

UNIVERSIDADE ESTADUAL PAULISTA
“Júlio de Mesquita Filho”
Instituto de Geociências e Ciências Exatas
Campus de Rio Claro

FILIPPE GIOVANINI VAREJÃO

**ABORDAGEM MULTI-INDICADORES DO SISTEMA MISTO
CARBONÁTICO-SILICICLÁSTICO DA FORMAÇÃO CRATO:
EVOLUÇÃO SEDIMENTAR, PALEOGEOGRAFIA E TECTÔNICA**

Tese de Doutorado apresentada ao Instituto de Geociências e Ciências Exatas do Campus de Rio Claro, da Universidade Estadual Paulista “Júlio de Mesquita Filho”, como parte dos requisitos para obtenção do título de Doutor em Geociências e Meio Ambiente.

Orientador: Prof. Dr. Lucas Veríssimo Warren

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V292a

Varejão, Filipe Giovanini

Abordagem multi-indicadores do sistema misto carbonático-siliciclástico da Formação Crato : Evolução sedimentar, paleogeografia e tectônica / Filipe Giovanini Varejão. -- Rio Claro, 2019

163 p. : il., tabs., fotos + 1 CD-ROM

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

Orientador: Lucas Veríssimo Warren

1. Geologia estratigráfica Cretáceo. 2. Rochas sedimentares. 3. Paleontologia. 4. Sedimentos marinhos. 5. Bacias sedimentares. I. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Biblioteca do Instituto de Geociências e Ciências Exatas, Rio Claro. Dados fornecidos pelo autor(a).

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Conceito: Aprovado

Rio Claro - SP, 2 de agosto de 2019

“Conta a lenda de origem do povo Kariri que antes do mar chegar à Chapada do Araripe existiu um grande lago que deu origem aos seus antepassados. Um dia esse lago se encantou e nos tempos de hoje, de vez em quando, se apresenta para pessoas que se perdem na floresta em cima da chapada.”

AGRADECIMENTOS

A execução e sucesso de um trabalho de doutoramento muito se deve à colaboração de diversas pessoas e instituições. Em primeiro lugar não posso deixar de externar meu mais profundo reconhecimento ao meu grande amigo e orientador **Lucas Warren**, a quem muito devo por me influenciar, estimular e transformar em um cientista. Ao também grande amigo e ex-orientador **Mario Assine**, com quem toda minha jornada começou, cujo suporte e conhecimento são inestimáveis. Também não posso deixar de agradecer ao grande amigo **Marcello Simões**, que me mostrou a importância dos fósseis na análise sedimentar e pelo estímulo científico. Agradeço também à minha grande companheira **Mariza Rodrigues** que contribui sempre para meu crescimento e por me suportar em todos aspectos da minha vida.

Aos colegas do LESTE, DGA/Unesp - **Milena Rosa, Patricia Mescolotti, Amanda Santa Catharina, Paloma Lorenzo, André Santiago** – por fazerem parte do dia a dia de todos esses anos de convivência. Aos colegas do Laboratório de Paleozoologia Evolutiva, IBB/Unesp – **Suzana Matos, Victor Silva e Vitor Guerrini** – que também têm papel importante nesses anos de trabalho em conjunto.

A forma final desta tese contou com os comentários e sugestões dos professores **Claudio Ricommini, Anelize Bahniuk e Mauricio dos Santos** que em muito acrescentaram no fechamento do trabalho.

À Fundação de Amparo à Pesquisa do Estado de São Paulo (**FAPESP; 2016/13214-7**) pelo financiamento de bolsa e reserva técnica durante a execução desta tese de doutorado. O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001. Ao Projeto de Pesquisa e Desenvolvimento “Relações entre Tectônica e Sedimentação em Bacias do Interior do Nordeste do Brasil” (**Petrobas; 2014/00519-9**) pelo apoio durante os trabalhos de campo. Ao Laboratório de Análise de Minerais e Rochas (**LAMIR**) e ao Laboratório de Isótopos Estáveis (**LABISE**) pelas análises isotópicas de carbono e oxigênio. Ao Departamento de Petrologia e Metalogenia (**DPM, Unesp**) por fornecer acesso ao microscópio eletrônico de varredura (MEV) e espectroscopia de raios-X por dispersão de energia (EDS) e ao **UNESPetro** pelo uso do microscópio óptico.

RESUMO

A megassequência evaporítica transicional de idade aptiana constitui importante registro da abertura da margem equatorial brasileira, das primeiras conexões entre as águas dos oceanos Atlântico Sul e Central, e de depósitos das bacias interiores do Nordeste do Brasil. Nesse contexto, destaca-se a Formação Crato da Bacia do Araripe, composta por sucessão mista carbonática-siliciclástica com espessuras de até 90 m. A Formação Crato é mundialmente reconhecida pela excepcional preservação de fósseis continentais que conferem a unidade o status de *Konservat-Lagerstätte*. A unidade faz parte de sequência deposicional constituída pela porção superior da Formação Barbalha (predominantemente fluvial) e pela Formação Ipubi (depositada em condições evaporíticas), e é considerada como depositada em um sistema lacustre, associado à deposição deltaica nas porções proximais e carbonática nas porções bacinais. No entanto, tais interpretações vêm sendo questionadas devido a recentes descobertas de atividade microbiana nos calcários laminados da unidade. Face ao panorama exposto, este trabalho buscou aplicar abordagem calcada na análise multi-indicadores (sedimentologia, tafonomia, icnologia, estratigrafia de sequências, química orgânica, isótopos estáveis de oxigênio e carbono e análises de estrutura de deformação sin-sedimentar) dos depósitos da Formação Crato. A utilização de múltiplas técnicas de investigativas foi necessária afim de amparar a interpretação dos ambientes deposicionais, além de determinar o posicionamento estratigráfico e auxiliar na definição dos mecanismos de preservação de um dos mais importantes *Konservat-Lagerstätte* do Cretáceo mundial. Os dados apresentados nesta tese apontam para sedimentação em ambiente marinho transicional durante partes da Formação Crato. Ao menos dois ciclos transgressivos pontuados por breves incursões marinhas foram reconhecidos com base em sua associação de facies e ocorrências de dinocistos e icnofósseis tipicamente marinhos. As fases regressivas se diferenciam pela ocorrência de calcários laminados com assinaturas isotópicas tipicamente continentais. No topo da primeira fase regressiva ocorre sucessão de laminitos microbiais, estromatólitos, oncóides e trombólitos, atestando deposição dos laminitos do intervalo do Konservat-Lagerstätte em águas rasas. Esteiras microbianas são observadas recobrando e fornecendo condições ideais de fossilização. Tais evidencias e interpretações divergem das antigas hipóteses para a deposição da Formação Crato e representam inovações significativas na compreensão da evolução dos depósitos mistos da unidade.

Palavras-chave: Aptiano; microbialitos; *Konservat-Lagerstätte*; sedimentação mista; mar epicontinental.

ABSTRACT

The Aptian evaporitic transitional megasequence constitutes important register of the equatorial margin rifting, development of the seaway between the South and Central Atlantic oceans, and deposition in the interior basins of the NE Brazil. In this context, highlights the up to 90-m-thick mixed carbonate-siliciclastic succession from the Crato Formation, Araripe Basin. This unit is worldwide renowned for the exceptional preservation of terrestrial assemblages in laminated limestones and as one of the most important Cretaceous *Konservat-Lagerstätte* of the world. The occurrence of such well-preserved fossils boosted paleontological and sedimentological research focused in the origin of the laminated limestones. The Crato Formation is part of a transgressive-regressive depositional sequence of which the Barbalha (fluvial-lacustrine) and Ipubi (playa lake evaporites) formations are part. The unit is considered a lacustrine system with deltaic deposition in the shallow waters and carbonate precipitation in the basinal areas. However, these interpretations have been questioned in the last years, mainly by the discovery of microbial activity in the limestone intervals. Considering this context, the present research used a multi-proxy approach (sedimentology, taphonomy, ichnology, sequence stratigraphy, organic geochemistry, stable isotopes, and analysis of sin-sedimentary deformation structures) for the interpretation of the mixed deposits of the Crato Formation. The application of multiple techniques is considered essential to support a credible interpretation of the depositional environments, and to characterize the stratigraphic positioning, and definition of the preservational mechanisms of one of the most important Cretaceous *Konservat-Lagerstätte* in the world. The data presented herein points to marginal marine deposition during parts of the Crato Formation. At least two transgressive phases were recognized by typical facies associations and occurrence of dinocysts and marine ichnofossils. The regressive phases are highlighted by the occurrence of laminated limestones with distinctive continental isotope signature. At the top of the first regressive phase, microbial laminites, stromatolites, oncoids, and thrombolites, attests to shallow water deposition at the *Konservat-Lagerstätte* layers. Microbial mats of this interval were observed recovering fossils and potentializing mineralization of soft tissues, in a process known as “microbial entombment”. These evidences and interpretations are divergent from the old interpretations for the Crato Formation and represent significative innovations in the comprehension of mixed sedimentation in the unit.

Keywords: Aptian; microbialites; *Konservat-Lagerstätte*; mixed sedimentation; epicontinental sea

ORGANIZAÇÃO DA TESE

Esta tese foi concebida e organizada no intuito de apresentar os resultados da pesquisa em forma de artigos científicos. Estes artigos, redigidos em língua inglesa, constituem a maior parte dos capítulos e possuem listas de referências bibliográficas individuais cuja formatação atende aos padrões específicos de cada periódico para qual foram submetidos. Um breve resumo em língua portuguesa é feito antes de cada artigo a fim de contextualizar a produção no âmbito do presente documento.

O **Capítulo I** apresenta a tese, as principais problemáticas envolvidas e o objetivo do trabalho, contextualizando a área estudada em seu âmbito regional, bem como as principais metodologias aplicadas.

O **Capítulo II** apresenta a integração dos principais dados sedimentológicos, estratigráficos, estruturais e geoquímicos da Formação Crato. Os dados constam no manuscrito intitulado “*Mixed siliciclastic-carbonate sedimentation in an evolving epicontinental sea: new interpretations for the Aptian Crato Formation, Northeast Brazil*”. Este trabalho propõe um novo modelo deposicional integrado para a Formação Crato e enfatiza o primeiro registro de ingresso marinha na Bacia do Araripe.

O **Capítulo III** apresenta a primeira descrição de microbialitos da Formação Crato, incluindo estromatólitos dômicos e pseudo-colunares, estruturas sedimentares induzidas por esteiras microbianas (MISS) e oncoides. Esses dados são apresentados no artigo intitulado “*Stromatolites from the Aptian Crato Formation, a hypersaline system in the Araripe Basin, northeast Brazil*” publicado no periódico *Facies*.

A descoberta de microbialitos em diversos afloramentos da unidade nos quais estão preservados um dos mais famosos *Konservat-Lagerstätte* do Cretáceo mundial incentivou a análise conjugada das morfologias macroscópicas, microscópicas e ultraestruturais de estruturas microbianas e sua relação com a preservação excepcional de tecidos moles dos organismos fossilizados. O **Capítulo IV** aborda, dessa forma, os principais resultados obtidos na forma do manuscrito “*Exceptional preservation of soft tissues by microbial entombment: insights into the taphonomy of the Crato Konservat-Lagerstätte*” publicado no periódico *PALAIOS*. Este trabalho propõe um modelo inédito de preservação para organismos de tecido mole na Formação Crato e discute sua gênese e importância no contexto global.

No **Capítulo V** é discutida a gênese de uma importante estrutura de deformação na Formação Crato, o *loop bedding*. Tais estruturas são recorrentes no registro geológico e

usualmente interpretadas como produto de deformação sin-sedimentar gerada por abalos sísmicos. No entanto, a observação dessas estruturas em fácies predominantemente evaporíticas e em associação direta com gretas de sinerese permite interpretação alternativa. Dessa forma, o manuscrito intitulado “*Loop bedding structures: evidences of seismic activities, salt nucleation or both?*” discute a gênese evaporítica para estas estruturas.

Finalmente, o **Capítulo VI** apresenta as conclusões parciais e considerações adicionais desta tese. No **Apêndice**, consta o manuscrito intitulado “*Stromatolite fields developed in a protected rocky coastline: the shallow carbonate ramp of the Aptian Romualdo Formation (Araripe Basin, NE Brazil)*” publicado no periódico *Sedimentary Geology*, tratando da primeira descrição de estromatólitos para a Formação Romualdo e seu significado estratigráfico e paleambiental.

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I. CONSIDERAÇÕES INICIAIS

I.1. Introdução

O limite Aptiano-Albiano registra a ruptura final entre os continentes Sul-Americano e Africano (Moulin et al., 2010; Chaboureaud et al., 2012; 2013). Durante esta fase, importante troca faunística entre o paleo-oceano Tethys e o proto-oceano Atlântico Sul é reconhecida nas bacias marginais equatorial e leste brasileira, indicando que a conexão marinha entre esses oceanos se deu a partir do Aptiano (Koutsoukos et al., 1991). A correlação existente entre as curvas de isótopos estáveis de carbono e enxofre em seções carbonáticas e evaporíticas de bacias pertencentes a esses dois oceanos corroboram com a existência de um *seaway* entre esses oceanos durante o Aptiano (Tedeschi et al., 2017).

A sequência aptiana pós-rifte transicional representa o último estágio preservado no registro sedimentar da evolução do sistema de riftes do interior do continente Sul-Americano e compreende importantes sucessões transgressivas-regressivas que culminaram na deposição de depósitos marinhos epicontinentais (Assine et al., 2014; Assine et al., 2016; Custódio et al., 2017). A Formação Crato da Bacia do Araripe, destaca-se pela preservação de intervalos carbonáticos originados por atividade microbiana (Catto et al., 2016; Warren et al., 2017) associados a importantes depósitos evaporíticos da Formação Ipubi. Enquanto depósitos aptianos das bacias marginais brasileiras encontram-se abaixo de grande coluna de água e de espessa pilha de sedimentos pós-aptianos da margem passiva, a Formação Crato se destaca por consistir de excelente análogo aflorante, o que permite a realização de estudos específicos e relevantes inferências paleoambientais e paleogeográficas.

A Formação Crato é mundialmente reconhecida pela preservação excepcional de organismos terrestres fossilizados em calcários laminados, que conferem à unidade o status de *Konservat-Lagerstätte* (Martill et al., 2007a). Desde a primeira descrição de fósseis nos carbonatos da Formação Crato por Silva Santos (1947), o interesse pela taxonomia dos diversos grupos fósseis encontrados foi crescente. No entanto, trabalhos de detalhe focados na tafonomia dos organismos, nos ambientes deposicionais da unidade e no posicionamento estratigráfico das ocorrências fossilíferas são mais escassos. Com exceção de poucos resumos publicados em congressos (Santos, 1982) e teses de doutoramento (Neumann, 1999), os estudos que versam sobre a geologia da unidade estão restritos ao intervalo do *Konservat-Lagerstätte* (Heimhofer

et al., 2010) e a níveis fossilíferos específicos que são predominantemente carbonáticos (Coimbra et al., 2002; Neumann et al., 2003; Carmo et al., 2004).

Face ao panorama exposto, este trabalho teve como objetivo aplicar uma abordagem calcada na análise multi-indicadores (sedimentologia, tafonomia, icnologia, estratigrafia de sequências, química orgânica, isótopos estáveis de oxigênio e carbonos e análises de estruturas de deformação sin-sedimentar) de detalhe em toda a sucessão da Formação Crato. Este procedimento é considerado necessário para amparar uma interpretação plausível e integrada dos ambientes deposicionais visto que estudos calcados em um único tipo de análise não têm avançado substancialmente na resolução de problemas envolvendo sua origem, posicionamento estratigráfico e definição dos mecanismos de preservação de um dos mais importantes *Konservat-Lagerstätte* do Cretáceo mundial. A integração da descrição macro, micro e ultraestrutural de carbonatos aliada a dados estratigráficos, geoquímicos, e estruturais, é fundamental para a correlação regional das diversas áreas de ocorrência da unidade, bem como na caracterização de sua arquitetura deposicional e contexto paleogeográfico, permitindo a definição da extensão e posicionamento da primeira ingressão marinha no interior do continente durante os últimos momentos da fragmentação da África e América do Sul.

I.2. Objetivos

A presente tese teve como objetivo estabelecer a evolução tectono-sedimentar da Formação Crato com base em dados sedimentológicos, icnológicos, estratigráficos, e geoquímicos de detalhe. Esta abordagem inédita para a unidade permitiu a determinação segura de seu ambiente deposicional, bem como a correlação da unidade nas bacias do Araripe, Jatobá e Tucano Norte e integração de seu registro ao contexto paleogeográfico regional e aos padrões de variação isotópica e eustática globais. Como objetivos secundários, pretendeu-se identificar os mecanismos que condicionaram a sedimentação mista na bacia e determinar as condições que promoveram a excelente preservação dos fósseis desse importante *Konservat-Lagerstätte* do Cretáceo mundial.

I.3. Contexto geológico

Os eventos tectônicos responsáveis pela separação entre América do Sul e África e consequente formação do Oceano Atlântico Sul geraram uma série de bacias rifte na margem continental brasileira (Milani et al., 2007). O rifteamento deste supercontinente provocou ainda

a reativação de antigas estruturas do embasamento pré-cambriano no Nordeste do Brasil, responsável pela formação de uma série de bacias rifte interiores, em especial a Bacia do Araripe e as bacias do Recôncavo, Tucano e Jatobá (Matos, 1992; Ponte & Ponte Filho, 1996; Brito Neves et al., 2000; Assine, 2007). Essas bacias registram evolução complexa, associadas a fases tectono-sedimentares distintas e representadas basicamente por três megasequências deposicionais: pré-rifte continental, sin-rifte lacustre e pós-rifte transicional (Ponte et al., 1978; Asmus & Baisch, 1983, Chang et al., 1988; 1992; Cainelli & Mohriak, 1999; Milani et al., 2007).

A Bacia do Araripe encontra-se estruturalmente encaixada em terrenos Pré-cambrianos da Província Borborema, delimitada a sul pela Zona de Cisalhamento de Patos e a norte pelo Lineamento de Pernambuco (Matos, 1992; Brito Neves et al., 2000). Estende-se por uma área de aproximadamente 9.000 km², distribuída pelos estados do Ceará, Pernambuco, Piauí e Paraíba (Assine, 2007). A bacia se destaca geomorfologicamente pela elevação conhecida como Chapada do Araripe, limitada por escarpas erosivas e íngremes, de topo plano com mergulho suave para oeste (Morales & Assine, 2015). A topografia atual da bacia é possivelmente oriunda de recentes movimentos ao longo de falhas reversas de direção NW-SE com mergulho para NE, associados a uma fase de inversão causada por esforços compressivos relacionados à movimentação da placa de Nazca e da cordilheira meso-oceânica (Assumpção, 1992; Coblenz & Richardson, 1996; Cogné et al., 2012; Marques & Moulin, 2011). Dados gravimétricos e magnetométricos (Castro & Castelo Branco, 1999) mostram que a Bacia do Araripe é dividida em duas sub-bacias, a de Feira Nova e a do Cariri, separadas entre si pelo Alto de Dom Leme (Matos, 1992). Por outro lado, assume-se que depósitos da fase pós-rifte (*sag*) ultrapassem os limites da bacia, recobrando o embasamento pré-cambriano (Assine, 2007; Assine et al., 2014).

A sucessão pós-rifte transicional é composta, da base para o topo, pelas formações Barbalha, Crato, Ipubi e Romualdo, que compõem o Grupo Santana (Assine et al., 2014). Além da Bacia do Araripe, unidades correlatas também ocorrem preservadas em dois morros-testemunho na Bacia do Jatobá (Serra Negra e Serra do Periquito) e na Serra do Tonã na Bacia do Tucano Norte (Varejão et al., 2016; Fig. 1). Na Bacia do Jatobá, o registro pós-rifte é representado pelas formações Marizal (correlata à Formação Barbalha), Crato, Romualdo e Exu (Neumann & Rocha, 2014). A preservação dos estratos aptiano-albianos diminui para sul, sendo que na Bacia do Tucano, apenas as formações Marizal e Crato compõem a estratigrafia da sucessão pós-rifte local (Varejão et al., 2016; Freitas et al., 2017).

Após a fase de ruptura, as bacias interiores e da margem continental do nordeste brasileiro sofreram importante soerguimento, responsável pela elevação de blocos altos a patamares muito acima do nível do mar (Magnavita et al., 1994; Japsen et al., 2012). Estas porções soerguidas das bacias foram então denudadas em sucessivos eventos que perduraram desde o Cretáceo Superior (Campaniano) até o Mioceno (Morais-Neto et al., 2009; Japsen et al., 2012; Marques et al., 2014). A remoção por erosão de boa parte dos depósitos das bacias do sistema de riftes Reconcavo-Tucano-Jatobá, porção marinha proximal (*onshore*) da Bacia de Sergipe-Alagoas e Bacia do Araripe, acarretou na separação geográfica do registro da fase pós-rifte dessas bacias.

Dentre as unidades que compõem a sucessão transicional a que mais se destaca é a Formação Crato. Isso se deve ao fato desta apresentar registro fóssil abundante e com preservação única, o que faz dela um importante *Konservat-Lagerstätte* do Cretáceo mundial (Martill et al., 2007a). Os fósseis mais representativos da assembleia faunística incluem insetos, crustáceos, aracnídeos, pequenos peixes, quelônios e pterossauros (Martill et al., 2007a; Assine, 2007). Já sua flora fóssil é constituída principalmente por gimnospermas e representantes da fase inicial de diversificação das angiospermas (Martill et al., 2007a). Esta rica associação fossilífera é caracterizada ainda pela aparente ausência de formas marinhas, sugerindo que os sedimentos carbonáticos que contém estes organismos tenham se depositado em condição lacustre (Neumann, 1999; Neumann et al., 2003).

