low Cr low Ni ‘olivine-liquid field` cluster. The Fortaleza de Minas deposit as a ponded flow facies does not support the low potential of lava lake sequences as an exploratory geochemical tool. In the same way, the Cr versus MgO plot reveals that the Fortaleza de Minas flow has a high Cr/MgO signature (Fig. 18c), in contrast with many komatiite hosted Ni deposits from Western Australia where a low Cr high MgO mineralized trend associated with channelized high MgO cumulates has been reffered to as the “Kambalda trend”.

Progressive fractioning of olivine from barren komatiite lava depletes the lava in Ni resulting in a linear positive correlation of Ni with MgO. In dynamic extrusive systems the overall level of Ni depletion is usually low and high levels of Ni depletion in host lavas are a positive sign for exploration, although little or no Ni depletion may not be a negative sign (Hill, 2001). Figure 18d shows that no signifficant Ni depletion is observed in the Fortaleza de Minas ore host flow, and there is no discriminating Ni versus MgO signature for the mineralized flow when compared with the barren sheet flows from the Guariroba – Peroba area.

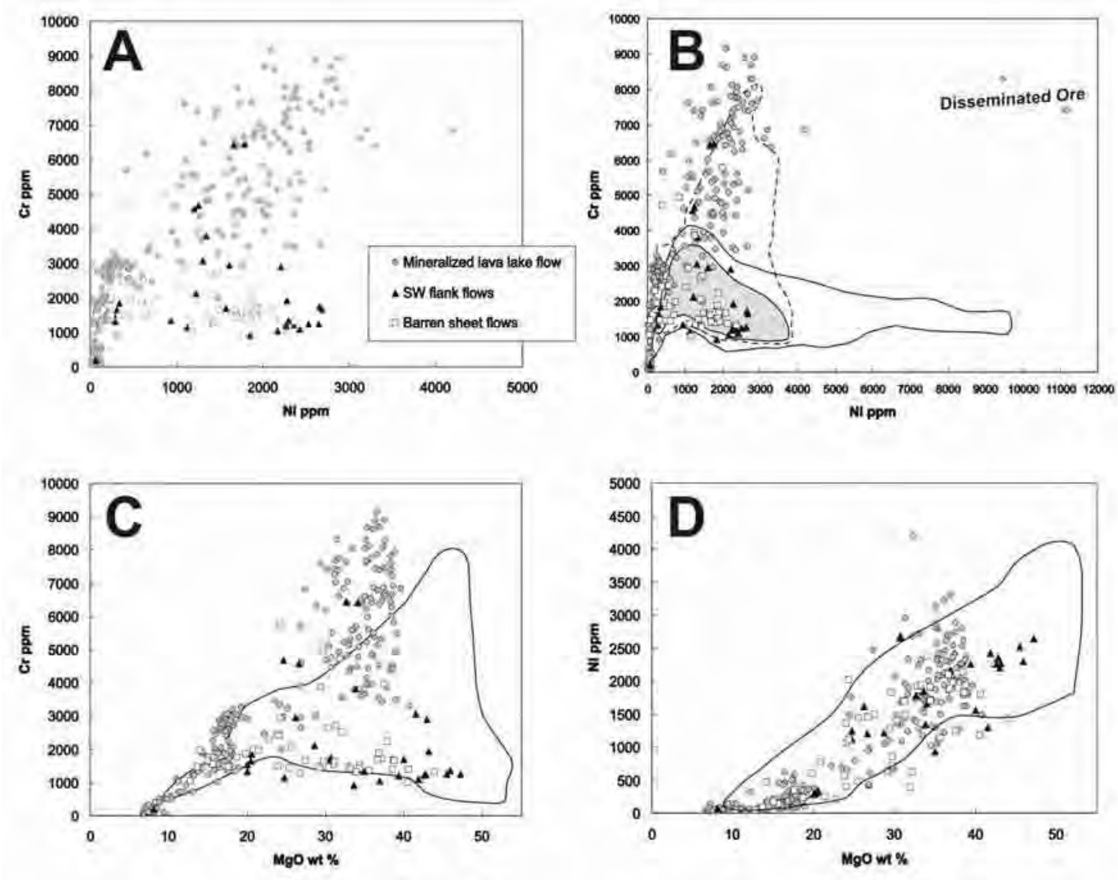

Fig. 18. Mineralized and barren komatiite whole rock plots for Cr, Ni and MgO. **a** Cr versus Ni plot of mineralized fractionated flow and barren komatiitic sheet flows. **b** Cr versus Ni plot showing barren (hatched line) and mineralized (black line) fields and the overlapping "olivine-liquid field" (grey) after Barnes & Brand, 1999. **c** Cr versus MgO plot. **d** Ni versus MgO plot. Black outlines in plots **c-d** show data density contour enclosing 90% of literature data on Al-undepleted komatiites from Archean terrains, after Barnes, Hill and Evans, 2004.