Do ponto de vista litológico, a Formação Crato é composta principalmente por camadas carbonáticas métricas, intercaladas a sucessões igualmente espessas de folhelhos verdes e arenitos finos a grossos, compondo uma seção média de aproximadamente 60 m de espessura (Neumann, 1999; Neumann et al., 2003). A deposição dos calcários laminados diretamente sobre o embasamento atesta a ampliação da área de deposição para além dos limites da bacia (Assine, 2007). A alternância de bancos de calcários laminados, e de intervalos dominados por fácies siliciclásticas são interpretados como o produto de momentos de expansão e retração de sistemas lacustres, constituindo ciclos transgressivo-regressivos (Neumann, 1999; Neumann et al., 2003). Pseudomorfo de halita são encontrados nos carbonatos e evidenciam que a bacia também experimentou flutuações climáticas, em condições de crescente aridez (Martill et al., 2007b; Heimhofer et al., 2010). Brechas carbonáticas no topo da sucessão carbonática, bem como a presença de paleossolos na parte superior de alguns níveis calcários da Formação Crato (Silva, 1986), sugerem eventos de queda do nível dos lagos, com exposição subaérea das áreas marginais emersas associada a crescente aridização (Assine, 2007).

I.4. Métodos

I.4.1. Análise de fácies sedimentares

Para a descrição das fácies foram adotados procedimentos usuais na descrição e interpretação de fácies sedimentares. Cada fácies sedimentar é compreendida como um corpo de rocha individual caracterizado por seus atributos físicos, não confinado a uma posição estratigráfica e definido a partir de critérios descritivos (Walker, 1992). Além das características físicas, cada fácies foi descrita de acordo com seu conteúdo fóssil e icnofóssil. A descrição de icnofósseis é particularmente importante em casos nos quais a preservação de fósseis é ausente (Buatois & Mángano, 2011) como nos intervalos siliciclásticos da Formação Crato. Os traços fósseis foram descritos em campo de acordo com sua morfologia e toponímia, seguindo os protocolos de descrição e classificação do modo de preservação e ocorrência (Buatois & Mángano, 2011). O grau de bioturbação foi estimado com base no esquema de Taylor & Goldring (1993), que definiram o índice de bioturbação (BI index) variando de 0 (sem bioturbação) a 6 (totalmente bioturbado).

Ao todo, foram medidos sete perfis estratigráficos verticais nas adjacências dos municípios de Nova Olinda, Santana do Cariri, Crato, Barbalha e Jardins (Bacia do Araripe) e descritos quatro testemunhos de sondagem, sendo dois na Bacia do Araripe (SE-19 e 2-AP-RM-01) e dois na Bacia do Tucano Norte (2-TN-3a-BA e 2-TN-SM-BA). Dados sedimentológicos e geoquímicos de testemunho da Bacia do Jatobá foram retirados de trabalho previamente publicado (Gratzer et al., 2013). Os testemunhos utilizados são de domínio público (DNPM, Recife) e oriundos de projetos de apoio (Prof. Dr. Virgínio Neumann, UFPE). A descrição dos poços teve por objetivo adensar a malha de dados, auxiliando nas correlações interbaciais e também possibilitando a coleta de amostras sem alteração intempérica. Os principais testemunhos estão alocados na sede do DNPM em Recife e na UFPE e foram perfurados pelo Projeto Santana (PS) nos quais fácies microbianas foram identificadas (PS-11; Catto et al., 2016) e pelo Projeto Gipsita (SE) da extinta SUDENE.

A descrição macroscópica e petrográfica das rochas carbonáticas foi pautada nas classificações e protocolos estabelecidos por Dunham (1962), Embry & Klovan (1971), Buick et al. (1981), Demicco & Hardie (1994), Riding (2000) e Fairchild & Sanchez (2015). Ao todo foram confeccionadas 61 lâminas delgadas em amostras de carbonatos da Bacia do Araripe e 33 lâminas delgadas em amostras de calcário e arenito da Bacia do Tucano. A análise detalhada

dos carbonatos foi fundamental na definição dos níveis originados por comunidades microbianas, as quais têm conotação paleoambiental muito importantes, inclusive na preservação fossilífera.

Os dados obtidos em campo foram organizados e representados através de: (1) documentação fotográfica para cada fácies identificada; (2) confecção de esquemas e fotomosaicos de afloramentos; (3) montagem de perfis estratigráficos verticais de detalhe (escala 1:20). Para a interpretação paleoambiental, fácies sedimentares geneticamente relacionadas, ou seja, fácies que ocorrem associadas umas às outras e que não apresentam conotação paleoambiental, foram agrupadas em associações e sucessões verticais de fácies.

I.4.2. Análise de paleocorrentes

Estações de paleocorrentes foram estabelecidas a fim de se interpretar os padrões de paleofluxo e dispersão sedimentar atuantes durante a deposição das camadas. É importante destacar que os dados foram discriminados segundo as diferentes associações de fácies, a fim de separar paleocorrentes geradas por processos hidrodinâmicos distintos. Ao todo foram realizadas 119 medidas de superfícies deposicionais (*foresets* de estratificações cruzadas acanalada, sigmoide e hummocky), sempre que possível com a obtenção de ao menos 25 medidas por estação de coleta de dados, número mínimo recomendado para determinar o vetor médio do sentido geral de transporte sedimentar (Miall, 1974; Selley, 1982; Miall, 1996).

A definição do padrão das paleocorrentes foi fundamental na identificação de áreas-fonte da unidade e de seu mergulho deposicional, inferência da possível paleolinha de costa, além de fornecer subsídios para interpretação dos tratos de sistemas deposicionais. Constituiu, portanto, um método bastante econômico e rápido com dados adquiridos com auxílio de bússola Brunton Geo Transit e posteriormente tratados em softwares gratuitos especializados (PALEOCOR 2.0).

I.4.3. Microscopia eletrônica de varredura

Lâminas delgadas e amostras frescas de carbonato da Formação Crato foram selecionadas a fim de se investigar a origem biótica ou abiótica dos intervalos carbonáticos. A combinação entre a petrografia e o uso de microscopia eletrônica de varredura, foi essencial na seleção das amostras mais adequadas para as análises isotópicas de C e O. A hipótese de que as

fácies microbianas estão relacionadas à preservação de fósseis foi verificada, estabelecendo critérios de correlação entre ambas. Além disso, a microscopia eletrônica acoplada ao analisador semi-quantitativo EDS constituiu ferramenta fundamental na identificação dos elementos presentes na rocha e nos fósseis, sendo essencial na determinação de sua origem.

As amostras foram quebradas a fim de expor superfícies frescas e utilizadas em análises de microscopia eletrônica de varredura (MEV) e espectroscopia de raios-X por dispersão de energia (EDS), no Laboratório de Microscopia Eletrônica de Varredura (IGCE, UNESP). Estas análises buscaram caracterizar as texturas e realizar mapeamentos geoquímicos qualitativos a semi-quantitativos. O equipamento utilizado foi o microscópio eletrônico de varredura JEOL JSM-6010LA, equipado com detectores de elétrons secundários, elétrons retroespalhados e espectroscopia de raios-X por dispersão de energia.

I.4.4. Químioestratigrafia e análise de isótopos estáveis de C e O

A análise de isótopos de carbono (C) e oxigênio (O) se iniciou pela coleta seletiva de amostras em campo buscando porções da rocha não alteradas ou fraturadas. A amostragem de detalhe foi realizada a fim de refinar intervalos que necessitavam de detalhamento químioestratigráfico, principalmente pontos chave próximos às superfícies de correlação estratigráfica, porções com variação faciológica marcante e camadas fossilíferas. Nesta etapa, também foi realizado teste *in loco* para a identificação de calcita e dolomita, ora a partir da pulverização da amostra com posterior aquecimento e ataque com ácido clorídrico (HCl 10%), ora utilizando difratograma de raios-X (DRX).

Todos os exemplares coletados foram adequadamente posicionados estratigraficamente em seções colunares levantadas em escala de detalhe (1:20). A amostragem se deu em litotipos carbonáticos coletados a aproximadamente cada 30 centímetros em sucessões litologicamente homogêneas ou respeitando a variação de fácies sedimentares. O procedimento laboratorial para as amostras previamente selecionadas compreendeu inicialmente a escolha de pontos ideais de amostragem por meio de análise petrográfica buscando locais com a textura original da rocha preservada, evitando-se assim fraturas, estilólitos, vênulas microscópicas e porções diageneticamente ou pedogeneticamente alteradas, além de fração terrígena. Após a etapa de seleção das áreas adequadas à amostragem, foi realizada a extração de pequenas porções pulverizadas com broca milimétrica diamantada, posteriormente armazenadas em recipientes herméticos individuais do tipo *eppendorf*.

As análises de isótopos de C e O, bem como a determinação das razões isotópicas de Sr, foram realizadas no Laboratório de Isótopos Estáveis (NEG-LABISE) da Universidade Federal de Pernambuco e no Laboratório de Análise de Minerais e Rochas (LAMIR) da Universidade Federal do Paraná. Ao todo foram analisadas 212 amostras, sendo que 127 análises foram realizadas no NEG-LABISE e 85 no LAMIR. Segundo procedimento usual para a análise isotópica de elementos leves, inicialmente foi realizada a extração de gás CO² de amostras pulverizadas a partir da reação com ácido fosfórico 100% à temperatura constante de 25°C durante 24 ou 72 horas, dependendo da razão entre material calcítico e dolomítico. Após a extração do gás, este foi purificado criogenicamente a partir de uso de armadilha química de nitrogênio líquido e álcool, a fim de se retirar a água gerada durante a reação entre o carbonato e o ácido. A amostra de gás foi então analisada em espectrômetro de massa SIRA II de dupla admissão e coletor triplo do NEG-LABISE e em espectrômetro de massa Delta Advantage do LAMIR. Os resultados são apresentados na notação "*per mil*" referentes ao padrão VPDB (Viena - "*Pee Dee Belemnite*").

O estabelecimento do arcabouço quimioestratigráfico integrado da Formação Crato foi fundamental para a correlação das diversas sucessões analisadas e comparação com padrões globais de variações de C e O para o intervalo estudado. A correspondência de valores locais com a curva marinha global e com dados publicados em depósitos coevos foi também essencial no estabelecimento e entendimento de como a ingressão marinha afetou a deposição da Formação Crato.

I.4.5. Geoquímica orgânica

O teor de carbono orgânico total (COT) e de enxofre (S) de 89 amostras de folhelhos e carbonatos foi determinado por meio da combustão das amostras pulverizadas (250 g) e acidificadas com ácido clorídrico (HCl), utilizando o analisador LECO SC-144 com detector de infravermelho, utilizando método proposto pelo *American Society for Testing and Materials* (ASTM D-4239). A alíquota de amostra não eliminada pelo ataque ácido foi separada para ser utilizada na análise, bem como, para o cálculo do resíduo insolúvel (RI). As análises foram realizadas no Laboratório de Palinofácies e Fácias Orgânicas (LAFO) da UFRJ, coordenado pelo Prof. Dr. João Graciano Mendonça Filho, em parceria com o projeto Petrobras (SIGITEC 2014/00519-9) coordenado pelo Prof. Dr. Mario Luis Assine e que está associado à presente pesquisa.

Além do teor de COT e S também foi definido o conteúdo palinológico das amostras (fitoclastos, palinomorfos e matéria orgânica amorfa). As análises qualitativas, com a identificação das partículas, e quantitativa, com a contagem de 300 a 400 partículas, foram realizadas em lâminas organopalinológicas usando luz transmitida e fluorescência. Todas as amostras foram preparadas e analisadas no LAFO-UFRJ.

A determinação dos teores orgânicos em carbonatos e folhelhos e do conteúdo palinológico foi de extrema importância para análise integrada com dados geoquímicos e a definição dos ambientes deposicionais, das condições químicas da água e para correlações estratigráficas e posicionamento de superfícies-chave.

I.4.6. Análise de Sequências e correlações estratigráficas

Os perfis estratigráficos verticais foram integrados aos demais dados analisados a fim de identificar discontinuidades no registro sedimentar e limites de sequências, superfícies transgressivas e de inundação máxima, padrões de variação arquitetural nas associações de fácies, tratos de sistemas deposicionais e ciclos de diferentes frequências.

Para tal finalidade foram empregadas técnicas de análise e correlação provenientes do método de Estratigrafia de Sequências atrelados à análise de multi-indicadores. Em linhas gerais, este método permite interpretar espessas sucessões sedimentares do ponto de vista genético, geométrico e evolutivo, bem como efetuar correlações de diferentes sucessões em nível de bacia (Vail et al., 1977; Van Wagoner, 1988; Posamentier, 1988). A correlação do registro estratigráfico das bacias analisadas permite verificar se os eventos registrados localmente são reconhecidos em escala bacinal (regional), sejam eles de natureza eustática, climática ou tectônica. Os dados referentes à proveniência sedimentar foram reavaliados e integrados às informações existentes na literatura, de modo a estabelecer cenários paleogeográficos e paleotectônicos adequados.

I.4.7. Análise da deformação sin-sedimentar

Estruturas de deformação em sedimentos inconsolidados (soft-sediment deformation structures) ocorrem em sedimentos pouco coesivos ou não coesivos submetidos a eventos de deformação durante sua deposição o logo após o início do soterramento (Owen & Moretti, 2011). Tais estruturas são comuns na Formação Crato e observadas em intervalos restritos,

relacionadas de forma direta com superfícies estratigráficas. Nos trabalhos de campo foram descritas e medidas feições de deformação sin-sedimentar e analisadas as relações destas com as fácies afetadas. Esta análise foi fundamental para avaliar a influência ou não da tectônica na sedimentação, bem como o controle de possíveis reativações no padrão sedimentar misto da unidade. Neste contexto, foram identificadas e classificadas estruturas de deformação associadas ou não com atividade tectônica (Owen & Moretti, 2010). A identificação da origem sísmica para estruturas de deformação sin-sedimentar é complexa e sua caracterização como tal é controversa. Nesse sentido, procurou-se descrever as estruturas de deformação em campo e a partir de fotografias, relacionando-as com as estruturas e litologias adjacentes a fim de descartar quaisquer outros agentes desencadeadores (*e.g.*, pegadas, estruturas evaporíticas, estrutura de sobrecarga).

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II. SEDIMENTAÇÃO MISTA CARBONÁTICA-SILICICLÁSTICA EM MAR EPICONTINENTAL: NOVAS INTERPRETAÇÕES PARA A FORMAÇÃO CRATO

A Formação Crato de idade aptiana pode alcançar até 90 m de espessura e é interpretada como sistema lacustre, alternando depósitos siliciclásticos e carbonáticos (Neumann et al., 2003). A unidade é mundialmente reconhecida em função de seus calcários laminados portadores de fósseis excepcionalmente bem preservados, contendo partes esqueléticas e tecidos moles (Martill et al., 2007). Este intervalo é interpretado como produto de precipitação química

em porções euxínicas e distais do sistema lacustre (Heimhofer et al., 2010). Pesquisas recentes (Catto et al., 2016) apontam para atividade microbiana em águas rasas e oxigenadas para estes depósitos, inaugurando novas perspectivas para interpretações paleoambientais na unidade. No presente capítulo são descritas e associadas as fácies sedimentares da Formação Crato, integrando-as ao conceito de Estratigrafia de Sequências, a fim de elaborar arcabouço completo para interpretações paleoambientais e paleogeográficas. O trabalho é galgado na aplicação integrada de diversas metodologias, tais como sedimentologia, icnologia, tafonomia, estratigrafia e geoquímica. Os dados adquiridos na Bacia do Araripe foram também integrados a dados publicados e inéditos adquiridos nas bacias do Jatobá e Tucano Norte, nas quais a unidade também se encontra preservada. Os dados foram tratados de forma conjunta e constituem o manuscrito intitulado “*Mixed siliciclastic-carbonate sedimentation in an evolving epicontinental sea: new interpretations for the Aptian Crato Formation, Northeast Brazil*”.

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Mixed siliciclastic-carbonate sedimentation in an evolving epicontinental sea: new interpretations for the Aptian Crato Formation, Araripe Basin, NE Brazil

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ABSTRACT

The Aptian evaporitic transitional megasequence of the Brazilian marginal basins records the first connection between the Central and South Atlantic oceans. This particular succession is fully covered by thick post-Aptian passive margin deposits and ultra-deep waters. In contrast, well-preserved Aptian strata crop out in the interior basins of northeastern Brazil. The Aptian Crato Formation is a geological unit in the Araripe Basin, interpreted as an isolate lacustrine system that allowed the exceptional preservation of a rich fossil assemblage. Herein, new sedimentologic, geochemistry and stratigraphic data are presented, and a new interpretation is done based on an integrated multi-proxy approach, allowing a novel interpretation of the depositional evolution of the Crato Formation through geologic time. During a pronounced transgressive phase, alluvial beds transitioned to lacustrine deposits with increased salinity, culminating into the worldwide famous Crato Konservat-Lagerstätte beds. The rise of sea-level and the rapid increase in the accommodation space due to tectonic reactivation, triggered the deposition of a tide-dominated succession characterized by the presence of typical transitional facies and marine/brackish benthic invertebrates and trace fossils. This is the oldest evidence of epicontinental marine ingression in the interior of Northeast Brazil during the Cretaceous. Regressive facies are recorded in the top of the succession and document the reestablishment of lacustrine environments that culminated with the deposition of playa lake evaporites. The stratigraphic architecture and paleocurrents suggest that marine waters reached the basin coming from the south. Detailed stable isotope curves revealed significant variations in salinity

and primary productivity mainly due to the restriction/connection of the waterbody with the ocean system. This unequivocally record the first brief marine ingressions of the newly formed South Atlantic Ocean over the interior basins of the northeast Brazil. Finally, the Crato Formation constitutes a fine analogue to the Pre-Salt succession and a key record of the extent of the evaporitic transitional phase in the interior basins of the northeastern Brazilian territory.

Keywords epicontinental marine ingressions, mixed carbonate-siliciclastic system, Cretaceous Konservat-Lagerstätte, Pre-Salt analogue, Aptian.

INTRODUCTION

The Aptian transitional evaporitic megasequence (*sensu* Chang et al., 1988) records the final geological events in the Equatorial Marginal basins tied to the breakup between Africa and South America (Matos, 1992). It consists of complex mixed carbonate-evaporite-siliciclastic successions, developed in the Brazilian marginal basins as well as in the interior rift basins of northeastern Brazil, with significant hydrocarbon reserves. Carbon isotope curves reveal that the evaporites and carbonates from the South Atlantic sector are correlate with those of Tethyan sector, showing that marine connection between these distinct segments occurred during the Aptian (Tedeschi et al., 2017). Marine flooding took place during the rifting of the Brazilian equatorial margin (Koutsoukos et al., 1991), when most of the interior basins of the NE Brazil were in development. While the marginal basins and thick sedimentary successions (i.e., post Aptian passive margin deposits) are nowadays under ultradeep waters (> 2000 m), well preserved and exposed Aptian strata crop out in the Araripe, Tucano and Jatobá basins in the interior of NE Brazil. Therefore, these basins provide substantial and relevant source of information for paleoenvironmental and paleogeographic reconstitutions during Aptian times.

The Aptian pre-salt Crato Formation of the Araripe Basin (Fig. 1 A) is a key sedimentary archive. Sedimentary rocks of this unit are also recorded in the Tucano and Jatobá basins (Varejão et al., 2016; Figure 1 B), forming a fragmented record of the Aptian in the interior of northeastern Brazil. The Crato Formation is worldwide renowned for its rich and diverse fossil record, which is exceptionally well preserved in lacustrine laminated limestones that boosted most of the paleontological and sedimentological research in the Araripe Basin (Martill et al., 2007a; Heimhofer et al., 2010). However, an integrated and detailed sedimentological, stratigraphic, geochemical and paleontological study encompassing the entire unit is still lacking. Yet, the unit is key to our knowledge of the spatial-temporal distribution of the marine

ingressions that flooded the rift system basins developed in the northeastern interior of the Brazilian territory.

Based on the absence of marine fossils (Neumann et al., 2003; Heimhofer et al., 2010) and the occurrence of conchostracans, ostracodes and continental fossils in specific intervals (e.g., Coimbra et al., 2002; Neumann et al., 2003; Heimhofer et al., 2010), the Crato Formation was interpreted as a mixed carbonate-siliciclastic succession deposited in a lacustrine system. The recent discovery of widespread microbially-induced sedimentary structures in the laminated limestones in direct association with well-preserved fossils indicates that carbonate precipitation was probably mediated by microbes, under shallow water conditions (Catto et al., 2016; Warren et al., 2017). These microbialites also played a key role in the soft-tissue conservation of exceptionally preserved fossils, providing ideal conditions for rapid entombment and anoxia (Warren et al., 2017). Moreover, the occurrence of typical continental allochthonous fossils (e.g., pterosaurs, angiosperms, conchostracans) in some particular stratigraphic intervals (all associated to limestone beds), does not necessarily indicate that the whole unit was exclusively deposited under lacustrine conditions. Indeed, the presence of possible marine (or brackish) bivalves (see Bruno and Hessel, 2006) in the Crato Formation suggests that the depositional history of this unit must be deeply reevaluated. In this context, the Crato Formation seems to be the product of combined climatic, tectonic and eustatic variations, conditioning both continental and marine sedimentation.

Herein, a multi-proxy (i.e., sedimentologic, paleontological, litho-, and chemo-stratigraphic) analysis was conducted along the whole sedimentary succession of the Crato Formation in distinct areas of the Araripe Basin in order to: (a) better understand the sedimentary environments and associated depositional history, particularly of those intervals linked to the marine ingressions and (b) establish a stratigraphic-sedimentologic framework to the fossil-rich deposits of the Crato Formation. Integration of such data allowed us to construct a novel depositional model for the unit, with relevant implications to our understandings of the epicontinental marine sedimentation within the Araripe Basin, and the geological evolution of the NE Brazilian interior. Finally, the timing and place of the Aptian marine ingressions pathway is a key piece to better understand the formation of the Pre-Salt petroleum systems and the initial stages of the break-up between South America and Africa.

GEOLOGICAL SETTING

The tectonic events responsible for the Gondwana break-up and the origin of the South Atlantic Ocean generated several rift basins in the Brazilian continental margins (Chang et al., 1992; Matos, 1992). This intense distensive process also produced the reactivation of pre-Cambrian basement structures in the NE Brazil, triggering the formation of several basins in the EBRS, specially the Potiguar, Araripe, Recôncavo, Tucano and Jatobá basins (Matos, 1992; Brito Neves et al., 2000). These basins have complex geological evolution tied to distinct tectono-stratigraphic phases, as follows: (a) continental pre-rift, (b) lacustrine syn-rift and (c) transitional evaporite phase (Chang et al., 1988; Cainelli and Mohriak, 1999).

The Araripe Basin is structurally fitted in a pre-Cambrian shear zone located in the Borborema Province, bounded in the south by the Pernambuco Lineament and in the north by the Patos Lineament (Matos, 1992; Brito Neves et al., 2000). It has an area of approximately 9.000 km² distributed in the states of Ceará, Pernambuco, Piauí and Paraíba. Gravimetric and magnetometry data (Castro and Castelo Branco, 1999) show that the syn-rift phase of the Araripe Basin was deposited in two distinct depocenters separated by the Dom Leme High, constituting the Feira Nova and Cariri sub-basins (Matos, 1992). On the other hand, the later transitional evaporite phase is assumed to overlap the basin original limits (Assine et al., 2014). Presently, the basin rocks constitute a remarkable > 900-m-high geomorphic structure known as Araripe Plateau, surrounded by steep and erosive scarps and with plane top slightly dipping to the west (Morales and Assine, 2015). Locally, the plateau is a prominent relict structure resulting of the effects of post-Cretaceous landform regional evolution (Peulvast et al., 2008). The topography of the basin is related to reactivations of recent reverse faults with NW-SE direction and dipping to NE, associated with an inversion phase caused by the compressive stress originated by the Nazca plate and the meso-oceanic ridge movements (Marques and Moulin, 2011).

In the Araripe Basin, the Aptian transitional phase is represented by the Barbalha, Crato, Ipubi and Romualdo Formations that integrate the Santana Group (Assine et al., 2014). These units are also preserved as scattered occurrences in other EBRS, such as the Jatobá (Serra Negra and Serra do Periquito plateaus) and North Tucano (Tonã Hill) basins (Varejão et al., 2016) (Fig. 1 B). The Crato Formation is one of the main records of the evaporitic transitional phase in the NE Brazil. The unit holds a world-famous fossil-rich deposit yielding exceptionally preserved continental fossils, making it one the most important Cretaceous insect-bearing Konservat-Lagerstätte (Hedges et al., 2008). Arthropods, fishes, turtles, pterosaurs, gymnosperms, mushrooms and early flowering plants are the best-preserved fossils (Maisey,

1991; Martill et al., 2007a). Notably, true marine fossils are missing, a fact used to assume a lacustrine origin to the whole unit (Coimbra et al., 2002; Neumann et al., 2003; Heimhofer et al., 2010).

The Crato Formation is a ~90-m-thick succession of meter-scale limestone banks interbedded with equally thick beds of shales and sandstones (Assine et al., 2014). The alternation of carbonate-siliciclastic beds representing transgressive-regressive cycles is interpreted as a product of periods of expansion and retraction of the lacustrine system (Neumann et al., 2003). Presence of halite pseudomorphs in the limestone beds are direct evidence that the basin experienced climatic variations with increasing arid and evaporitic conditions (Martill et al., 2007b; Heimhofer et al., 2010; Warren et al., 2017). Carbonate breccias and paleosols in the top of the unit point to a base level drop with subaerial exposition of its marginal areas (Assine, 2007). Microbialites are observed in different stratigraphic levels within the Crato Formation, suggesting that the bottom of the hypersaline lakes was probably covered by biomats and that the deposition of the laminated limestones was strongly influenced by microbial activity in shallow water settings (Catto et al., 2016; Warren et al., 2017).

METHODS AND MATERIALS

An integrated study was conducted through regional stratigraphic mapping in combination with high-resolution outcrop logging, description of available drill hole cores, and paleocurrent analyses. The facies analysis was based in various attributes, such as the geometry, texture, sedimentary structures, paleocurrents, taphonomy, body fossil content, and trace fossil associations recorded in the examined deposits as well as geochemical data when available (see below). These allowed the description of the spatial and temporal evolution of distinctive successions of mixed carbonate-siliciclastic deposits that accumulated in a range of sedimentary environments in the Aptian evaporitic transitional sequence of the Araripe, Tucano and Jatobá basins.

At least, eight columnar sections were measured and two drill hole cores (SE-19 and 2-AP-RM-01) described in the Araripe Basin and two others (2-TN-3a-BA and 2-TN-SM-BA) in the Tucano Basin. Sedimentological and geochemical data from the Jatobá Basin was compiled from the literature (Gratzer et al., 2013), and part of the stable isotope data from the Tucano Basin was provided by Silveira et al. (2014). The columnar sections are described in high detail information on sedimentary facies, paleocurrents, coupled with chemostratigraphic values.

Samples were collected during the fieldwork activities and photographs were taken in order to document the different lithofacies.

Trace-fossils are commonly preserved in sedimentary successions that lack preserved body fossils (Buatois and Mángano, 2011) and in the Crato Formation the macrofossils are mostly found in laminated limestone facies, while only a few (i.e., conchostracans, ostracodes, bivalves, gastropods) are preserved in the siliciclastic intervals. Thus, while limestones lack bioturbation, interbedded sandstones, shales, mudstones and heterolithic facies can be highly bioturbated and/or record abundant trace-fossil content. The description of the trace-fossils followed Buatois and Mángano (2011) and were associated to the respective sedimentary structures and lithology in which they are recorded. When possible, the traces-fossils were ranked at the ichnogenus level. The degree of bioturbation was also estimated based on the Taylor and Goldring (1993) scheme, who defined a bioturbation index (BI), ranging from zero (no bioturbation) to six (complete bioturbated).

Detailed paleocurrent and lithofacies data were precisely constrained on the measured sections. Paleocurrent data was determined based on the measurement of 119 depositional surfaces (i.e., foresets and trough forms exposed on well-exposed bedding surfaces). This sediment provenance investigation was undertaken to identify sediment-source areas and to establish regional palaeoflow trends of the distinct sedimentary environments within the Crato Formation.

Samples (192) were collected in the different limestone intervals of the measured sections of the Araripe Basin and in drill hole cores from the Tucano Basin to construct carbon and oxygen isotopic curves for inter- and intra-basin correlations. The carbonate powders were gathered by microdrilling of homogeneous samples avoiding fractured, weathered, and mineral-filled zones. Powders were reacted with 100% H_3PO_4 under He atmospheric conditions. The carbon and oxygen isotopic compositions of the CO_2 extracted through the process were then measured in a Delta Advantage mass spectrometer in the Laboratory of Minerals and Rocks Analysis (LAMIR) from the Federal University of Paraná (UFPR). Isotopic results are reported in the conventional per-mil delta notation ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) with respect to Vienna Pee Dee Belemnite (VPDB). We also used available isotopic data from the Crato interval of the Jatobá Basin (Gratzer et al., 2013) for correlation purposes.

A total of 67 samples were analyzed to the definition of the total organic carbon (TOC), total sulfur (TS) and palynological (phytoclasts, palynomorphs and amorph organic matter) content of shales and carbonate facies from the Crato Formation and transition facies of the lower Barbalha and upper Ipubi Formations. The TOC and TS samples were powdered and

acidified with HCl for elimination of the carbonate mineral fraction and analyzed in a SC-144 DR using the method proposed by the American Society for Testing and Materials (ASTM D-4239). Qualitative (identification of particles) and quantitative (300 to 400 counted particles) analysis were made in organopalynological thin sections using transmitted light and fluorescence. All samples were prepared and analyzed in the Laboratory of Microfossils Preparation, Department of Geology, Federal University of Rio de Janeiro (UFRJ).

FACIES ASSOCIATIONS

The sedimentary succession of the Crato Formation in the Araripe Basin and the stratigraphic position of the facies associations and its stratigraphic framework are recorded are shown in figure 2. The integrated analysis with the Barbalha, Ipubi and Romualdo Formations is also shown to provide a robust stratigraphic framework for the Aptian evaporitic transitional phase in the Araripe Basin, and to support its correlation with coeval strata elsewhere.

Meandering channels (FA-1)

Description

This facies association is characterized by meter-thick fining-upward cycles comprising, from base to top, conglomerates, pebbly sandstones and mudstones. Conglomerates are clast-supported (quartz vein, sandstone, mudstone), with clasts varying in size from granule to pebble, and a coarse-grained sandstone matrix. Beds usually presents a lenticular geometry, vertically and laterally transitioning to poorly-selected, medium to coarse grained pebbly sandstones organized in tabular to scour and fill sets with trough cross-stratification (Fig. 3 A). Granules are dispersed or accompanying foresets, while mud intraclasts are abundant at the base of sets. Sandstone beds are laterally continuous for dozens of meters and transition to decimeter-thick tabular beds of red-colored mudstones with root-marks. Paleocurrent data are unimodal and may be dispersed by an angle of up to 120°, presenting medium azimuth to south-southwest (Fig. 2). This facies association laterally and vertically transition to terminal splay and ephemeral lacustrine facies.

Interpretation

The fining upward succession is interpreted to be deposited in a meandering alluvial system characterized by unconnected channels separated by fluvial plains (Fisher et al., 2008). Scour and fill coarse-grained sandstone beds with conglomerate lenses are characteristic of fluvial bar accretion and channel deposits, while mudstones with root marks are common in

overbank areas. The association with terminal slays (FA-3) suggests a low gradient alluvial plain system that was later drowned by a lacustrine system (FA-2, FA-4). This facies association correspond exclusively to the deposits of the Barbalha Formation.

Terminal splay (FA-2)

Description

Up to 4-m-thick coarsening-upward cycles of shales, heterolithic beds and sandstones differentiate this facies association. These cycles begin with decimeter-thick tabular beds of shales usually with compressed carbonized plant fragments that rapidly transition to linsen and wavy heterolithic facies with moderate (BI 2) bioturbation degree (Fig. 3 B). At the top, well-selected sandstones (mainly quartz and mica) include decimeter-thick beds with ripple cross-lamination, horizontal-lamination and trough cross-stratification. Trough cross-stratified sandstones are disposed in lenses with ball and pillow structures at the base (Fig. 3 C). Ripple cross-bedded sandstones have moderate degree of bioturbation (BI 2). Identified traces include *Scoyenia*, *Planolites* and possibly *Tuberculichnus* in association with mud cracks (Fig. 3 D). In some sandstone beds, structures may be completely obliterated by intense bioturbation (BI 5-6) by *Beaconites* (Fig. 3 E). Cross-stratified sandstones shows a unimodal paleocurrent pattern with dispersion of up to 90° and medium azimuth to south-southeast (Fig. 2). This facies association is intrinsically related to the distributary channel and ephemeral lacustrine facies associations.

Interpretation

The described succession is interpreted to be a proximal terminal splay deposit (*sensu* Fisher et al., 2008). The direct association with distributary channel and ephemeral lacustrine facies associations and the size of the coarsening-upward cycles suggests that they are neither crevasse splay nor delta lake deposits. Moderate to intense bioturbation suggests an oxygenated bottom. The low diversity, abundance of horizontal traces as *Beaconites* and *Scoyenia* and the presence of locally highly bioturbated beds (BI 5-6) are the main elements to define the assemblage as belonging to the *Scoyenia-Mermia* ichnofacies (Buatois and Mángano, 2011), which suggest deposition under fluvial and lacustrine conditions.

Ephemeral lake (FA-3)

Description

This facies association is characterized by up to 10-m-thick deposits of shales, marls, and planar and nodular laminites (Fig. 3 F). Tabular beds, 0.1- to 1-m-high, are laterally continuous for dozens to hundreds of meters. Dark shales are the commonest facies and are characterized by the presence of calcite nodules, plant fragments, ostracodes and conchostracans (Fig. 3 G). Marls and laminites are commonly related to the occurrence of *Botryococcus* microalgae as well as lenticular gypsum, interstratal folds, loop bedding structures and popcorn crusts. Thin layers of gypsum between laminae and locally brecciated levels also occurs interbedded in the laminites (Fig. 3 H). This facies association is related to proximal splay deposits (FA-2) and to hypersaline lacustrine system (FA-4).

Interpretation

Dark shales and laminites associated to terminal splays and hypersaline lake facies are interpreted to be ephemeral lake deposits. Marls and laminites with evaporite structures are suggestive of deposition in shallow conditions with constant subaerial exposure. Conchostracans and ostracodes are characteristic of the lacustrine systems and corroborates the interpretations (Carmo et al., 2004). Plant fragments are indicative of existence of a nearby distributary system bringing occasional terrestrial plant debris to the lake. Overall, the FA-3 is suggestive of phases of drier conditions with minor contribution of freshwaters and terrigenous sediments.

Hypersaline lake (FA-4)

Description

Up to 12-m-thick tabular beds of laminites characterizes this facies association (Fig. 4 A). Despite been present in all measured sections, this facies association is better exposed in the Nova Olinda section. In this location, the lower interval is composed of tetrapod-bearing (e.g., pterosaurs, frogs, lizards) planar and wrinkle laminites interbedded with subordinated grainstones and up to 30-cm-high pseudo-columnar stromatolites with associated oncoids (Fig. 4 B-E). In the middle part, several small dome stromatolites (10- to 30-cm-high) are interbedded with planar laminites characterized by rhythmic lamination usually presenting large amounts of *Botryococcus* microalgae and halite hoppers between laminae (Fig. 4 F-H). The rhythmities are commonly associated with fishes and plants (mostly gymnosperms and angiosperms; Fig. 4 I). The upper beds are distinguished by arthropod- and plant-bearing planar laminites interbedded with thin laminae (2- to 5-cm-thick) of gypsum and big-sized domal stromatolites with up to 120 cm (Fig. 4 J-K). From base to top, gypsum and halite hoppers become larger and

loop-bedding structures increase in abundance. In the top of the succession, there is 0.3- to 1-m-thick flat base and irregular top lime mudstone bed with several soft-sediment deformation structures (i.e., folds, liquefaction structures, loop-bedding, micro-faults, and breccias) laterally continuous from dozens of kilometers (Fig. 5 A). This bed is predominantly ductile deformed, evidence provided by the occurrence of diapir-like structures (Fig. 5 B-E), structureless intervals (Fig. 5 F) and folds (Fig. 5 B and G). The original lamination can be preserved at the base since the deformation tends to increase up the top of the bed, which is particularly common in the northern areas of occurrence (near the Patos Lineament). Folds were only found in the Guaribas and Estiva sections (Figs. 2 and 5) and are constrained to up to 1-m-thick interval characterized by closely spaced (few centimeters), 10- to 60-cm-scale, open to tight, recumbent and inclined folds without main axis orientation. Brittle to ductile structures are also noted, mostly in the Nova Olinda section. They are enclosed in up to 0.5-m-thick bed with sharp and inclined base, and sharp and flat top, containing normal micro-faults, breccias and loop-bedding structures (Fig. 18 G-H). This facies association is associated at base to the terminal splay facies associations (FA-2) and at top to fossiliferous muddy shelf deposits (FA-5).

Interpretation

This facies association is interpreted as deposited in a hypersaline lake system based on the massive presence of evaporitic features (Heimhofer et al., 2010; Catto et al., 2016; Warren et al., 2017), its fossil content (lack of marine forms) and the complete absence of bioturbation. It represents a typical deepening upward succession, where grainstones, microbial mats and small-scale pseudo-columns and dome stromatolites characterizes the sedimentation in shallow waters. Towards the top, rhythmic laminites with loop-bedding structures and big-sized stromatolites comprehend deeper water facies. Presence of halite hoppers, lenticular gypsum and thin gypsum layers in the entire succession also suggests increasing salinity towards the top. These saline conditions facilitated microbial benthonic development by suppression of predators (Warren et al., 2017) and provided the ideal conditions for excellent soft-tissue preservation (Barling et al., 2015; Osés et al., 2017). The diapir-like (Fig. 5A) and structureless features (Fig. 5F) at the top of the FA-4 are interpreted as liquefaction structures (*sensu* Allen, 1982), characterized by variable degree of grain packing and pore fluid pressure and different grades of deformation originated inside the bed (Owen and Moretti, 2011). Brittle to ductile structures are interpreted to be extensional features that may laterally transition to diapir-like structures. Therefore, the brittle-ductile soft-sediment deformation structures in the top of the interval is interpreted to be a seismite (*sensu* Seilacher, 1969). The association with lacustrine

terminal splays (FA-2) in the base of the analyzed successions (Figs. 2 and 3) indicates that a prior humid condition with major terrigenous sedimentation was followed by a drier climate with major carbonate sedimentation.

Muddy shelf (FA-5)

Description

This facies association is characterized by a km-scale laterally continuous and up to 2-m-thick succession of interbedded fine-grained deposits (Fig. 6 A). Up to 1-m-thick tabular beds of massive to poorly laminated, green to yellow colored, mudstones occur at the base (Fig. 6 B-D). They are characterized by the noteworthy occurrence of bivalves, gastropods, and carbonized plant fragments (Fig. 6 E). Bivalve-bearing rocks are recorded in four sedimentary sections from the Araporanga, Nova Olinda, Crato and Arajara counties (Fig. 1 and 2). Bivalve shell abundances vary among outcrops and strata, but the valves are usually dispersed to loosely packed in the matrix. Dense accumulations of bivalve shells, as cm-thick shell-beds are not recorded. Field observation indicates that the shells are commonly articulated and predominantly preserved as splayed open valves. Closed articulated shells are also found, but these are not *in situ* (i.e., in position of life). Typically, the shells are splayed-out (= butterflyed). In those bivalve-rich bedding planes where the shells are abundant enough (~75 specimens) to allow field counting, no significant left/right 50-50 valve ratio deviation is noted in the disarticulated valves. Yet, the isolated valves are commonly in a convex-up posture. Literature data indicate that the bivalves can be referred to marine genera (e.g., *Barbatia*), which are also associated to non-marine forms (e.g., “*Unio*” or Unionoida, Martill, 2005; Bruno and Hessel, 2006, p. 36). In the northwestern areas of occurrence (see Figs. 2 and 6 B-C), this massive mudstone bed presents flat base and convex-up morphology with several irregular v-shaped cracks filled by shale (Fig. 6 C). A thickening-upward mudstone succession occurs above the fossiliferous sandy mudstones in the southeastern portions of the unit. Each tabular and massive bed is separated by thin levels of horizontally (*Planolites*) and vertically (*Diplocraterion*; Fig. 6 F) bioturbated mudstones filled by sand. This facies association is related to seismite beds (FA-4) at base and to storm-dominated shelves, subtidal sandbars, and intertidal mixed flats at top (FA-6, -7 and -8).

Interpretation

The bivalve-rich mudstones are interpreted to be deposited in a muddy inner shelf that occupied the entire eastern area of the basin after the deposition of the Konservat-Lagerstätte

microbial laminites (FA-4). The abundance of articulated valves (closed or splayed), the absence of fragmentation, abrasion and other taphonomic signatures indicative of tractive lateral transport, indicates little shell transportation and short residence time at the taphonomically active zone (TAZ, Aller, 1982). The bivalves are clearly autochthonous to parautochthonous (*sensu* Kidwell et al., 1986). The most abundant bivalve species in this muddy interval have thin, posteriorly elongated and equivalve shells, suggesting a burrowing, deposit-feeding mode of life (see Stanley, 1970). Their gross shell morphology close resembles that of tellinacean bivalves (Dario G. Lazo, personal communication, 2019). These bivalves are well-known trace makers (Bromley et al., 2003; Pazos and Fernández, 2010; Ekdale and Ekdale, 2018) inhabiting shallow subtidal muddy sand bottoms (MacGinitie and MacGinitie, 1968) where they feed by making repetitive probings across the sediment surface, sucking in organic-rich muds (Ekdale and Ekdale, 2018, p. 123). Notably, in some bedding planes where articulated shells are common the mudstone is massive, a condition that may be related to the intense intrastratal activity of these benthic invertebrates. V-shaped cracks filled by shale in the northern areas of occurrence resembles mud cracks commonly found in shallow mud flats subject to prolonged periods of subaerial exposition. Intense bioturbation by the permanence of bivalves and gastropods in the TAZ followed by subaerial exposition, was the causes that destroyed the previously existent lamination. The presence of thin laminae of sandstone with possibly bivalve feeding and resting traces (e.g., *Lockeia*) are strong indicative that bivalves colonized the entire interval, despite they are not preserved in the upper part of the succession. Location of the mudstone just above the seismite-bearing interval suggests that this brief marine ingression was probably promoted by tectonic causes in under base-level rising conditions.

Storm influenced subtidal shelf (FA-6)

Description

This facies association is characterized by 4- to 8-m-thick fining-upward successions of interbedded sandstones and shales. Wave ripple cross-laminated and swaley/hummocky cross-stratified sandstones occurs at base transitioning to grey shales with wavy to linsen bedding (Fig. 7 A-D). The cm-scale hummocky cross-bedded sandstones are organized in up to 0.2-m-thick flat base and undulated top beds with dm- to m-scale amplitude (Fig. 7 A). Paleocurrent data shows bimodal pattern with northwest-southeast direction. Green to gray colored shales conforms approximately 5-m-thick tabular beds in the top of this facies association (Fig. 7 B). Bioturbation is uncommon, but low to moderate bioturbated beds (BI 2-3) with dominance of

horizontal traces (*Planolites*, *Thalassinoides* and *Teichichnus*) may occur in shales with linsen bedding (Fig. 7 D), while fugichnia traces may be present in ripple cross-laminated sandstones (Fig. 7 E). This facies association is vertically and laterally related to muddy shelf deposits (FA-5), subtidal sandbars (FA-7), mixed intertidal flats (FA-8) and to barrier island/lagoon deposits (FA-10).

Interpretation

This facies association is interpreted to be a storm-influenced shelf based on the occurrence of swalley and hummocky cross-bedded sandstones interbedded to thick shale intervals. Rhythmic intercalation of hummocky, wave ripple and shales are characteristic of recurrent storm events (Aigner, 1985) separated by deposits indicative of fair-weather conditions. Paleocurrent data acquired in hummocky cross-bedded sandstones attests the interaction between oscillatory and unidirectional flows. The presence of fugichnia traces in the shales reinforces the existence of event deposition associated to storm events (Buatois and Mángano, 2011). The presence of dominating horizontal traces associated to linsen bedding and to hummocky cross-bedded sandstones may be related to the *Cruziana* ichnofacies (Frey, 1990). The occurrence of escape traces is a response to rapid changes in sedimentation and is expected to occur in storm-influenced settings.