Discussion

The thick fractionated ore host flow shows remarkable differences to the typical komatiite related type 1 and type 2 deposits described in Western Australia and seems to have been formed in a large pond or lava lake oscilating from shallow to deep water environment probably at the distal portions of a lava channel (Fig. 10). Most deposits display a thick ortho-cumulate or adcumulate channelized flows with lateral thinning and development of olivine or pyroxene spinifex top zones. Most of these channelized flows are poorly fractioned. Well preserved lava channels associated to both type 1 and type 2 deposits have been recently described in the Black Swan area, Western Australia (Hill et al, 2004; Barnes et al, 2004; Dowling et al, 2004), and has also been identified in many komatiite hosted deposits (Kawahikawa et al, 1998; Barnes et al, 1998; Dowling et al, 2002; Lesher & Keays, 2002;

Beresford, 2005; Stone, 2005). Although the ore formation is essencially related with very similar ore types, the Fortaleza de Minas flow shows a significantly different environment of ore formation.

Similar highly fractionated flows are also found in Munro, Township where two thick fractionated flows occur in the same area, one komatiitic (Fred’s Flow) and the other tholeitic (Theo’s Flow) (Arndt, 1977; Arndt et al., 1977). They both display equivalent fractioned products ranging from olivine-cumulates to pyroxene-cumulates and gabbro. The major differences between them are shown in figures 19 a-b. Same chemical profiles were provided for the Fortaleza de Minas fractioned flow from selected drill holes (Fig. 19c). Although the amount of pyroxene-cumulate is close to the tholeitic flow, the MgO fractionation trend is even closer to the komatiitic Fred’s Flow. The MgO profile from Fortaleza de Minas shows a fractionation trend similar to the komatiitic flow for the olivine-cumulate. Due to metamorphism and strong shearing most of the original textures and magmatic mineralogy has been obliterated. The fine-grained zone at the top of the gabbro unit is tentatively correlated to the flow top units. The possible metamorphic equivalent of flow tops observed in cores is more likely to be derived from aphanitic pyroxenite than to spinifex. Interpreted flow tops are quite thin and were not sampled. The drop in MgO trend at the border zone (base of flow) is similar to the komatiitic Fred’s flow. Fractionated trends from the deposit lower flow units are analogous to those of the uppermost mineralized flow unit. The different flow units are always separated by thin to thick horizons of chemical sediments (BIF) and also show equivalent differentiation trend in the western limb of the syncline. They are considered all together as part of a thick highly fractionated flow.

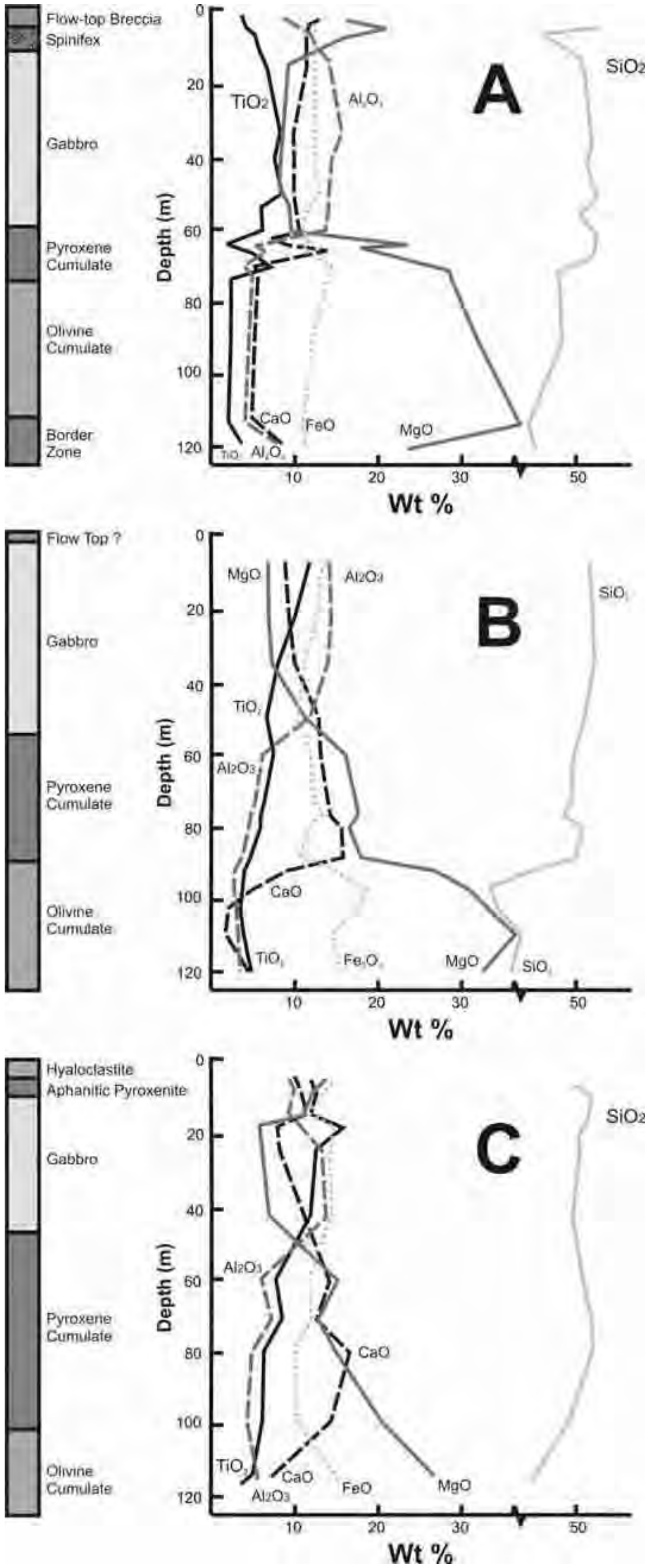

Fig. 19. Comparison between **a** Fred's Flow (komatiitic), **b** Fortaleza de Minas Flow (komatiitic), and **c** Theo's Flow (tholeitic), modified after Arndt, 77. Besides the absence of spinifex textures, the tholeitic profile display a much thicker pyroxene cumulate zone than the komatiitic profile. The thick pyroxene cumulate zone at Fortaleza de Minas display similarities with the tholeitic flow. The proportion of olivine cumulate at Fortaleza is somewhere in between the two types of flow at Munro.

Figure 20 shows the whole rock composition of Fred’s and Theo’s flows from Munro and their distinctive fractionation trends, and the Fortaleza de Minas fractionated flow for comparison. The skew to the CaO side in the pyroxene-cumulate zone from the fractionated flow is also observed in other komatiitic known areas like Barbeton (Viljoen and Viljoen, 1982).