Subtidal sandbars (FA-7)

Description

This facies association is characterized by meter-scale successions of up to 3-m-high channelized sand bodies laterally continuous for dozens of meters confined by shale beds (Fig. 8 A). The channelized sand bodies usually present erosive base, sometimes with flame structures (Figure 8 B), and flat to undulated top, with dune crests oriented perpendicularly to the maximum length of the channel. Sandstones are fine to medium-grained and are organized in dm- to m-scale sets with trough and sigmoidal cross-stratification (Fig. 8 C). Mud drapes usually bounds sets and rip up to low rounded mud intraclasts are common in the foresets. Fine-grained sandstones organized in tabular sets with horizontal stratification and climbing ripple cross-lamination (flaser/wavy bedding) are common (Fig. 8 D). Fluid scape structures and settled mud in the troughs of ripples are locally present. This succession is also characterized by low to medium bioturbed (BI 2-3) intervals with *Arenicolites*, *Diplocraterion*, *Skolithos*, *Teichichnus* and possibly *Zoophycus* traces (Fig. 8 E-F). Paleocurrent data is unimodal, presenting low to moderate dispersion and medium azimuth towards southeast. This facies

association is associated to storm influenced shelf at base (FA-6) and to intertidal flats at top (FA-8).

Interpretation

The channelized sand bodies are interpreted to be subtidal bars due to the morphology and orientation of dunes disposed perpendicularly to its maximum length (Olariu et al., 2012). These sandbars are characterized by high-energy events that occasionally rework exposed mudflats and carry mud fragments to deeper areas. Occurrence of horizontally-stratified sandstones and settled mud in the troughs of ripple marks suggests waning energy towards the top with local fluid scape. Predominance of the vertical traces with few examples of horizontal traces are suggestive of the deposition in bathymetry consistent with the *Skolithos-Cruziana* ichnofacies. Paleocurrent data points to predominance of ebb tide deposition.

Mixed intertidal flat (FA-8)

Description

Up to 4-m-thick successions of interbedded heterolithic facies, sandstones and shales characterizes this facies association (Fig. 9 A). Decimeter-scale beds of shales with thin laminae of fine-grained sandstones (linsen bedding) occurs at base of the succession. This heterolithic facies transitions to fine- to medium-grained ripple cross-laminated sandstones with thick (up to 1 cm), massive dark mud laminae between sets (Fig. 9 B). Above, medium to coarse-grained trough cross-stratified sandstones are organized in up to 0.5-m-high sigmoidal bars laterally continuous for dozens of meters (Fig. 9 C). These sigmoidal bars are usually bounded by mud drapes and may present intervals with mud in the foresets as well as, reworked rip-up clasts (Fig. 9 D-E). Heterolithic successions are common, and green to gray-colored shales with linsen bedding occur interbedded with fine-grained sandstones, showing flaser to wavy bedding (Fig. 9 E). The entire succession is characterized by low to moderate bioturbation (BI 2), mainly by *Planolites*, *Arenicolites*, *Skolithos*, and *Diplocraterion* traces. Paleocurrent data in the cross-stratified sandstones presents medium azimuth to south-southeast. This facies association is bounded at base by subtidal sandbars (FA-7) and at top by supratidal sabkhas (FA-9).

Interpretation

This facies association is interpreted to be an intertidal mixed flat due to occurrence of heterolithic facies (linsen, wavy and flaser), features of fluid mud, tidal bundles, and its close association with the mud intertidal flat facies association with marine mollusks at base, and with supratidal sabkhas at top. The stacking pattern is typical of progradation of distributary

tidal channels in a shallowing upward mixed flat (Longhitano et al., 2012). The most notorious structures are cross-bedded sandstones with mud drape and rip-up clasts interpreted to tidal bundles, and fluid mud structures in ripple cross-laminated sandstones. These fluid muds represent the slack water period in a single spring tidal cycle (Longhitano et al., 2012). Presence of mud cracks to the top attest to subaerial exposure of the intertidal flat in a shallowing upward pattern. The quasi-unimodal paleocurrent pattern is suggestive of ebb flow predominance. Dominance of vertical trace fossils in the intertidal flats suggest deposition in bathymetry compatible with the *Skolithos* ichnofacies.

Sabkha (FA-9)

Description

Up to 10-m-thick successions of interbedded laminites and shales characterizes this facies association (Fig. 10 A). Brown to red colored tabular beds of planar laminites varying in size from 0.25 to 1.5 m are notable for its levels with ductile deformed laminae and notable amount of loop bedding structures (Fig. 10 B-C). Commonly in the top of the loop bedding laminae, the surface is covered by syneresis cracks, while at top of undeformed laminae thin layer of cm-sized breccias are also common. Green to grey colored shale beds are thinner at base and thicker to the top of the succession, reaching up to 2 m in these parts. These shales present several levels of enterolithic folds that are delineated by horizontal and vertical discontinuous laminae of calcite and gypsum (Fig. 10 A). Dark shales with carbonate nodules are also common (Fig. 10 D). Presence of gypsum in this succession increases to the top, where shale beds are highly deformed. This facies association is thicker in the northwestern areas (Fig. 2), decreasing in thickness to southeast. Its commonly associated at base to mixed intertidal flats (FA-8) and at top to storm dominated shelf (FA-6), subtidal sandbars (FA-7) and to intertidal flats (FA-8).

Interpretation

The interbedded laminites and shales with enterolithic folds are interpreted to be deposited in a sabkha in the supratidal part of the mixed flat (FA-8). The definition as sabkha consider that these deposits were formed in a shallow basin limited to marginal marine settings and are associated with several evaporitic features (Briere, 2000). The presence of plastic deformation, loop-bedding structures, syneresis cracks, breccias in laminites and gypsum laminae forming ascending structures are interpreted as the product of intense evaporation associated with some seismic activity (Calvo et al., 1998; Rodríguez-Pascua et al., 2000). The

increasing in the intensity of evaporation towards the top and association with tidal flats at base are suggestive of progradational architecture, with typical continental facies overlapping marine deposits.

Barrier island / lagoon complex (FA-10)

Description

This facies association is characterized by a 5- to 10-m-thick fining-upward succession of sandstones and shales. The lower part of the succession is marked by the presence of up to 3-m-thick interval of fine-grained sandstones with low angle cross-stratification and occasional climbing ripple cross-lamination (Fig. 11 A-B) interbedded with sandstones with trough cross-stratification organized in dm-scale tabular sets (Fig. 11 C). Paleocurrent data acquired in the cross-bedded sandstones presents dispersion of approximately 90° with medium azimuth to southeast, while cross-laminated sandstones present medium azimuth to northeast. Above the basal sandstone is common the presence of fining-upward successions with up to 3 m characterized by interbedded trough cross-bedded sandstones and shales (Fig. 11 D-E). These sandstone facies usually present ball-and-pillow structures at base of sets and dispersed quartz granules. Paleocurrent data acquired in this stratigraphic level presents a bimodal dispersion in the northwest-southeast direction. Cross-bedded sandstones in the upper part of the succession present medium degree of bioturbation (BI 3) mostly by *Skolithos* and *Arenicolites* traces (Fig. 11 E-F). Also, few meniscate vertical and horizontal burrows resemble *Taenidium*. This succession is associated at base with storm influenced deposits (FA-6) and at top with hypersaline coastal lakes (FA-11).

Interpretation

This facies association is interpreted to be a progradational barrier island complex with tidal inlets due to its fining-upward stacking pattern and association at top with a hypersaline coastal lake. The progradational architecture is also confirmed by the existence of typical facies deposited in foreshore conditions (breaking bar wave dunes and beach low angle cross-bedded sandstones) overlapped by facies deposited in protected lagoons (shales and heterolithic facies, Sáez et al., 2018). Between the beach barrier and the protected lagoon, cross-bedded sandstones with ball-and-pillow structures are interpreted to be flood and ebb deltas with typical paleocurrent pattern developed according the tidal inlets. Presence of several layers with vertical burrows (*Skolithos*) developed in the top of delta lobes suggests that they were formed in distinct events separated by slack water periods in the lagoonal setting. In addition, migration

of dunes to southeast and deltas to northwest-southeast suggest that the barrier island was in the northeast-southwest direction.

Hypersaline coastal lake (FA-11)

Description

An up to 8-m-thick succession of interbedded dark shales, grainstones, planar and nodular laminites, evaporitic features (*e.g.*, tepees, breccias, popcorn crust), and silicified stromatolites characterizes this facies association (Fig. 12 A). At base, dark shales with carbonate nodules and conchostracans, transitions to grainstones and planar laminites. Laminites forms thick beds with up to 2 m and are locally deformed, forming folded layers. The planar laminites are also characterized by interbedded grainstones and ostracodites and by the occurrence of halite hoppers (Fig. 12 B), fishes and few *Botryococcus* microalgae. Nodular laminites overlap the lower succession and are associated to breccias, tepees and popcorn crusts (Fig. 12 C-E). In this portion, silicified pseudo-columnar stromatolites with brecciated top occur rarely (Fig. 12 F). Dark shales with enterolithic folds interbedded with silica-rich intervals as well as dome-shaped breccias with up to 70 cm imbedded in dark shales are typical of the upper succession (Fig. 12 G). These facies are associated at base with barrier islands (FA-10) and at top to playa lakes (FA-12).

Interpretation

This facies association is interpreted to be deposited in a hypersaline lacustrine system near to the coast. Differently from the lower lacustrine system (FA-4), this lake has a typical shallowing upward architecture. Soft-sediment deformation structures in the basal planar laminites (*i.e.*, recumbent folds, loop-bedding, interstratal folds, breccias, and truncated beds) are interpreted to be slump deposits in the deep parts of the lake. Nodular laminites, tepees, breccias, popcorn structures and surfaces with abundant halite hoppers suggests intense evaporation in shallow waters. In this restricted environment, some stromatolites grew in the shallow areas. The rapid transition at base of tidally-dominated settings to a lacustrine system indicates continentalization processes that culminates in playa lake evaporites at the top of the Ipubi Formation (see Nascimento et al, 2016).

Playa lake (FA-12)

Description

Tabular beds of shales, sandstones, limestones and evaporites in successions with up to 20 m are characteristic of this facies association. Shales with subaerial exposure features predominate the entire succession and may conform 1- to 8-m-scale beds interbedded with planar and nodular laminites. Decimeter-scale tabular beds of fine-grained sandstones with horizontal stratification, ripple cross-lamination and flaser to wavy bedding occur in the top of coarsening upward successions that begin with thick shale beds. These facies are usually weakly to moderately bioturbed (BI 2-3) by horizontal traces (*Planolites* and *Scoyenia*). In the upper part, shales conform thinner beds interbedded with up to 10-m-thick halite and gypsum deposits. Shales in this portion present several nodules and stains of gypsum and calcite. The deformation of shales and evaporites are probably related to halokinesis processes. This facies association is intrinsically related to hypersaline coastal lake deposits at base (FA-11).

Interpretation

This facies association is interpreted to be a continental playa lake deposits based on the predominance of shales with subaerial exposure features, the increasing in salinity towards the top culminating in evaporite deposition and presence of truly continental trace fossils. Playa lakes are considered to be developed on intracontinental basins that remains dry for a long period of time (halite and gypsum precipitation) but having occasional discharging waters bringing terrigenous sediments to the basin (Briere, 2000). The fining upward succession of interbedded sandstones and shales at base and shales with evaporitic features interbedded with nodular laminites at top are characteristic of a shallowing upward evaporitic water body. Predominance of horizontal trace fossils suggests affinity with the *Scoyenia* ichnofacies supporting the terrestrial environment interpretation. Association at base with hypersaline coastal lake deposits points to increasing in evaporation rates, drying the preexistent coastal lake and completing the continentalization process. This facies association correspond exclusively to the deposits of the Ipubi Formation.

STABLE ISOTOPE SIGNALS AND TOC CONTENT

The stable isotope curves of all limestone facies of the Crato Formation are plotted in the main measured sections (Fig. 13; Table 1). They show a very clear pattern and together with the precise sedimentologic description and recognition of facies associations can be used to correlate the different levels within the Crato Formation (Fig. 14). The cross-plot diagram of all analyzed samples reveals $\delta^{13}\text{C}$ values varying from +4 to -15‰ and $\delta^{18}\text{O}$ values varying

from 0 to -9‰ (Fig. 15A). Three major clusters are observed, but the most clouded area is observed close to 0‰ for $\delta^{13}\text{C}$ and between -4 and -9‰ for $\delta^{18}\text{O}$ (Fig. 15A).

The first carbonate lacustrine phase, represented by ephemeral lake deposits (FA-3) at base of the unit, is better exposed in the Nova Olinda, Guaribas and Batateira sections (Fig. 2). They are characterized by cycles with predominantly negative $\delta^{13}\text{C}$ values (-9 to 0‰) at base and positive values in the top (-2 to +2‰, Fig. 13). These values are associated with the presence of dark shales and organic rich carbonate laminites that show TOC content varying between 0.5 and 2.5% (see Fig. 16). The $\delta^{18}\text{O}$ values varies between -3 and -8‰, representing a slight positive incursion. A cross-plot of stable carbon and oxygen isotope values for FA-3 show two distinct clusters, one dominated by positive $\delta^{13}\text{C}$ values and other dominated by negative values (Fig. 15B). This situation is probably related to higher restriction and increased evaporation rates at the base of the succession, where organic matter is trapped in the sediment and benthic microbial activity is higher.

The hypersaline lacustrine phase (FA-4), which constitutes the *Konservat-Lagerstätte* interval, is better exposed in the Nova Olinda section, but it is also well preserved in the Guaribas and Caldas section (Fig. 2). This carbonate interval is characterized by consistent positive $\delta^{13}\text{C}$ values at base (+2 to 0‰) passing to negative values at top (0 to -2‰), constituting a very regular negative shift. Such negative incursion is suggestive of enrichment in microbial carbon, which is corroborated by generalized benthonic microbial activity in the hypersaline lake. This symmetry is also recognized by the cross-plot diagram of FA-4 facies, where a single $\delta^{13}\text{C}$ cluster is formed near zero ‰ (Fig. 15C). The $\delta^{18}\text{O}$ values (-3 to -9‰), reveal a more pronounced positive incursion, revealing increasing conditions of restriction and evaporation rates. In this facies association, TOC levels are very low and varies between 0.005 and 0.3%. Values of $\delta^{13}\text{C}$ around -2‰ are characteristics of the lime mudstones with soft-sediment deformation structures.

Carbonates deposited in sabkhas (FA-9) are common in the proximal settings, mostly in the Nova Olinda and Guaribas sections (Fig. 2). They are characterized by higher levels of TOC that varies between 0.5 and 3.5%. Where TOC is higher, $\delta^{13}\text{C}$ values are more negative (up to -8‰). The opposite is also true, low TOC content is associated to less negative values (up to +1‰). This facies association is characterized by two main carbonate intervals (Figs. 2, 13, and 14). While the first interval is characterized by a negative $\delta^{13}\text{C}$ incursion from ~0 to -8‰, the second interval presents a positive incursion from -4 to +1‰. In the other way, $\delta^{18}\text{O}$ values in the lower interval shows a positive incursion from -6 to -4‰, while the upper interval presents a negative incursion from -5 to -7‰. The cross-plot diagram of FA-9 is organized in a

single cluster that shows a more negative tendency (Fig. 15D). The predominant negative $\delta^{13}\text{C}$ values of this sabkha facies is associated to high salinity rates, evaporation conditions and decrease in the photosynthetic activity.

The laminites from FA-11 are well exposed in all measured sections (Fig. 2) and their isotopic signal is very similar in the entire basin (Fig. 13). This suggest that it represents a single depositional phase, but not necessarily isochronous, as proximal depositional settings are present in the northern while distal areas are positioned towards southern part of the basin (see also Fig. 14). The $\delta^{13}\text{C}$ values are positive at base of the succession (+4 to 0‰), but towards the top it reaches the more negative values of the entire succession (-14.5‰). Such negative values are associated to the beginning of deposition of playa lake evaporites from FA-12 that present predominantly negative $\delta^{13}\text{C}$ values (-10 to -14‰). This condition is clear when $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from both FA-11 and FA-12 are plotted in the same diagram (Fig. 15E). The FA-11 are clustered in three groups, where the last phase is the same of the single cluster represented by the FA-12 (Fig. 15F). This situation is characteristic of the transition between Crato and Ipubi Formation. Such transition is also confirmed by analyzing the overall architecture of the Barbalha, Crato and Ipubi Formations that shows no evidence of discordances or local diastema between units (Figs. 2 and 14). The TOC value of the FA-11 is almost uniform, varying between 0 and 3%, but a maximum of ~10.5% is observed in dark shales at base of the facies association. The existence of such $\delta^{13}\text{C}$ negative values in the upper part of the Crato Formation is associated to the increasing in the salinity rates in the basin. Such situation is a strongly suggestive of high methanogenesis rates associated to the high TOC content in the dark shales, paleosols and evaporitic limestones. Is important to note that biogenic and thermogenic methane shows $\delta^{13}\text{C}$ values ranging from -110 to -30 (Kiel and Peckmann, 2007), but is also common that these values may vary between -30‰ to +6‰ (Campbell, 2006). The negative values obtained for the top of the FA-11 are compatible with low and diffusive methane seepage rates associated (or not) with oil production (Joye et al., 2004).

DEPOSITIONAL MODEL AND BASIN EVOLUTION

The Aptian evaporitic transitional phase of the Araripe Basin can be divided in three distinct depositional sequences (Assine et al., 2014). The middle sequence is bounded by two regional unconformities and is composed by the upper part of the Barbalha Formation, and the entire Crato and Ipubi formations (DS-2 of Assine et al., 2014). The sequence is a transgressive-regressive cycle encompassing several sedimentary settings linked to the mixed deposition of carbonates, shales, evaporites and sandstones (Fig. 17).

Transgressive System Tract (TST)

The lower sequence boundary (LSB) is defined by a disconformity in the middle of the Barbalha Formation, top of the Batateira Bed (*sensu* Hashimoto et al., 1987), that records the final stage of the underlying DS-1 of Assine et al. (2014). The LSB varies laterally, changing its expression throughout the basin. In its eastern limits, the Crato Formation occurs in transitional contact with the Barbalha Formation and both are, apparently constrained by the rift boundaries. In the northeastern limits, the Crato Formation occurs above the Jurassic Brejo Santo Formation (Fig. 14), but may also be present above the Paleozoic Cariri Formation near basement highs. To the west and south, beyond the Present-day basin limits, limestones (FA-4) from the Crato Formation occurs directly above the basement, which is noted in the Tatajuba, Ipubi and Apertada Hora regions (Figs. 1A and 13).

The TST is dominated at the base by up to 30-m-thick fluvial deposits of the upper Barbalha Formation (Fig. 18-I), mainly recording coarse-grained sandstones and conglomerates organized in fining upward successions with occasional preservation of red mudstones with root marks in their tops (see Scherer et al., 2015). Paleocurrents towards south indicate source areas beyond the northern border of the basin (Fig. 2), probably placed in highlands formed on basement rocks of the Patos Lineament (Assine et al., 2016). Alluvial sediments transition to up to 50-m-thick succession of lake deposits characterized by background sedimentation of shales (0 to 1% of TOC) and high-energy terminal splay sandstones (Figs. 16 and 18-II). Analysis of palynological content points to an important contribution of palynomorphs (40%) associated to proximal splays and of phytoclasts (60 to 100%) in more distal or protected regions of the evolving lacustrine system (Fig. 18). Measurements of cross-bedded sandstones of terminal splays show sediment transport towards south, similarly to the fluvial paleoflow of the underlying facies association (Fig. 2).

Fluvial channels and terminal splays are less common towards the top of the succession. There, up to 5-m-thick intervals of planar and nodular laminites, interbedded with crustacean-rich (conchostracans and ostracodes) dark shales characterize the base of the Crato Formation (Fig. 2). This succession is characterized by medium to high TOC content (1 to 2%), high preservation of AOM (up to 100% in the shale facies) and high (65 to 90%) contribution of phytoclasts as well (Fig. 16). The existence of interlaminated limestones, evaporites and pseudomorphs of gypsum and nodular facies suggests that this lacustrine system became progressively more saline and restricted towards the top, until culminates into microbial laminites of the hypersaline lake system (FA-4, Fig. 18-III). In proximal settings (to the north),

tetrapods, fishes, plants and insects are exceptionally preserved in the microbially laminated limestones, conforming the world-famous Crato Konservat-Lagerstätte. Towards distal settings (southeast), the thickness decreases from ~10 m to ~4 m, and limestones became less fossiliferous (Fig. 2). Soft-sediment deformed limestones are present on the top of the laminites from the hypersaline lake system. In this bed there is no evidence of waves produced by high energy events (storms, tsunamis, breaking waves), turbulent flows, tidal shear, sediment load due to rapid sedimentation, active periglacial processes, extra-terrestrial impact, or groundwater seepage affecting the deformed. The intensity of deformation decreases towards southeast away from the Patos Lineament. Thicker and ductile deformed beds are found mostly at the Estiva and Guaribas sections, near the main shear zone, and thinner and less deformed beds occur southeastern (Caldas section; see Fig. 5).

The Aptian was an age of pronounced tectonic activity related to the rifting of the equatorial margin (Rosetti and Goés, 2001). Evidences of tectonic reactivation in the northeastern Brazil are found in the Grajaú and Tucano basins, where seismites (Rosetti and Goés, 2001; Varejão et al., 2019), deformation bands (Gomes Jr et al., 2018) and border-fault conglomerates (Figueiredo et al., 2016; Freitas et al., 2017) are described. In this context, the Araripe Basin is located between these deposits and near the equatorial and east margins, where the rifting process was active. Hence, the stress originated by the reactivation of these faults had some effect in the basin, making the seismic activity a viable trigger to the origin of the above described soft-sediment deformation structures.

The lacustrine deposits of the lower part of the Crato Formation are covered by a mollusk-rich mudstone bed that can be easily tracked for tens of kilometers (Fig. 2). The thickness of the bivalve-bearing bed decreases towards the northern basin margin, where subaerial exposition structures are found. In distal settings, the thickness of this bed increases passing laterally to subtidal facies (Figs. 14 and 17). This thin (dm-thick) mollusk-bearing bed contain marine/brackish bivalves (Bruno and Hessel, 2006, p. 36) and gastropods, associated to non-marine forms (Unionoida, see Martill, 2005; Bruno and Hessel, 2006) suggesting variable salinity. Regardless of rising base level revealed by deposition of mollusks-rich mudstones (see Fig. 17), fault-related subsidence may have had some importance in the generation of accommodation space. The Aptian was a time interval of relatively high (~150 m above Present-day) and stable sea level (Haq, 2014) and regional tectonic reactivations should have generated not so pronounced subsidence, but the intensity of crustal sinking was enough to connect the Araripe Basin with marine waters from the South Atlantic Ocean. Progradation of more terrestrial settings above the bivalve-bearing bed attests the regressive pattern upwards. In this

context, the maximum flooding surface (MFS) is positioned just on the top of a bivalve- and gastropod-rich mudstone interval (Fig. 18-IV).