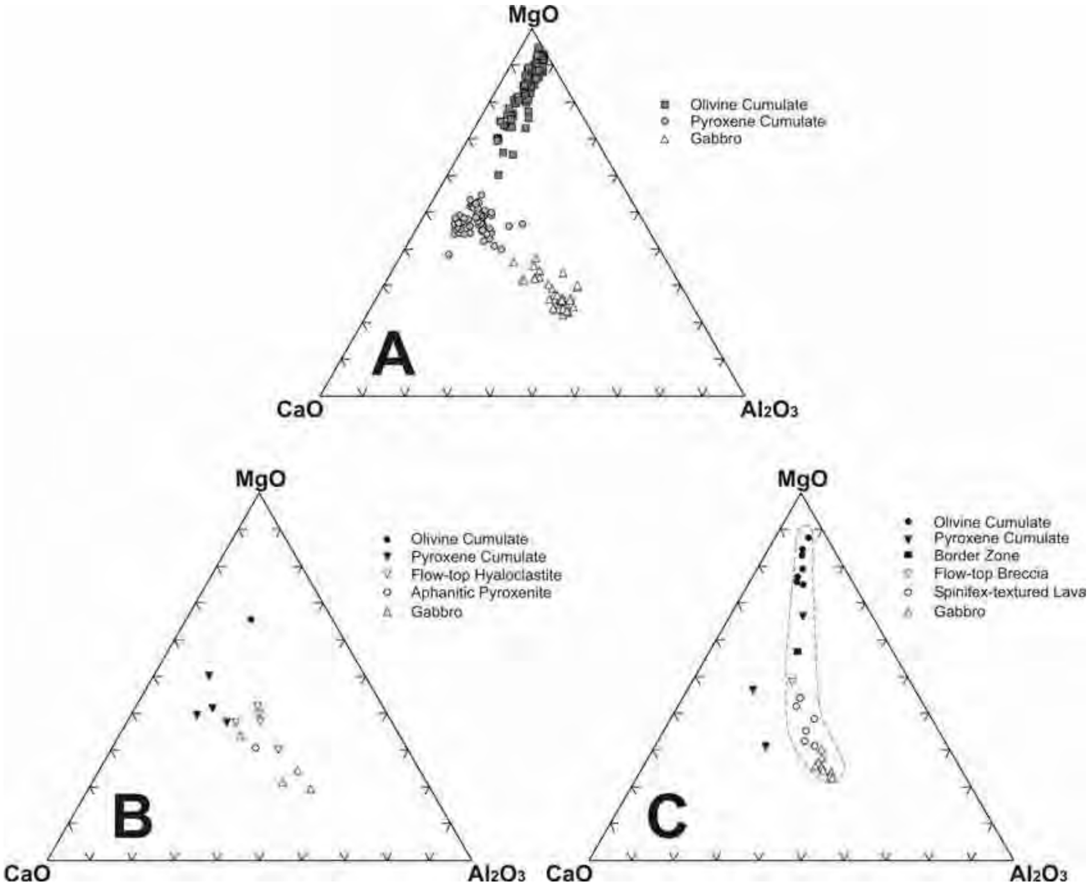

Fig. 20. Comparison of whole rock composition between Fred´s Flow and Theo´s Flow. Whole rock data from the Fortaleza de Minas deposit flows show a curved trend towards the calcium axis similar to the tholeitic flow but with olivine cumulates similar to the komatiitic flow.

Figure 21 plots TiO_2 versus MgO data for the fractionated flow with comparison to Munro komatiites and picrites from different volcanic environments. The highly fractionated flow had generated a large variation of rock types exhibiting a wider span of MgO content. According to the original Jensen classification (Fig. 9) part of the gabbro zone would fall into the tholeitic field, however this limit was later reviewed by Viljoen and Viljoen, 1982. The TiO_2 content indicates a good fit to the komatiitic field from Munro Township.

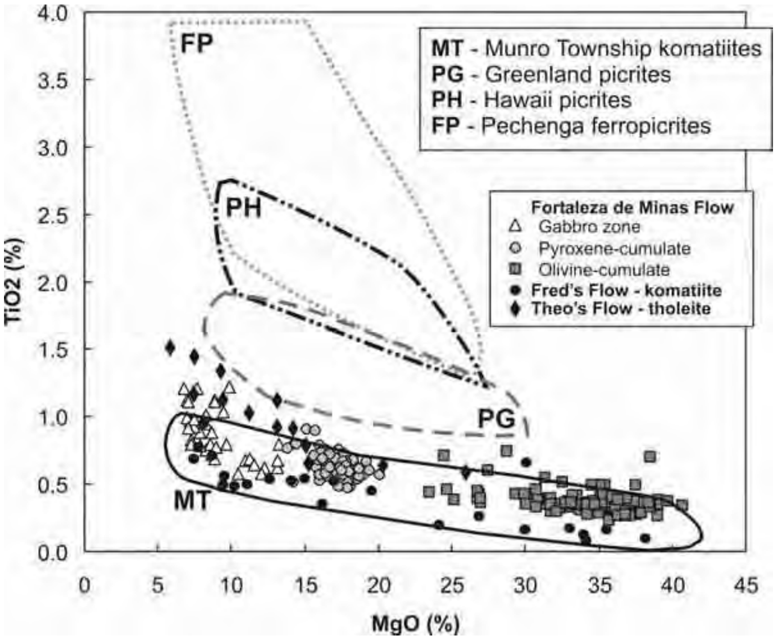

Fig. 21. TiO_2 versus MgO plot for the Fortaleza de Minas fractionated flow products and compiled samples from Fred's Flow and Theo's Flow. Plot of major compositional fields for komatiites from Munro Township and picrites from different ages and environments.

In Type 1 deposits the massive/ matrix ore hanging wall rock is typically an olivine-cumulate that occupied the lava pathway after the settling of the Ni sulfide orebody, being also chemically distinctive (Hill, 2001; Lesher and Keays, 2002). But at Fortaleza de Minas, in a lava lake environment, indications are that the deposit host is intimately related to the Ni mineralisation and there is a continuous transition of both Ni grades and sulfide content from the barren host to disseminated ore and from this to matrix ore. The ponded environment suported the high degree of fractionation and the settling of disseminated, matrix and massive ores along an open trough, possibly at the end of a lava channel in a shallow lava lake. The high Cr and the lack of Ni depletion pointed out by Oostindier et al., (1990) and the stratigraphic argument against crustal assimilation (Choudhuri et al., 1997) should be reviewed considering the distal ponded environment for this deposit, where many evidences points towards crustal assimilation related to thermo-mechanical erosion.