Highstand System Tract (HST)

The base of the Highstand System Tract (HST) starts above the bivalve-bearing mudstones. Regressive pattern is corroborated by shallowing upward cycles in tide-dominated settings (Fig. 17). The distal settings were subjected to sporadic storms, where wave ripple-laminated and hummocky cross-bedded sandstones occur interbedded with grey shales in thin successions with reduced thickness (> 3 m). These facies are succeeded by meter-thick deposits of subtidal sandbars (FA-7) characterized by wedge-shaped sigmoidal and trough cross-bedded sandstones laterally continuous for few dozens of meters that laterally and vertically transition to shales. Above these, up to 4-m-thick mixed sand-mud deposits constituted by predominating heterolithic facies and sigmoidal strata with mud drape typifies the intertidal flat deposits. When the tide was low, large tetrapods may have walked in these sediments generating undertracks in heterolithic strata (see Fig. 9 G). Paleocurrent data acquired in ebb-dominated tidal bundles of intertidal flats and in sigmoidal cross-bedded sandstones of subtidal sandbars are consistent and indicates sediment transport towards south-southeast where distal settings predominate. This predominantly marine interval is characterized by TOC values that varies between 0 and 1.5%, with high (~50%) MOA preservation (Fig. 16). The regressive pattern is corroborated by the deposition of evaporitic laminites and paleosols - rich in ostracodes, conchostracans and locally bivalves -, typical of sabkhas (FA-9, Fig. 18-V) above the tidally-dominated deposits. Paleosols presents dark colors, are rich in organic matter (TOC values that reach 2%) and characterized by equal contribution of MOA and phytoclasts (about 40% each, Fig. 16). The evaporitic limestone facies also present higher levels of TOC (3.5%) and preservation of MOA prevails (Fig. 16).

Sabkhas and intertidal flats are less common towards the top, and subtidal sandbars and storm-influenced outer shelf deposits predominate (Fig. 17). This interval is characterized by shale deposition in distal settings (i.e., Sobradinho section) subjected to frequent storms, as indicated by the presence of sandstones with hummocky cross-bedded and wave ripple cross-laminated sandstones, and also by ebb-dominated subtidal sandbars (see Guaribas, Batateira and Mina Caldas sections in Fig. 2). This interval is characterized by TOC values varying between 0 and 2%, and by high phytoclasts contribution (~60%) and low preservation of MOA (<20%), with higher contribution (~50%) of palynomorphs associated to subtidal sandbar deposits (Fig. 16). Also, subtidal intervals are characterized by a higher (up to 60%)

contribution of palynomorphs (see Fig. 16). Above these, barrier island deposits characterized by a thick (up to 5 m) succession of horizontal to low angle stratified sandstones are superposed by cross-bedded sandstones with bimodal paleocurrent pattern indicating formation of ebb and flood tidal deltas connecting a narrow lagoon with the marine waters (Fig. 18-VI). This barrier island-lagoon complex is characterized by both marine (*Skolithos* and *Arenicolites*) and terrestrial (*Taenidium*) ichnofossils and represents the last occurrence of marine deposits in the DS-2. The TOC content (0.5 to 2%) is similar to the previous marine facies associations, recording a slight increase in the preservation of organic matter (Fig. 16). In this stratigraphic level, phytoclasts contribution is very high (~100%) and palynomorphs and MOA are poorly preserved (Fig. 16).

The development of carbonates above the barrier island/lagoon complex is a direct evidence of the return of lacustrine condition in the basin. This condition is similar to what was observed by Sáez et al. (2018), where a back-barrier perched lake formed in the highstand phase of the Holocene NW Spain. After a brief sea level rise (TST phase) with flooding of continental area by the sea, back-barrier lagoon sedimentation took place and as this system evolve, the closure of the sand barrier favored the formation of a perched lake above the local sea-level (Sáez et al., 2018). The costal lake formed in the Crato Formation is characterized by typical planar laminites deposited in distal waters that progressively become shallower upwards where even stromatolites thrived. There, stromatolites and evaporitic and subaerial exposition structures occur attesting increasing high evaporation rates in the basin. Also, marine $\delta^{18}\text{O}$ values are present in the lower portion of this costal lacustrine system (see Fig. 13) corroborating the last marine influence in the Crato Formation. Overall, the lake is characterized at base by high TOC preservation, reaching more than 10%, associated to high amounts of MOA (up to 95%). Continentalization is also attested by the increase in preservation of phytoclasts and palynomorphs and by the decrease in TOC values and MOA preservation (Fig. 16). This condition also resembles that observed in the Spanish study case, where fine-grained sediments accumulated in both lagoon and in the perched lake were mainly fed from the continent by ephemeral rivers (see Sáez et al., 2018). In the case of the Crato Formation, evaporitic environments evolved, culminating in the deposition of the continental playa lake evaporites (FA-12) of the Ipubi Formation in conditions of gradual base-level fall (Figs. 17 and 18-VII). The Ipubi Formation is characterized by thick evaporite deposits separated by periods of more moisture conditions, when rivers contributed to deposition bringing clastic sediments to the depositional site.

The upper sequence boundary (USB) is characterized by alluvial coastal plain deposits, from the Romualdo Formation, above sediments of both Crato and Ipubi Formations (Custódio et al., 2017). The USB is also recognized in the Jatobá Basin, where the Romualdo Formation is recognized erosively above the Crato Formation (Neumann and Rocha, 2014). The presence of such similar deposits and stratigraphic surfaces in distinct basins are strong evidences of the existence of an integrated depositional context linking the evaporitic transitional successions of the interior basins of the NE Brazil.

PALEOGEOGRAPHIC IMPLICATIONS: SEDIMENTATION BEYOND THE ARARIPE BASIN LIMITS

The Aptian is a key Stage in the development of reservoir and seal rocks in the petroleum Pre-Salt systems, which makes the time-equivalent successions of the interior basins of NE Brazil key outcrop analogues. The Aptian is also the age of the first putative marine connection between the North and South Atlantic oceans that took place during the rifting of the South America equatorial margin (Koutsoukos et al., 1991; Arai, 2014). New high-resolution carbon isotope data reveal that the Aptian evaporites and carbonates from the South Atlantic are correlate of those from Tethyan sections, suggesting that the connection between these two oceans occurred before the deposition of the thick salt deposits (Tedeschi et al., 2017).

The Araripe Basin records the most complete sedimentary succession between the interior basins of northeastern Brazil, with preservation of the entire evaporitic transitional phase (Assine et al., 2014). There, the lower Barbalha Formation and the Batateira Bed (DS-1); upper Barbalha – Crato – Ipubi Formations (DS-2); and the Romualdo Formation (DS-3) constitutes three Aptian depositional sequences separated by two internal unconformities (Assine et al., 2014). All three depositional sequences record transgressive events in the basin that culminated in, at least, two Aptian marine ingressions (i.e., Crato and Romualdo Formations, Custódio et al., 2017; Fürsich et al., 2019).

Until now, the absence of typical marine sedimentary facies (e.g., fluid mud, tidal bundles) and marine fossils (macro- and microfossils), was used as evidence to support the hypothesis that the limestones and dark shales of the Crato Formation were generated under non-marine (lacustrine) conditions (Coimbra et al., 2002; Neumann et al., 2003; Heimhofer et al., 2010; Tomé et al., 2014). On the other hand, the record of possible marine bivalves (Bruno and Hessel, 2006) associated with a tidally influenced environment (FA-7, 8) above the main fossil-rich laminated limestone interval contradicts the previous studies and reinforce the

marine influence in this stratigraphic interval. In this context, the Crato Formation records the first marine ingression in the Cretaceous of the Araripe Basin, NE Brazil.

Based on the occurrence of *Sergipea variverrucata* (Coimbra et al., 2002), the Crato Formation is attributed to Aptian age. The widespread occurrence of this palynozone in the equatorial and interior basins of the northeastern Brazil suggests that an important transgression took place in the Aptian (Arai, 2009). Detailed palynological studies points to the dominance of *Classopollis* (Heimhofer and Hochuli, 2010), suggesting a massive presence of xerophytic flora thriving in arid to semi-arid conditions (Heimhofer and Hochuli, 2010; Carvalho et al., 2017). The *Classopollis* pollen is very abundant in lagoonal and marine nearshore environments, often associated to evaporites (Carvalho et al., 2017), and its relative abundance tends to increase close to the boundary with the Ipubi Formation (Heimhofer and Hochuli, 2010). The *Classopollis* pollens dominate until the top of the Romualdo Formation, where *Araucariacites* increases in abundance to up to 33% (see Heimhofer and Hochuli, 2010). The replacement of *Classopollis* by *Araucariacites* was also recognized in the Sergipe Basin, and reflects a drastic climate change (Carvalho et al., 2017). Such change from arid to humid conditions indicate an increase in the moisture following a zone along the opening of the Atlantic-Tethyan seaway during the Aptian (Carvalho et al., 2017).

Strata of the Crato Formation are also preserved outside the Araripe Basin, as in the Jatobá (Serra Negra and Periquito plateaus) and North Tucano (Tonã plateau) basins (Fig. 1 B). However, the Aptian sedimentary succession is thicker in the Araripe Basin, and towards the southern basins the upper portions of the succession are eroded (decapitated) and only thinner deposits are preserved (see Fig. 19). Geodynamic models show that after the complete breakup of the Brazilian marginal rift basins, the newly formed continental margins were subjected to compression uplift, exhuming post rift rocks of the NE interior basins (Magnavita et al., 1994; Japsen et al., 2012). This event probably occurred during Cenozoic, affecting the Borborema province (Peulvast et al., 2008) and lifted the adjacent Araripe and Jatobá basins to up to 1000 m above sea-level, while the Tucano Basin is nowadays up to 600 m above sea-level. This effect explains why Aptian strata are unequally preserved in distinct geographic areas.

The Aptian succession of the Jatobá Basin is almost complete, characterized by the occurrence of the Barbalha, Crato and Romualdo Formations (Neuman and Rocha, 2014). In the analyzed drill hole core from the Serra Negra (see Fig. 1 B), Gratzner et al. (2013) described a succession of sandstones, shales and limestones that are very similar to that observed in the TST of the DS-2. There, the succession begins with fining upward cycles of sandstones grading to siltstones and shales, suggestive of fluvial deposition. The shale interval is ~15 m-

thick, passing to sandstones at the top, suggesting deposition in a lacustrine environment with terminal splay contribution. Above, the first limestone beds occur, characterizing the base of the Crato Formation. These limestones have positive $\delta^{13}\text{C}$ values that varies between +1.5 and 2.5‰, and negative $\delta^{18}\text{O}$ values varying from -4 to -7.5‰, in agreement to what is expected for the FA-3 (Fig. 19). The main limestone bank of the FA-4 is also present (Konservat-Lagerstätte interval) and is characterized by a very defined $\delta^{13}\text{C}$ curve with positive values at base (up to +2.5‰) and negative values to the top (up to -1‰) (Fig. 19). Above this lacustrine interval, the succession is not easily distinguished. An approximately 6-m-thick shale-sandstone interval is probably correlate to the first marine facies (FA-5 to FA-8) in the Araripe Basin, but the absence of a detailed sedimentologic description of the Serra Negra succession does not allows to confirm this correlation. The $\delta^{13}\text{C}$ signal have a negative tendency towards the top, with values varying from +0.5 to -3‰, while $\delta^{18}\text{O}$ varies from -4 to -7‰ (Fig. 19). This occur because these data were acquired in limestones deposited on lakes or sabkhas, where the isotope values may vary according to particular conditions and not reflect global isotopic shifts, as expected for marine sediments.

The Aptian record of the Tucano Basin is not fully recorded, only the DS-1 and the TST of the DS-2 are preserved (Varejão et al., 2016). There, the LSB is marked by the presence of fluvial sandstones and conglomerates (i.e., Cicero Dantas Member, Marizal Formation) deposited erosively above paleosols from the so-called Amargosa Bed (*sensu* Freitas et al., 2017) at the top of the Banaê Member, Marizal Formation (Varejão et al., 2016; Freitas et al., 2017). The Amargosa Bed is correlate to the Batateira Bed (*sensu* Hashimoto et al., 1987), an interval of dark gray shales intercalated with limestones in the upper part of the Barbalha Formation and is a key stratigraphic marker in the Recôncavo-Tucano-Jatobá basins (Freitas et al., 2017; Varejão et al., 2019). In the Tucano Basin, the Crato Formation is incomplete, and limestones of the fossil-rich laminated limestone interval comprises the upper preserved strata, nearly 70 m above fluvial and lacustrine-terminal splay deposits of the Marizal Formation (Fig. 19). These limestones have the same isotopic values of the lacustrine succession found in the Araripe Basin. In the FA-3, the $\delta^{13}\text{C}$ signal is positive, varying from 0 to +2‰, and the $\delta^{18}\text{O}$ is negative, varying from -1 to -9.5‰ (Fig. 19). The FA-4 is characterized by a more stable $\delta^{13}\text{C}$ curve, with the predominance of values around ~1‰ for almost all interval, with a well-marked negative incursion in the top, where it can reach -8.5‰ (Fig. 20). The $\delta^{18}\text{O}$ signal is also stable, varying from -7.5 to -8.5‰ (Fig. 19).

The marine ingressão took place from south to north, as revealed by paleocurrent data as well as by dip direction of the paleodepositional settings and facies associations distribution

(Figs. 17 and 20, also see Assine et al., 2016; Varejão et al., 2016; Custódio et al., 2017; Freitas et al., 2017). This means that marine waters came from the Recôncavo-Tucano-Jatobá basins and probably the Sergipe-Alagoas basins (Assine et al., 2016). The record of marine foraminifers (Arai, 2014), bivalve mollusks belonging to cosmopolitan marine genera (see Bruno and Hessel, 2006, p. 36), and marine bivalves possibly corresponding to tellinaceans, which are also found in the South Atlantic Ocean (and elsewhere), are another evidence for marine ingression during sedimentation of the Crato Formation.

CONCLUSIONS

A new model for the sedimentary evolution of the Aptian Crato Formation, Araripe Basin, is here proposed based on a multiproxy approach that combines sedimentologic, stratigraphic, paleontological and geochemical data. According to the data gathered, the deposition began with lacustrine deposits generated in transgressive conditions. The sea-level rising was accompanied by a seismic event that probably triggered the deposition of marine beds just above the lacustrine succession. The first marine strata are constrained to the interval with marine and/or brackish water bivalve mollusks, directly above the fossil-rich laminated limestones. Regressive sedimentary conditions are recognized above, where sabkha limestones and paleosols cover tide-dominated siliciclastic deposits, with influence of storms in distal settings. The marine deposits are characterized by ichnofossils associated to the *Skolithos* and *Cruziana* ichnofacies. Towards the top of the succession, lacustrine conditions return to the basin culminating with the deposition of the evaporite succession of the Ipubi Formation. Detailed stable isotope curves revealed significant variations in salinity and primary productivity mainly due to the restriction/connection of the waterbody with the ocean system. These conditions were essential to generate signals that can be used in intra basinal correlations, allowing the recognition of particular stratigraphic intervals in the Crato Formation from distinct basins (i.e., Araripe, Jatobá and Tucano). Therefore, the Aptian stage marks the beginning of the North and South Atlantic water masses connection, an event that is substantially recognized in the sedimentary succession of the Crato Formation. Paleocurrent data and the marine regressive geometry reveal that the marine ingression took place from south to north. Similar pattern was already recognized for the overlaying Romualdo Formation, but our data show that the first marine ingression in the Araripe Basin occurred earlier than previously thought. This unequivocally record the first brief marine ingression of the newly formed South Atlantic Ocean over the interior basins of the northeast Brazil.

ACKNOWLEDGMENTS

Financial support was also offered by FAPESP (2016/13214-7), CNPq (401039/2014-5), and Petrobras (2014/00519-9). This work was made with institutional support of the São Paulo State University. M.L. Assine, M.G. Simões and L.V. Warren are fellows of CNPq. We are also in indebted with the Laboratory of Minerals and Rocks Analysis (LAMIR) from the Federal University of Paraná for the stable isotope analysis and to the Laboratory of Microfossil Preparation from the Rio de Janeiro Federal University for providing the TOC and palynological analyzes.

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FIGURES AND TABLES

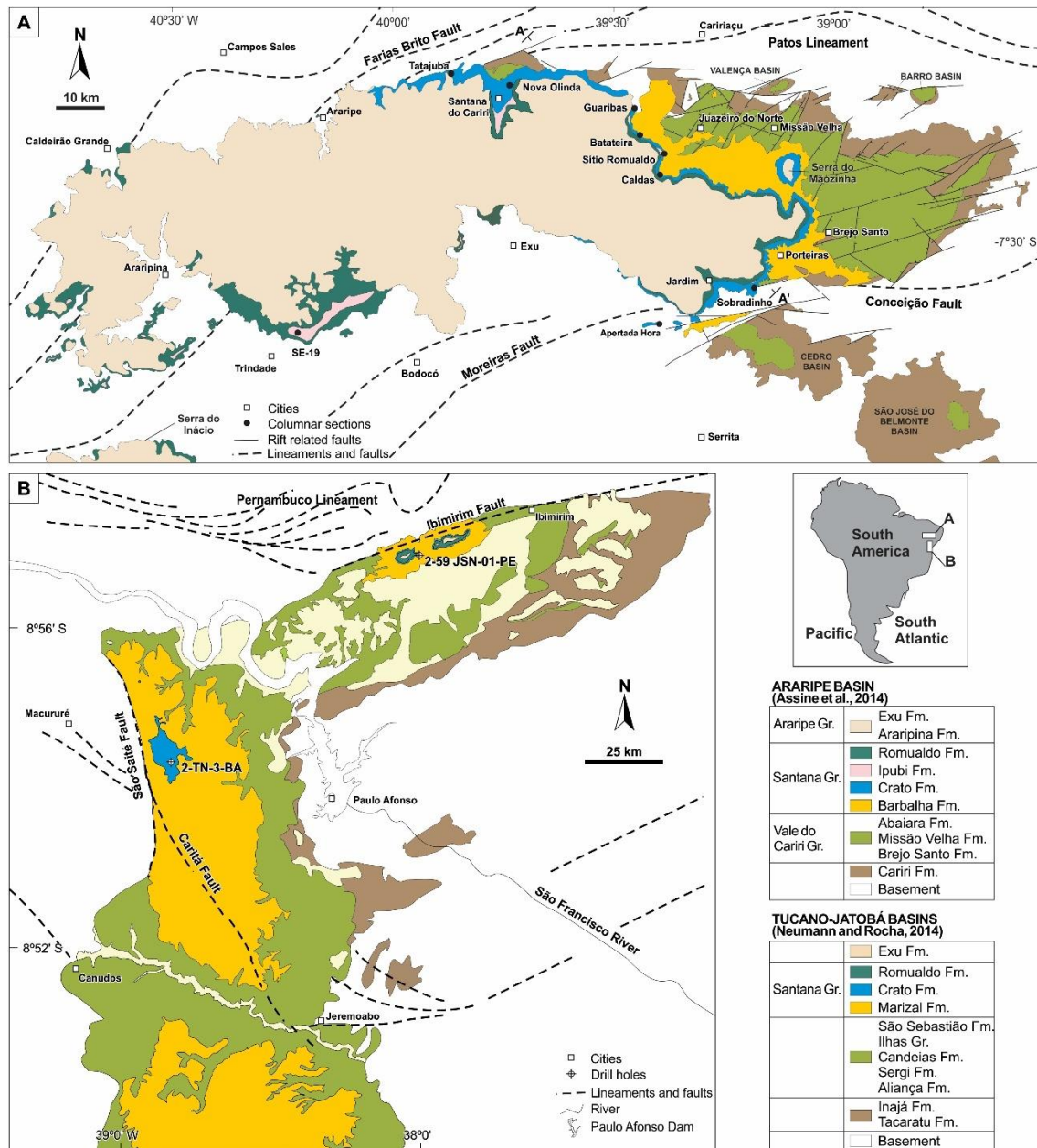


Figure 1 – Geological map of the investigated areas. A: Araripe Basin with location of the main columnar sections. Modified from Assine et al. (2014). B: Tucano and Jatobá Basins with the location of the analyzed drill hole cores. Modified from Freitas et al. (2017). Gr. = Group; Fm. = Formation

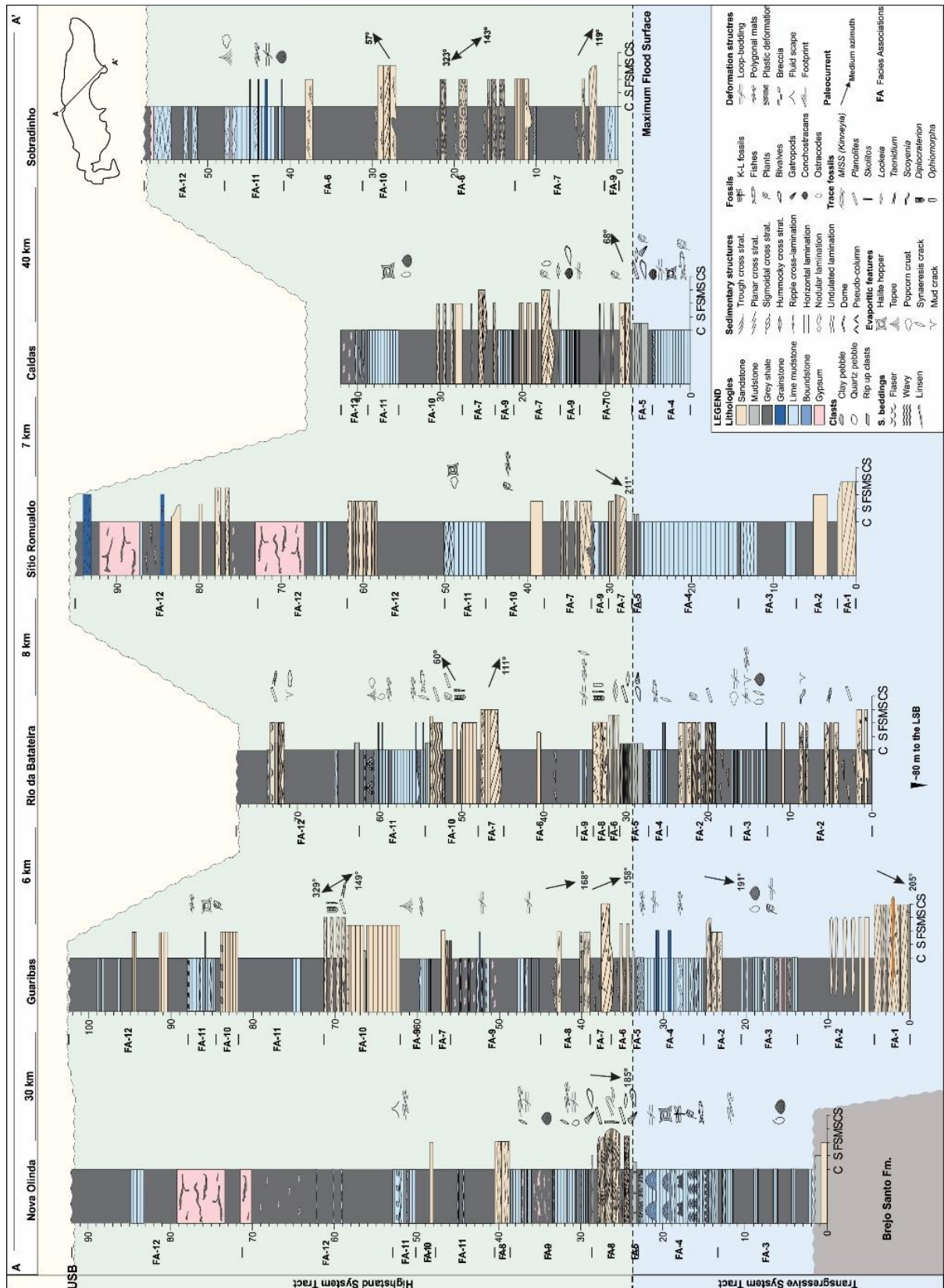


Figure 2 – Columnar sections measured in the Araripe Basin. Correlation among the sections was constrained using the maximum flood surface as the stratigraphic datum. USB = Upper Sequence Boundary; LSB = Lower Sequence Boundary. C = Clay; S = Silt; FS = Fine Sand; MS = Medium Sand; CS = Coarse Sand.

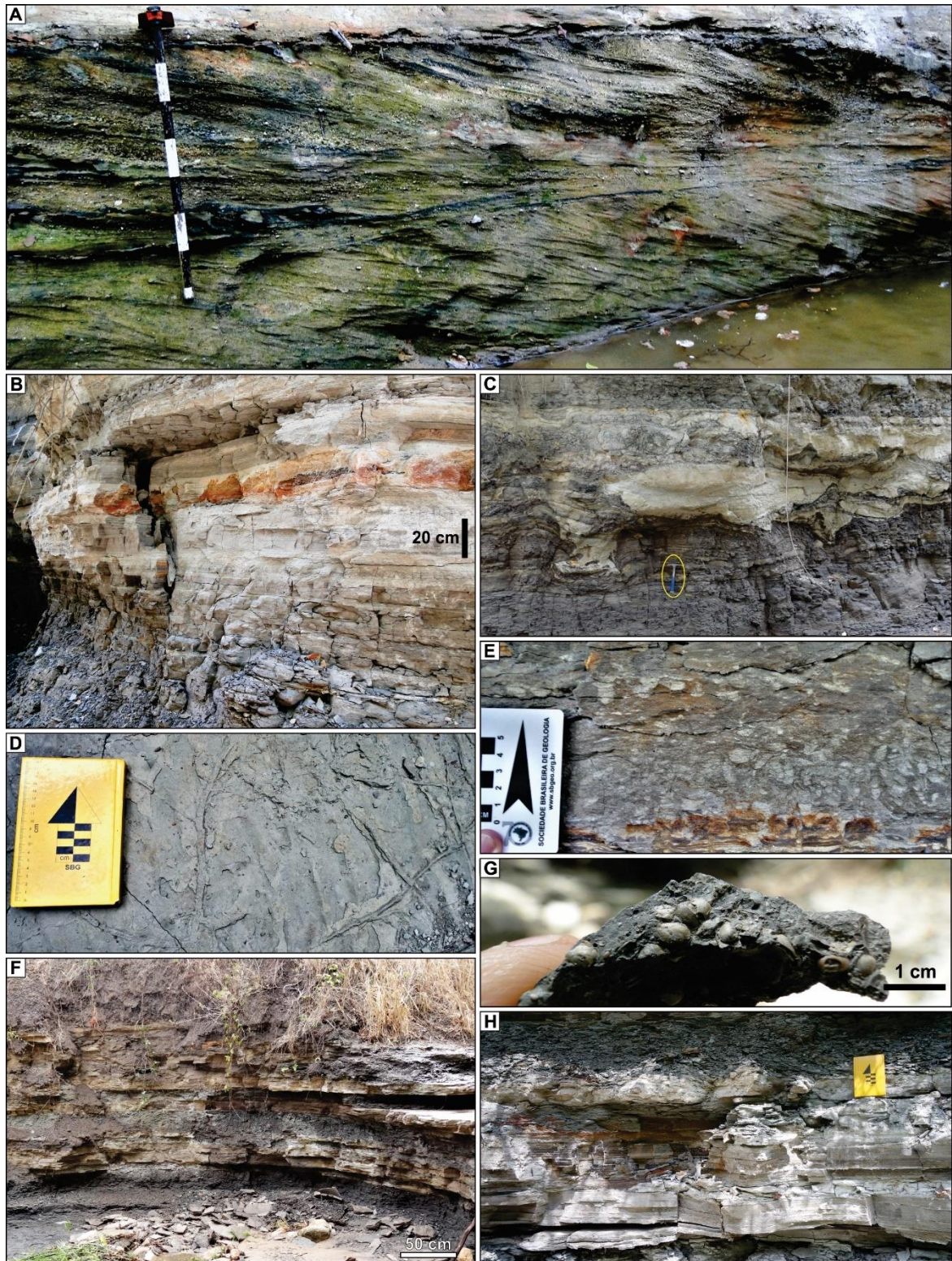


Figure 3 – Transition of fluvial to lake deposits (FA-1 to FA-3). A: Pebbly, coarse-grained sandstones with trough cross-stratification. B: Coarsening upward succession of mudstones grading to sandstones. Note the red level in the upper part of the image with a carbonized trunk. C: Cross-bedded sandstones in shales presenting flame and ball-and-pillow structures. D: Simple unbranched horizontal traces in the surface of ripple cross-laminated sandstones. E: Highly bioturbated mudstone bed with vertical traces. F: Interbedded limestones and dark shales. G: Conchostracan-rich shales. H: Planar laminites with evaporite laminae. The hoe in A is 75 cm and the hammer in C is 25 cm.

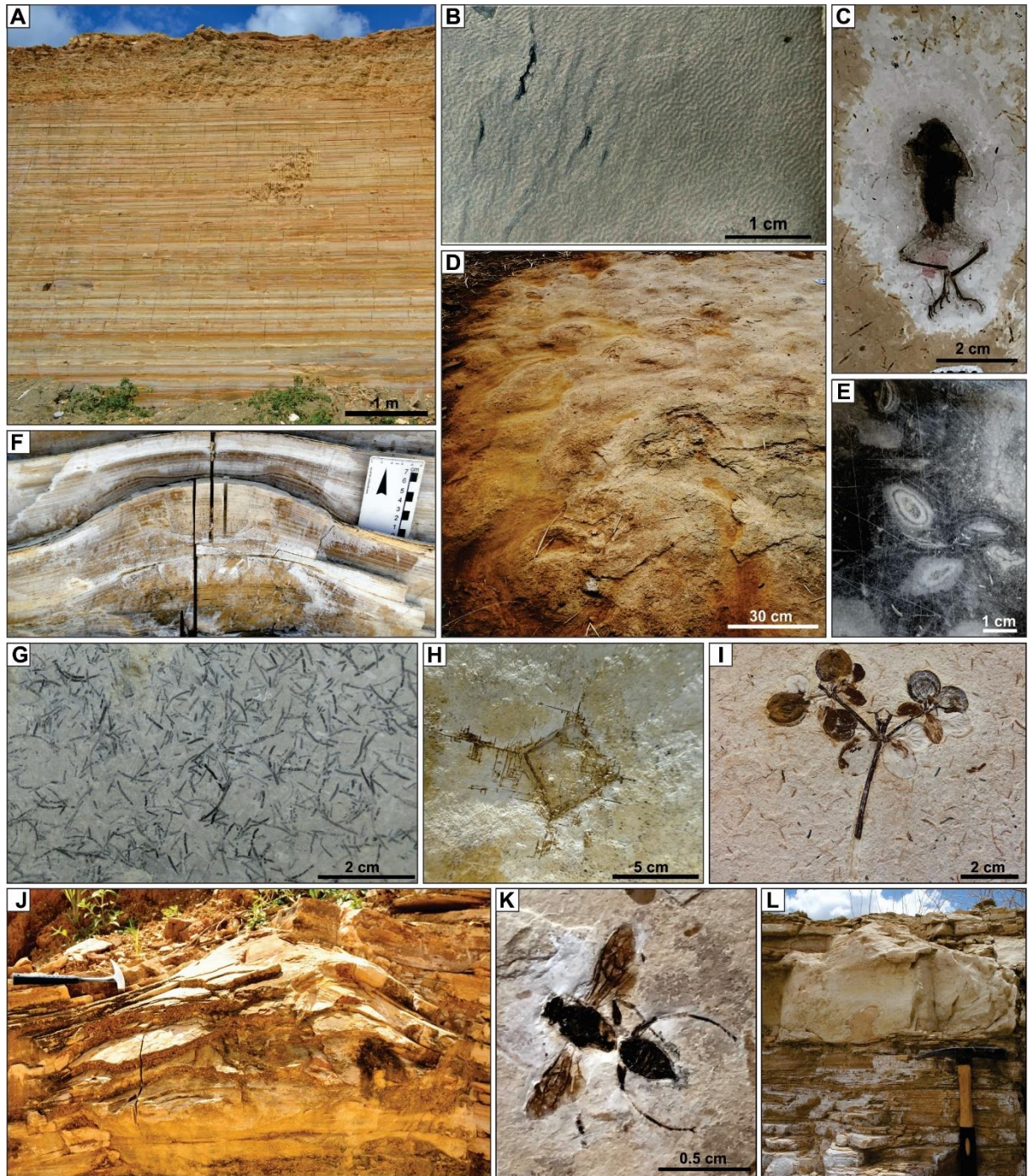


Figure 4 – The Crato Konservat-Lagerstätte interval (FA-4). A: General view showing monotonous planar laminated limestones. B: *Kinneyia*-type wrinkle structures. C: Frog preserved in the lower part of the carbonate bank. D: Small-size and coalescent pseudo-columnar stromatolites. E: Slab showing oncoids that are often associated to the pseudo-columnar stromatolites. F: Domal stromatolite showing branching in the top. G: *Botryococcus* algae. H: Halite hopper. I: Angiosperm specimen preserved in planar laminite. J: Big-size domal stromatolite. K: Insect specimen in the laminites of the upper bank. L: Massive limestone with flame structure in the top of the carbonate bank. The hammer in J and L is 33 cm long.

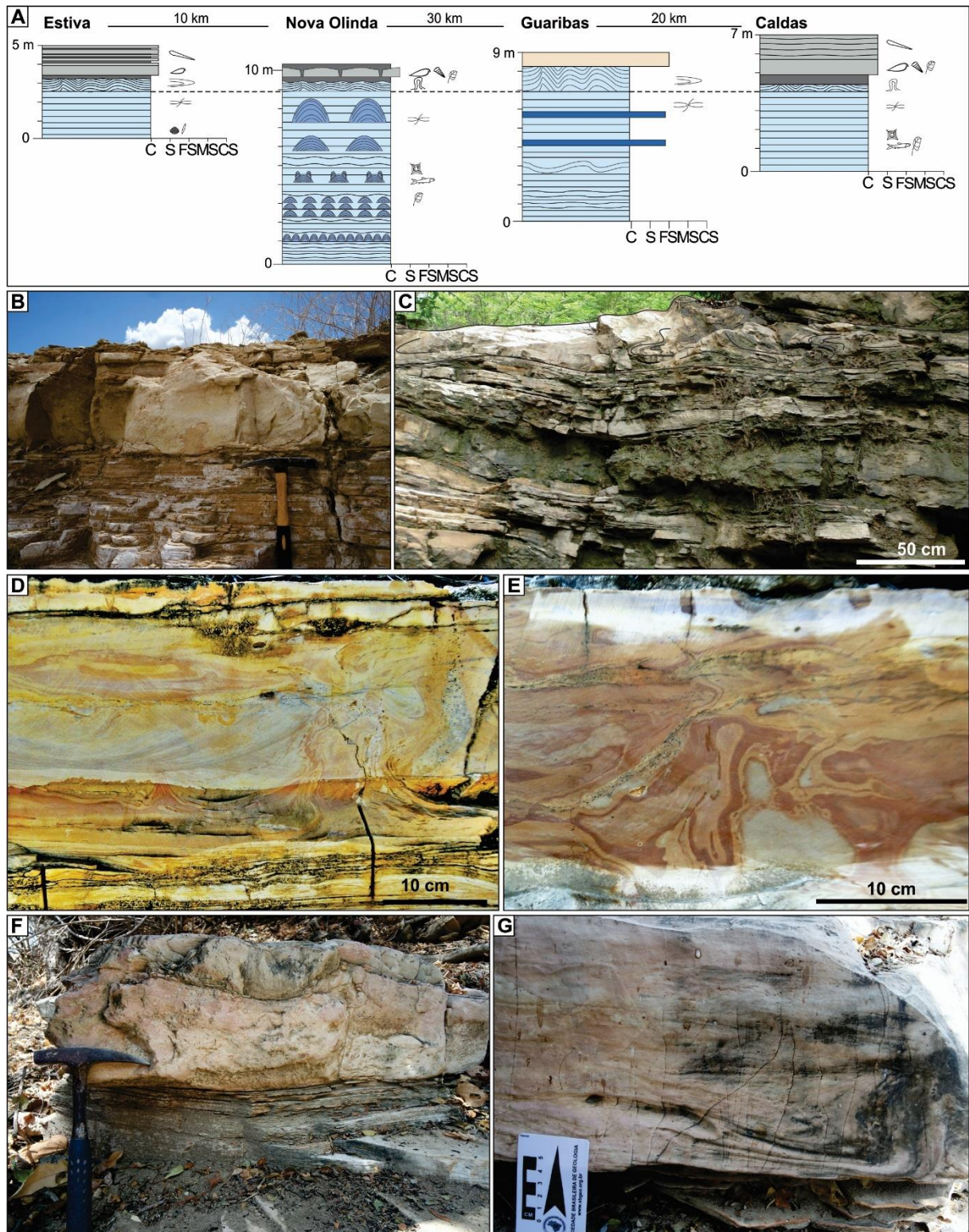


Figure 5 – Soft-sediment deformation structures (SSDS. A: Positioning of the SSDS in the top of the FA-4 and below the marine mudstone beds. B: Close up view of the positioning of the seismite bed in the top of the limestone bank of the FA-4. Note the massive aspect of the bed and the presence of a diapir-like structure. C: Deformed bed in the top of limestones in the Guaribas section, showing mostly recumbent folds. D-E: Ductile deformation and fluid scape structures in Santana do Cariri. F: Obliterated lamination by deformation in the Estiva section. G: Fold truncated by sub-horizontal lamination.

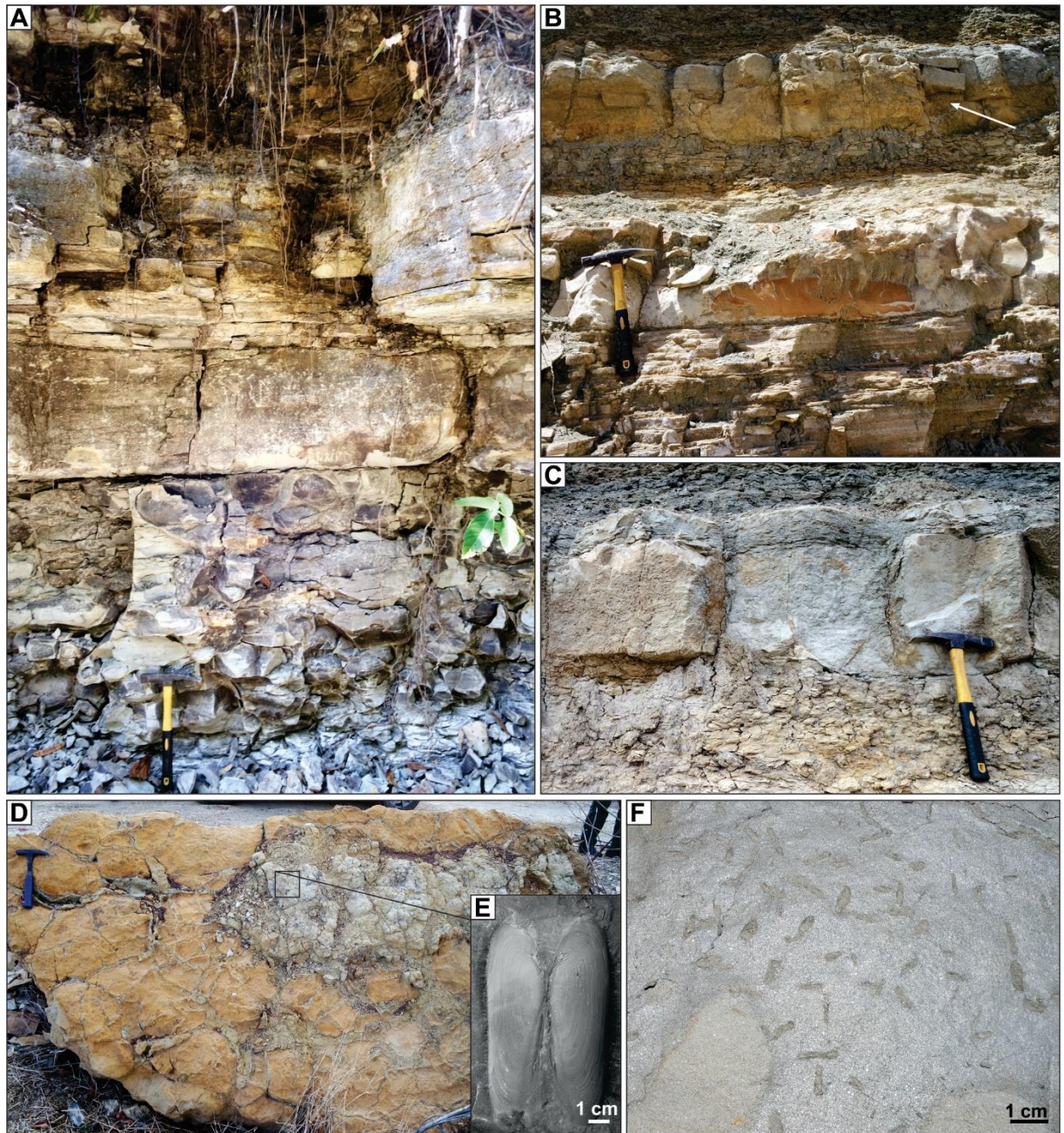


Figure 6 – Fossiliferous mudflat (FA-5). A: Bivalve- and gastropod-bearing mudstone succession in the Batateira section. B: Positioning of the mudstone bed (white arrow) in relation to the limestones of the FA-4. C: Detail of the bivalve-rich mudstone showing mud cracks filled by the upper shales. D: Cracked upper surface filled by siltstone. E: Examples of the tellinacean bivalve found in the mudstone beds. F: Moderately bioturbated surface by *Diplocraterion* and probably *Lockeia*. The hammer in A, B, and C is 33 cm long.