Conclusions

The Fortaleza de Minas deposit can be described as a Ni – Fe sulfide mineralization of Type 1 associated with komatiite flows (Lesher and Keays, 2002). The mineralization occur at an inner top zone of a thick highly fractionated flow, which has a very distinctive fractionation pattern and is distinctive from most of the typical Type 1 deposit hosts. Instead of being hosted by a typical ortho-cumulate with associated spinifex textured komatiites the Fortaleza de Minas deposit is associated with an olivine-cumulate, pyroxene-cumulate and gabbro. The high fractionation pattern observed troughout the thick flow suggests a lava pond or lava lake environment. The original composition of the magma is inferred to be positioned at the lower limit of typical komatiites, and can be classified as a pyroxenitic komatiite or a transitional type, encompassing komatiitic and basaltic komatiite composition. The pyroxenitic composition (tremolite – chlorite) of the fine grained flow top reinforces that conclusion.

Komatiite hosted deposits are not common in ponded flow facies or lava lakes and this has been reinforced in the literature by the ‘barren` Cr versus Ni signature of lava lake environment. The Fortaleza de Minas deposit has a distinctive high Cr prospective chemical signature and also a distinctive ponded facies volcanic environment with aplication in the construction of a new exploratory model for this type of deposit (high Cr and lack of Ni depletion in highly fractionated flows, associated with open embayments). In this sense lava lakes can not be excluded as a favourable environment for Ni deposits and must be reassesed worldwide.

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APPENDIX 1 - Estimation of bulk MgO composition of the fractionated flow

The Fortaleza de Minas fractionated flow has been intensely sheared and metamorphosed and therefore the olivine cumulates have been completely transformed into serpentinites and talc carbonate rocks. No original olivine and cromite has ever been detected so far in both open pit and underground mine samples or cores. The estimation of the original bulk composition must then be inferred from the proportions and average MgO contents of each fractionated zone of the flow. From the borehole database a total of 182 individual flow intersections were investigated. The true width of each flow was calculated along with true widths for the gabbro, pyroxene-cumulate and olivine-cumulate zones. The individual flows were classified into lower, intermediate and upper flow units for the SW and NE limbs of the Fortaleza de Minas Syncline. The NE limb being the mine limb and the upper flow unit the mineralized flow unit. The proportion of each fractionated unit was then calculated for each flow with the caution to minimize the effect of shearing which can be responsible for pinching out and thinning of individual units. This is particularly true for the base of the upper flow and the top of the intermediate flow in the mine NE limb. To estimate the correct proportions of primary fractionated units we should look for the less deformed zones of the flows, that is where the flows should have the fully preserved fractioned sequence. For that purpose it was considered a minimum width of 5m for each unit for average width calculation. The results are tabulated in table 5 for the major flow units for both SW and NE limbs of the Fortaleza de Minas Syncline. The average bulk MgO content was calculated weighting the proportion of each unit by its average MgO content. The data suggests that the original komatiitic magma of the Fortaleza de Minas flow should have a bulk MgO content between 18 and 23 wt% MgO. Table 5 indicates that the lower flows in the two limbs display the higher MgO content (22 wt%), followed by the intermediate flows (20 to 23 wt% MgO). The mineralized flow show lower MgO content (18 to 19 wt%) than the previous flow units. One interpretation for this gradual change in composition could be related to magma contamination by assimilation of lower MgO units. The intense deformation and shearing observed in the area severely impacted on the original distribution of the fractionated units. Although this effect was tentatively minimized by filtering the data set it is not guaranteed that this proportion is fully reliable. However the upward MgO decreasing trend in both limbs are consistent and may well reflect magmatic contamination.

Table 5. Average widths and percentage of individual flow units in the Fortaleza de Minas Syncline.

Flow unit	width (m)	% gabbro	% pyroxene-cum.	% olivine-cum.	n	%MgO
NE upper	66	47	28	25	50	18
NE interm	40	23	32	45	7	23
NE lower	31	28	28	44	2	22
SW upper	53	43	28	29	7	19
SW interm	37	37	32	31	3	20
SW lower	26	32	27	40	1	22

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