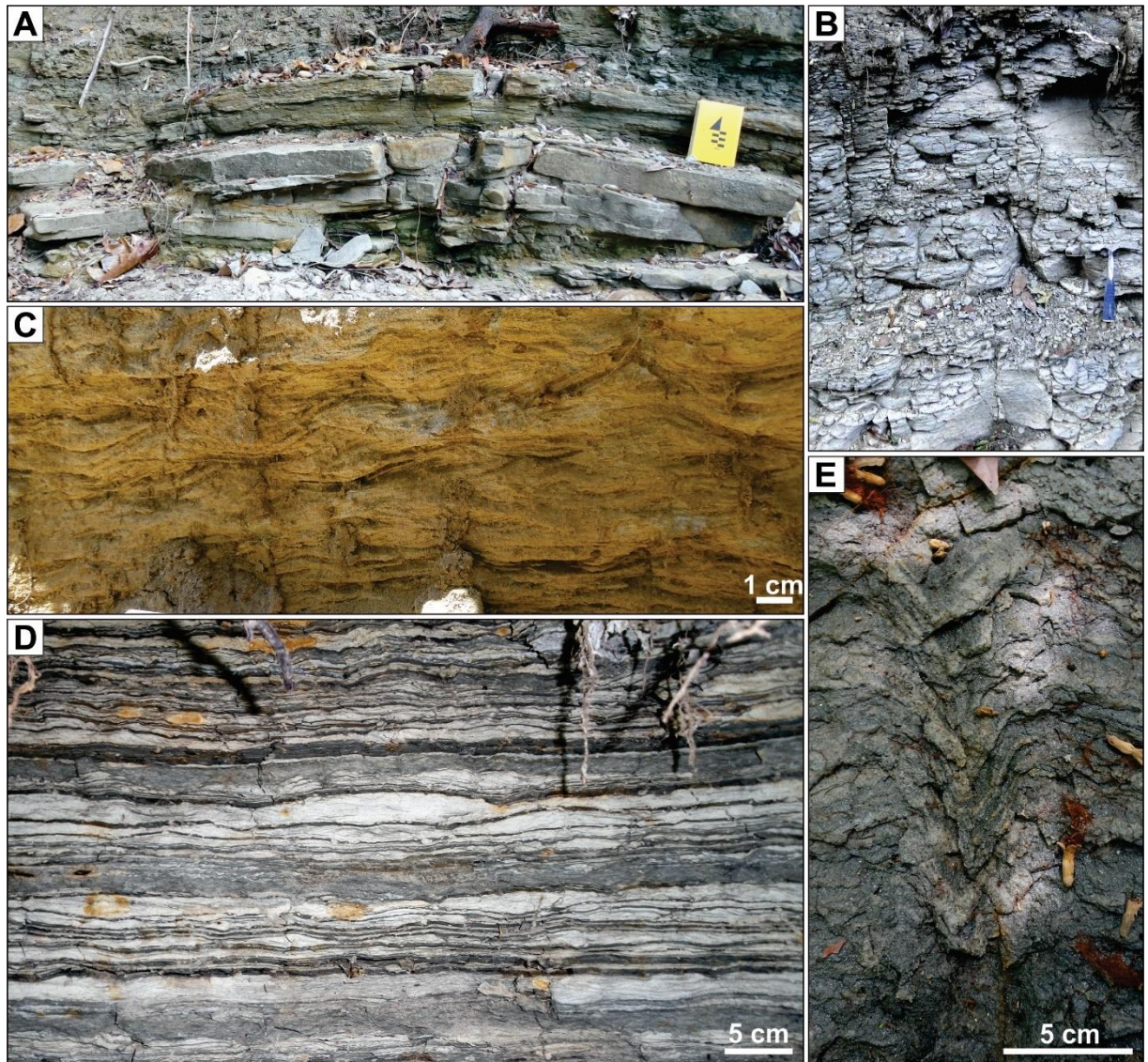


Figure 7 – Storm-influenced distal shelf deposits (FA-6). A: Hummocky cross-bedded sandstone. B: Grey shales. C: Wave ripple cross-laminated sandstones. D: Low to moderate bioturbated shale with linsen/wavy bedding. E: Fugichnia trace in micaceous, fine-grained sandstone.

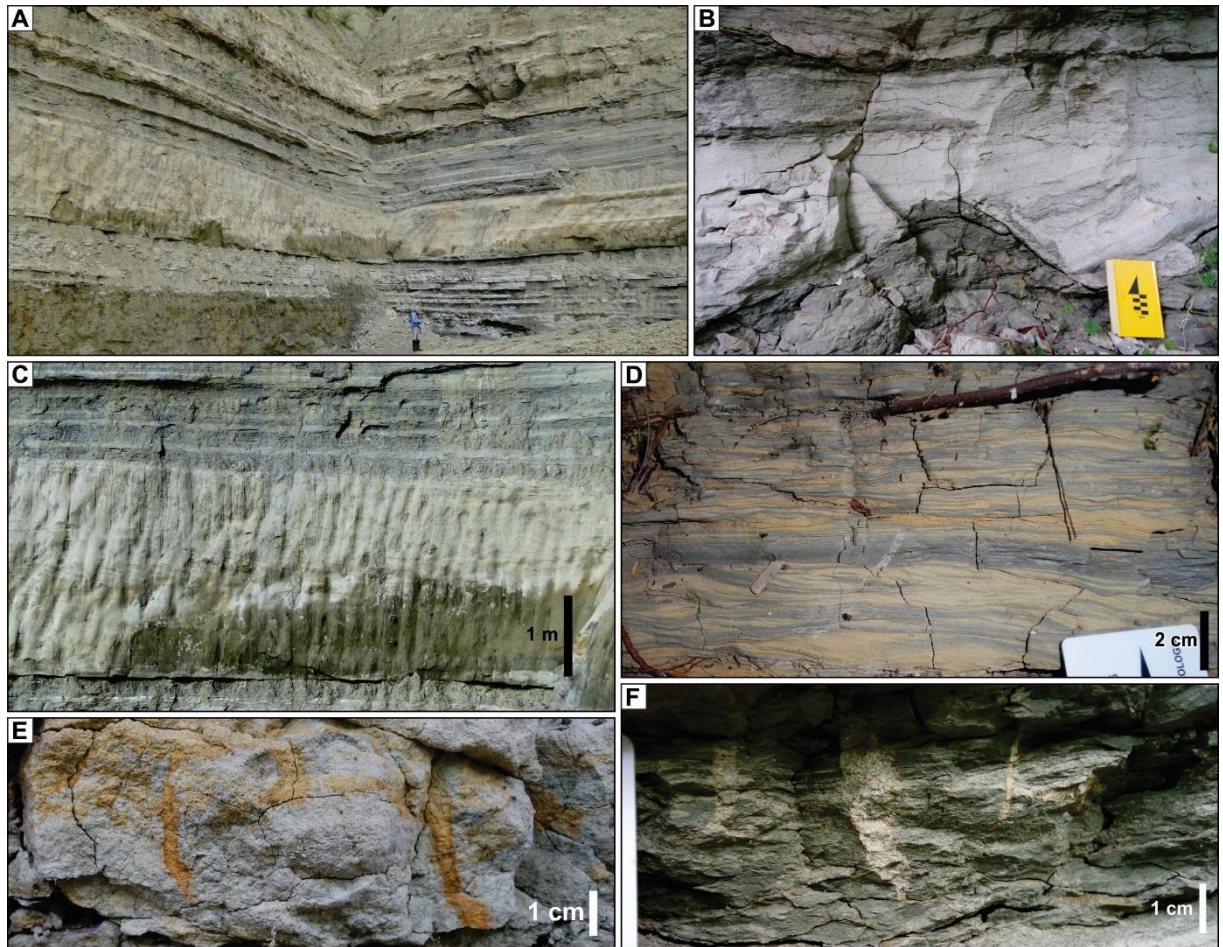


Figure 8 – Subtidal sandbar deposits (FA-7). A: General view showing successions with cross-bedded sandstones interbedded with shales. B: Detail of the base of cross-bedded sandstones showing flame structure. C: Sigmoid cross-bedded sandstone. D: Fine-grained sandstone with wavy bedding. E: Vertical traces in the top of a sandstone bed. F: Vertical traces filled by sand in shales.

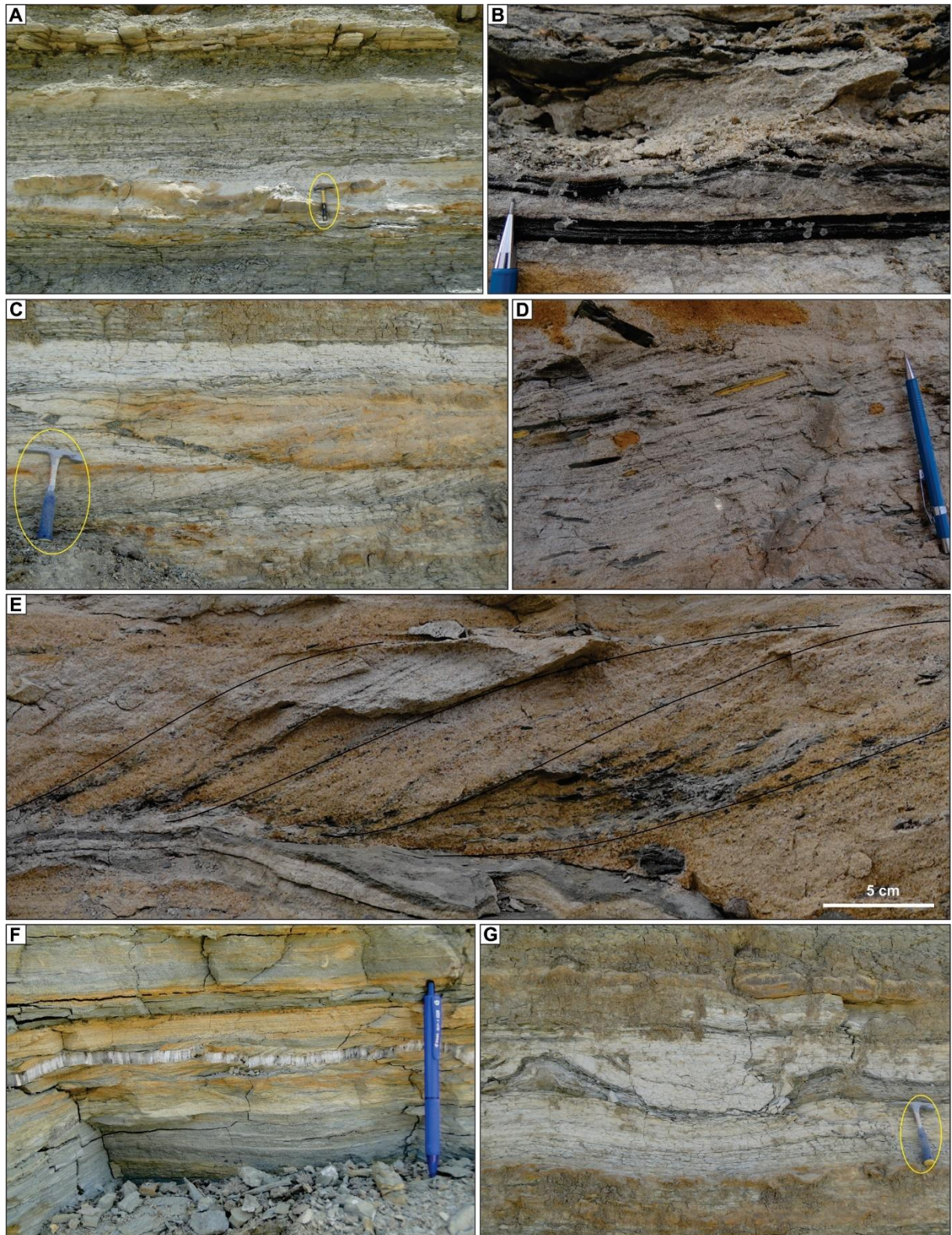


Figure 9 – Mixed tidal flat facies association (FA-8). A: Meter-scale heterolithic succession. B: Ripple cross-laminated sandstone with fluid mud. C: Reactivation surface in cross-bedded sandstones. Note the occurrence of rip-up clasts. D: Rip-up clasts in the foresets of cross-bedded sandstones. E: Sigmoidal strata with mud drapes in distinct intervals probably showing neap-spring cycles. F: Sandstone with flaser/wavy bedding. G: Undertrack in heterolithic strata. The hammer in A is 33 cm long and the hammer in C and G is 25 cm. The automatic pencil in B, D, and F is 15 cm in length.

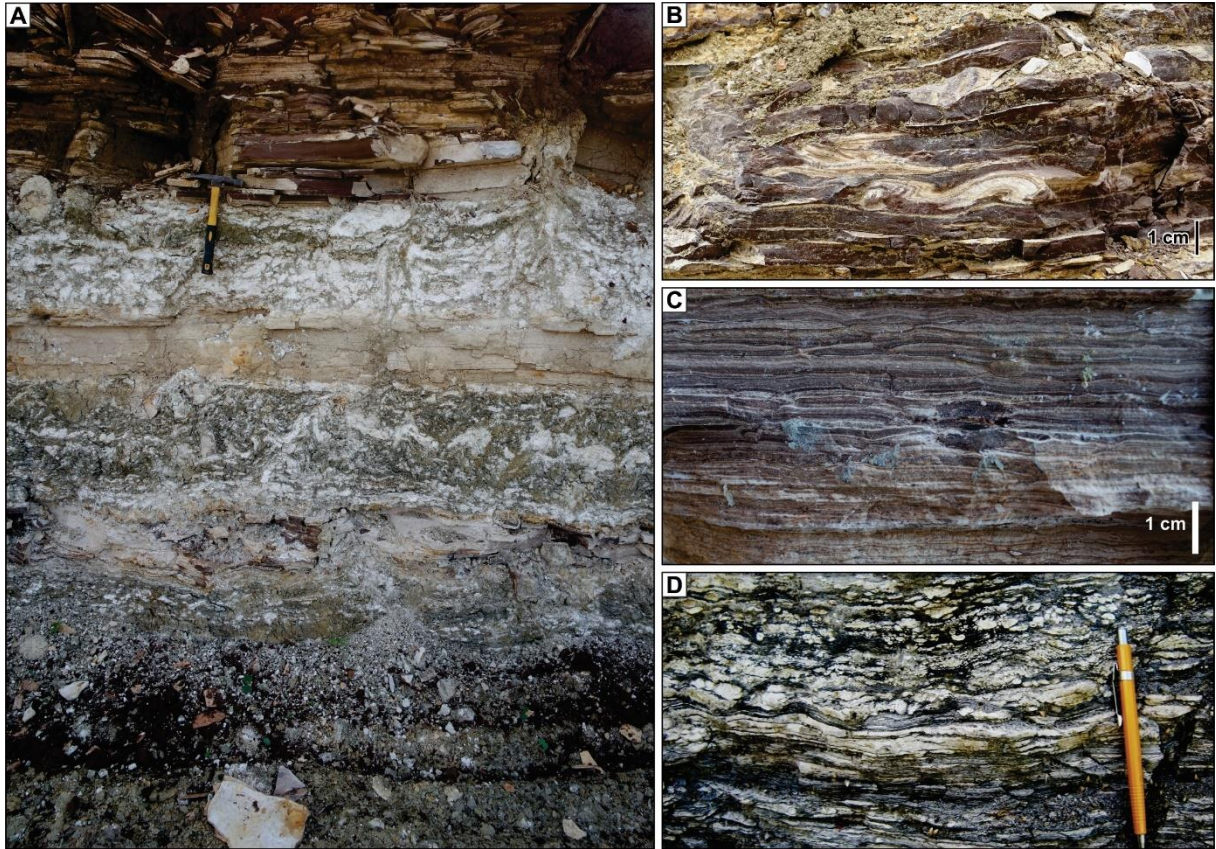


Figure 10 – Sabkha facies association (FA-9). A: Interbedded paleosols (shales with enterolithic folding) and limestones. B: Evaporitic deformation in limestones. C: Loop-bedding structures in limestones. D: Gypsum/carbonate nodules in black shales.

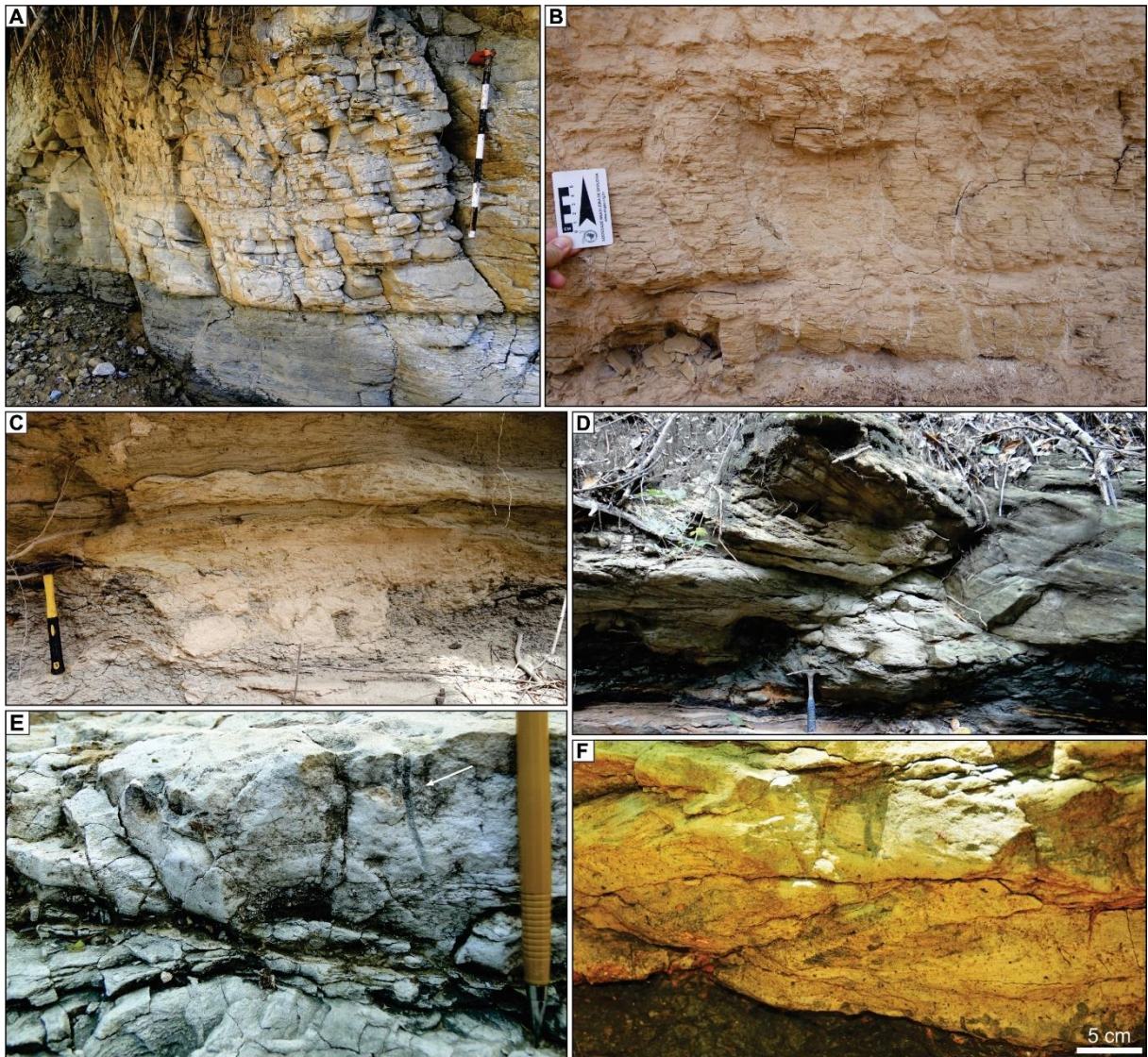


Figure 11 – Barrier island/lagoon deposits (FA-10). A: Tabular bed of sandstones with horizontal stratification and ripple cross-lamination B: Horizontally stratified sandstones. C: Ball-and-pillow deformation at base of sandstone bed containing ripple cross-lamination. D: Ebb/flood delta characterized by cross-bedded sandstones interbedded with lagoonal shales. E: Vertical traces in the top of the cross-bedded sandstones. F: Different types of vertical bioturbation in sandstones.

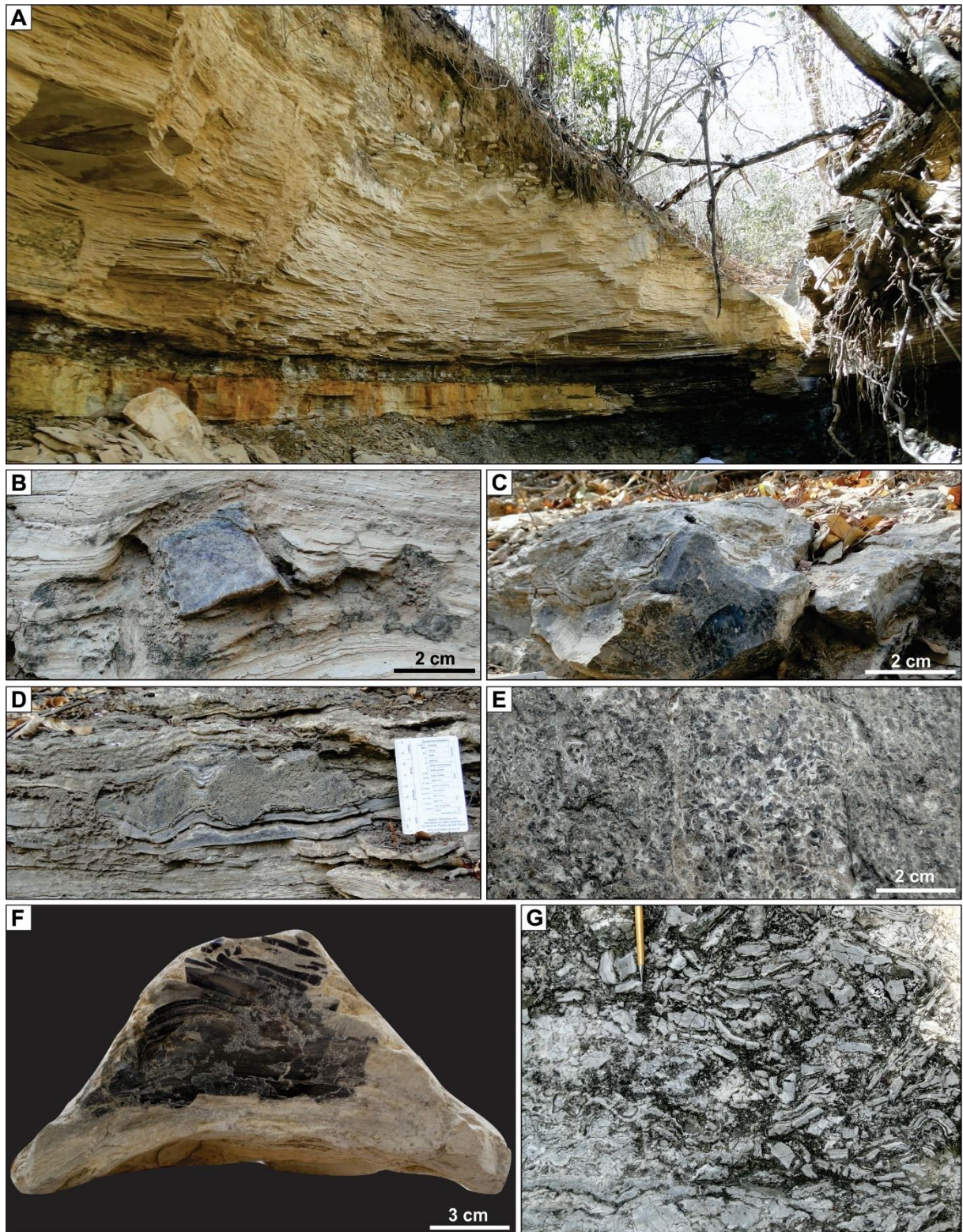


Figure 12 – Coastal hypersaline lake deposits (FA-11). A: General view of the limestone beds typical of the FA-11. B: silicified halite crystal deforming planar laminites; C: Tepee-structure in the upper portion of laminites. D: Nodular laminite. E: Popcorn crust. F: Silicified stromatolite with brecciated top. G: Evaporitic breccia. The automatic pencil in F and I is 15 cm in length.

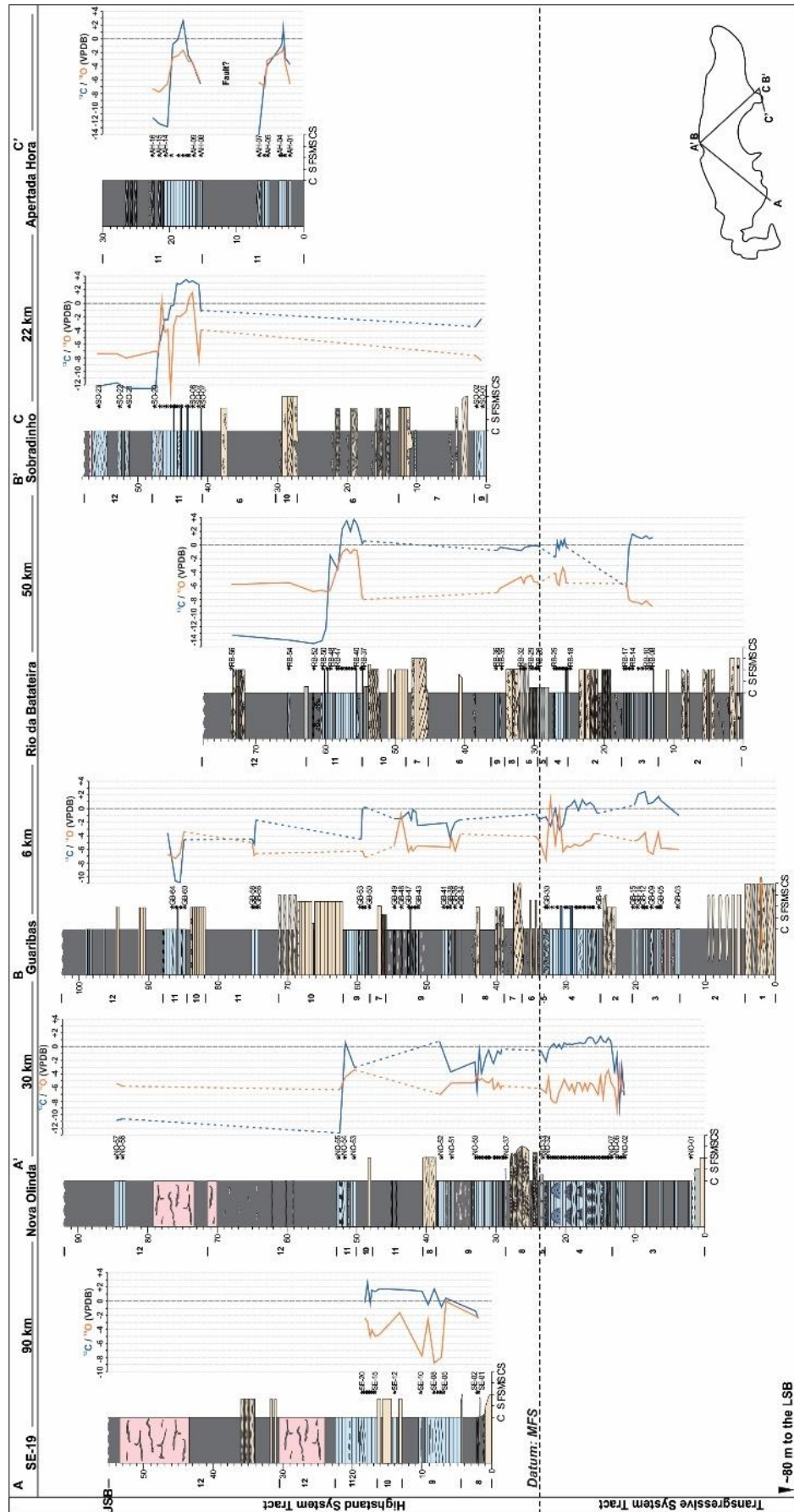


Figure 13 – Stable isotope curves in the main Crato Formation sections of the Araripe Basin. C = Clay; S = Silt; FS = Fine Sand; MS = Medium Sand; CS = Coarse Sand.

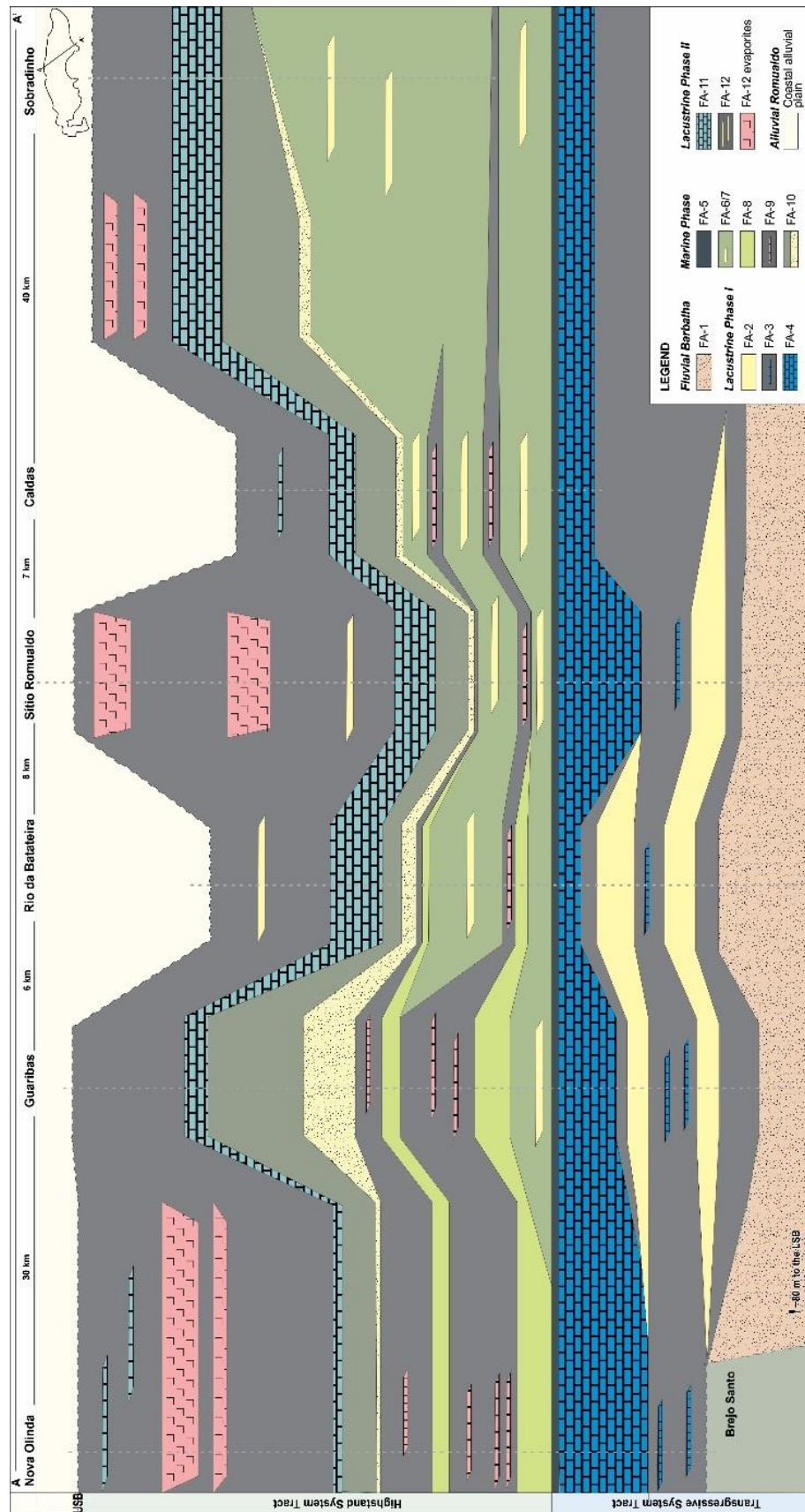


Figure 14 – Correlation of the different facies associations in the measured columnar sections.

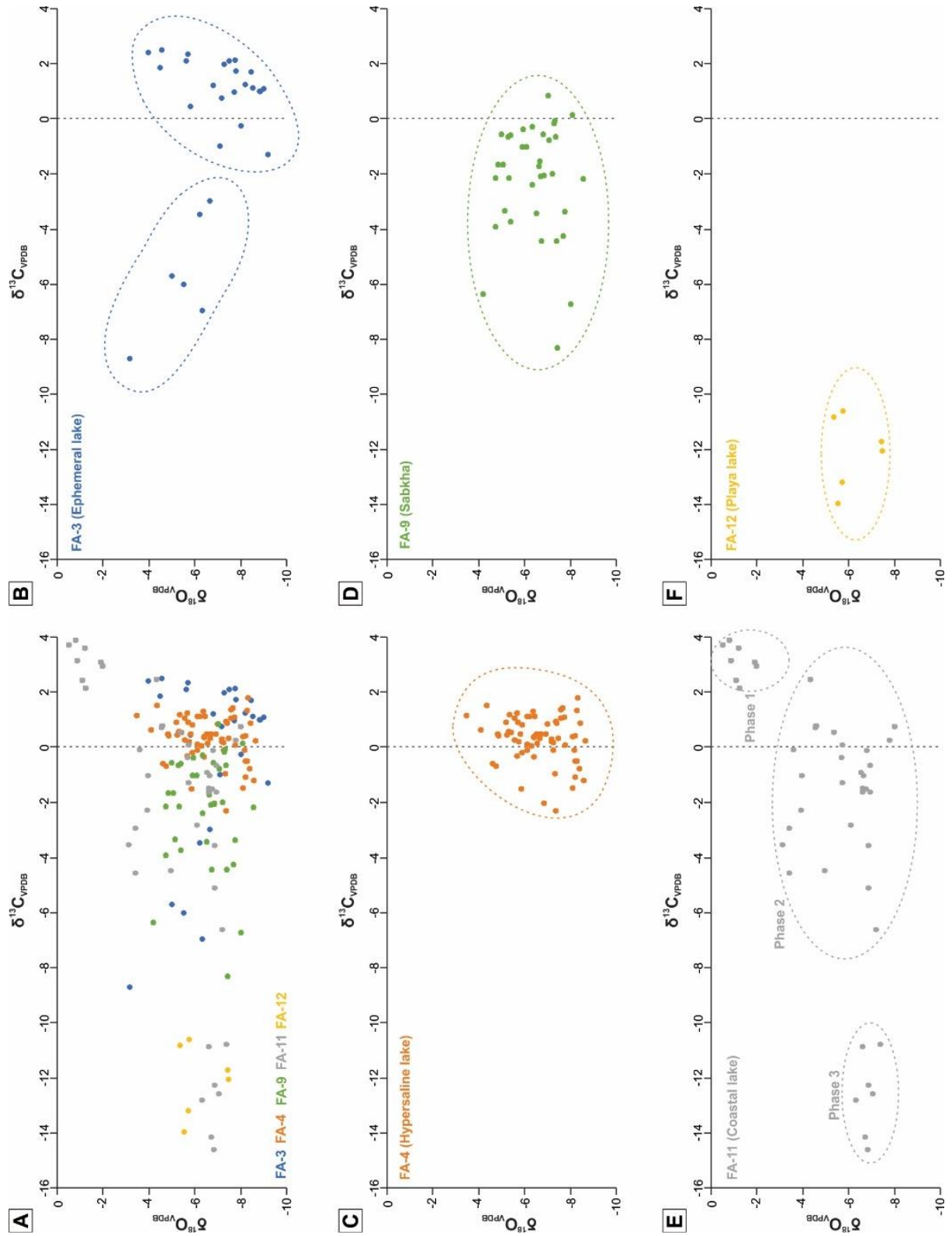


Figure 15 – Cross-plot diagrams of the stable carbon and oxygen isotopes. A: Cross-plot of all facies associations. B: Ephemeral lake. C: Hypersaline lake. D: Sabkha. E: Coastal lake. F: Playa lake.

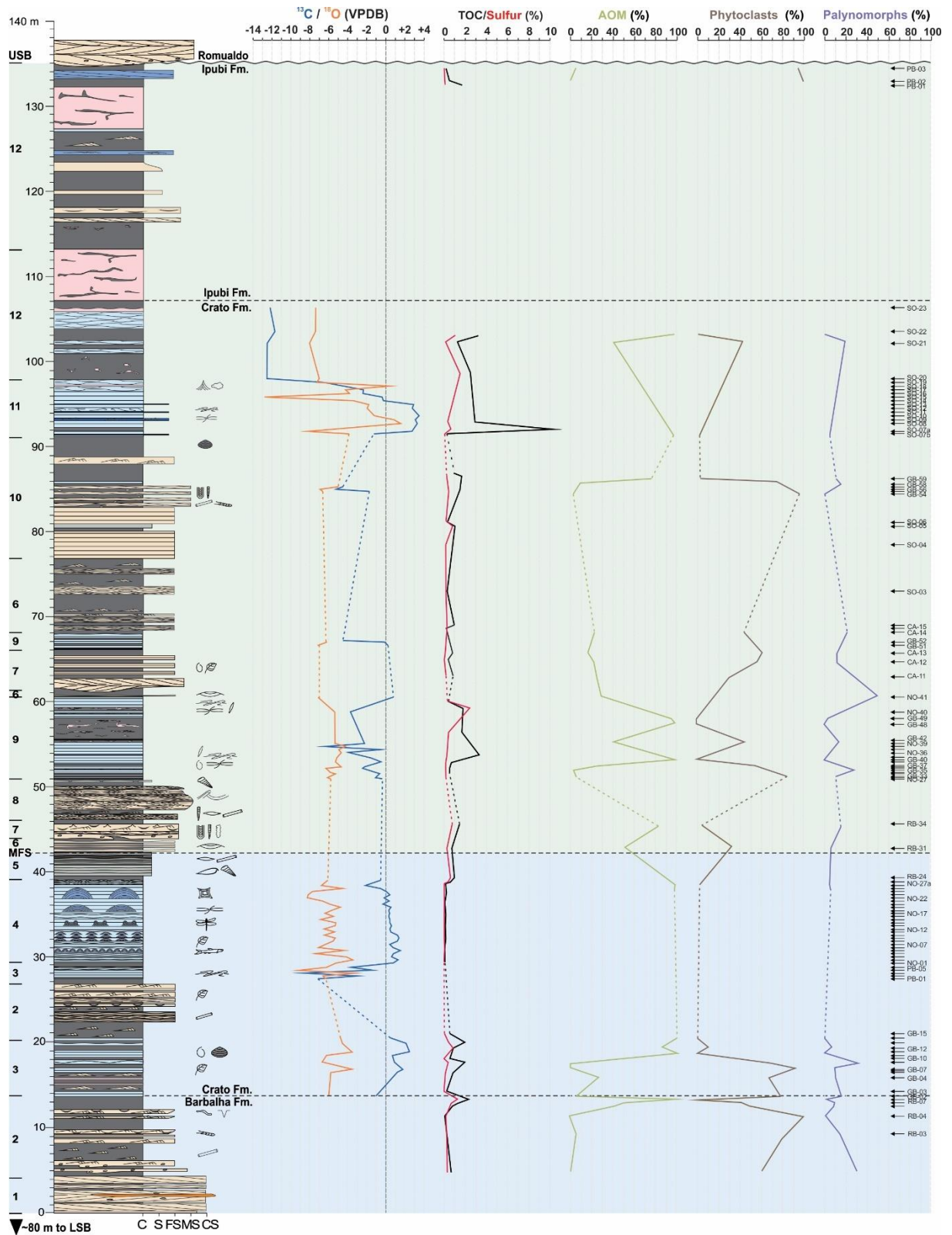


Figure 16 - Composite section of the Crato Formation constructed by stacking of different parts of the measured sections. Note the position of the stable isotope curves, TOC and S curves, and palynological content.

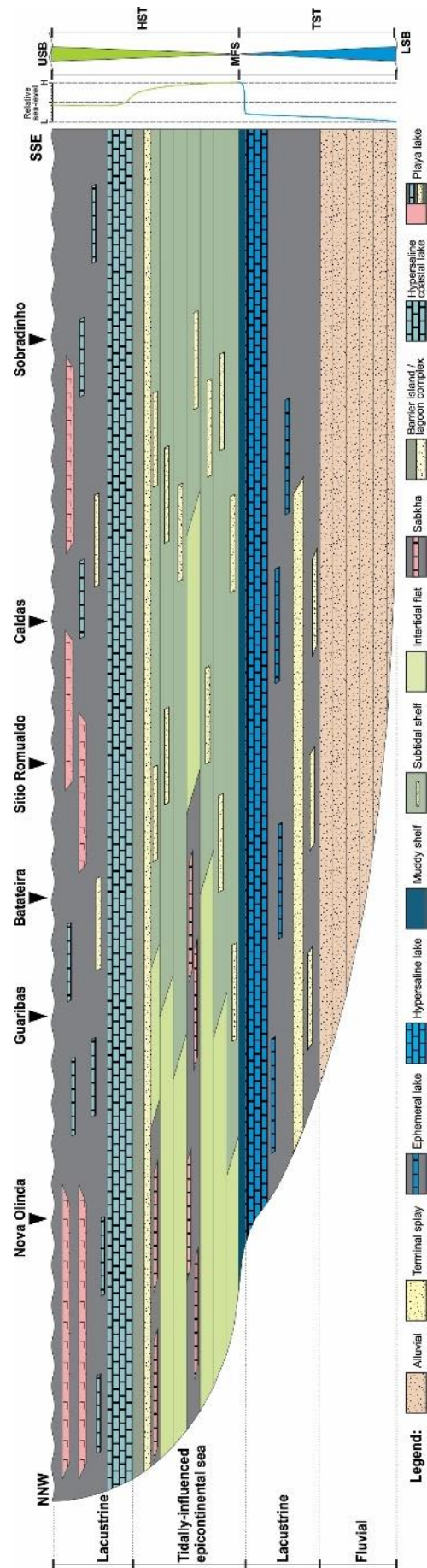


Figure 17 – Stratigraphic architecture of the DS-2 in the NNW-SSE direction.

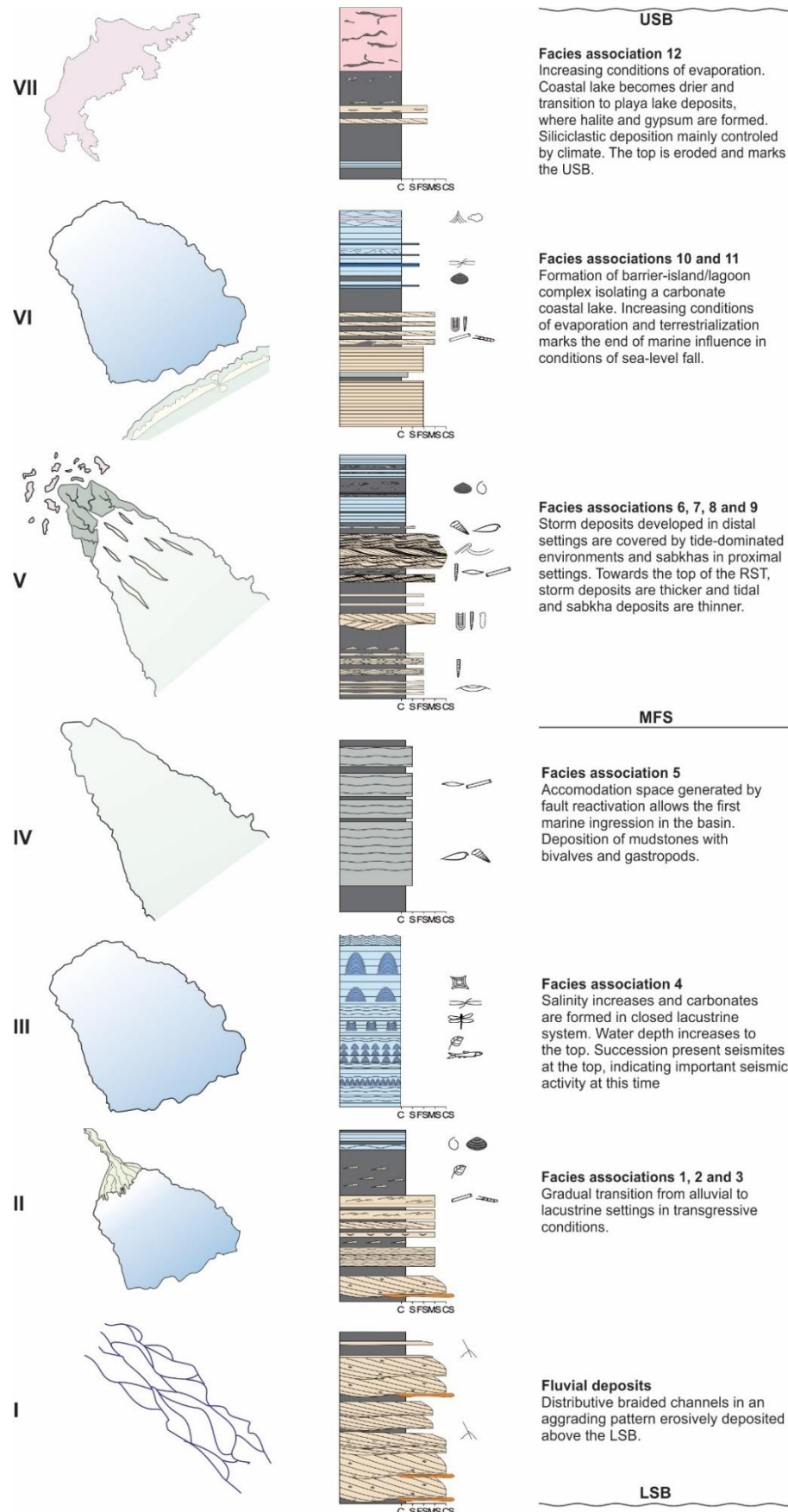


Figure 18 – Depositional model of the DS-2 showing the succession of events and the main stratigraphic surfaces.

Figure 19 – Chemo and lithostratigraphic correlation of the distinct scattered occurrences of the Crato Formation in NE Brazil.

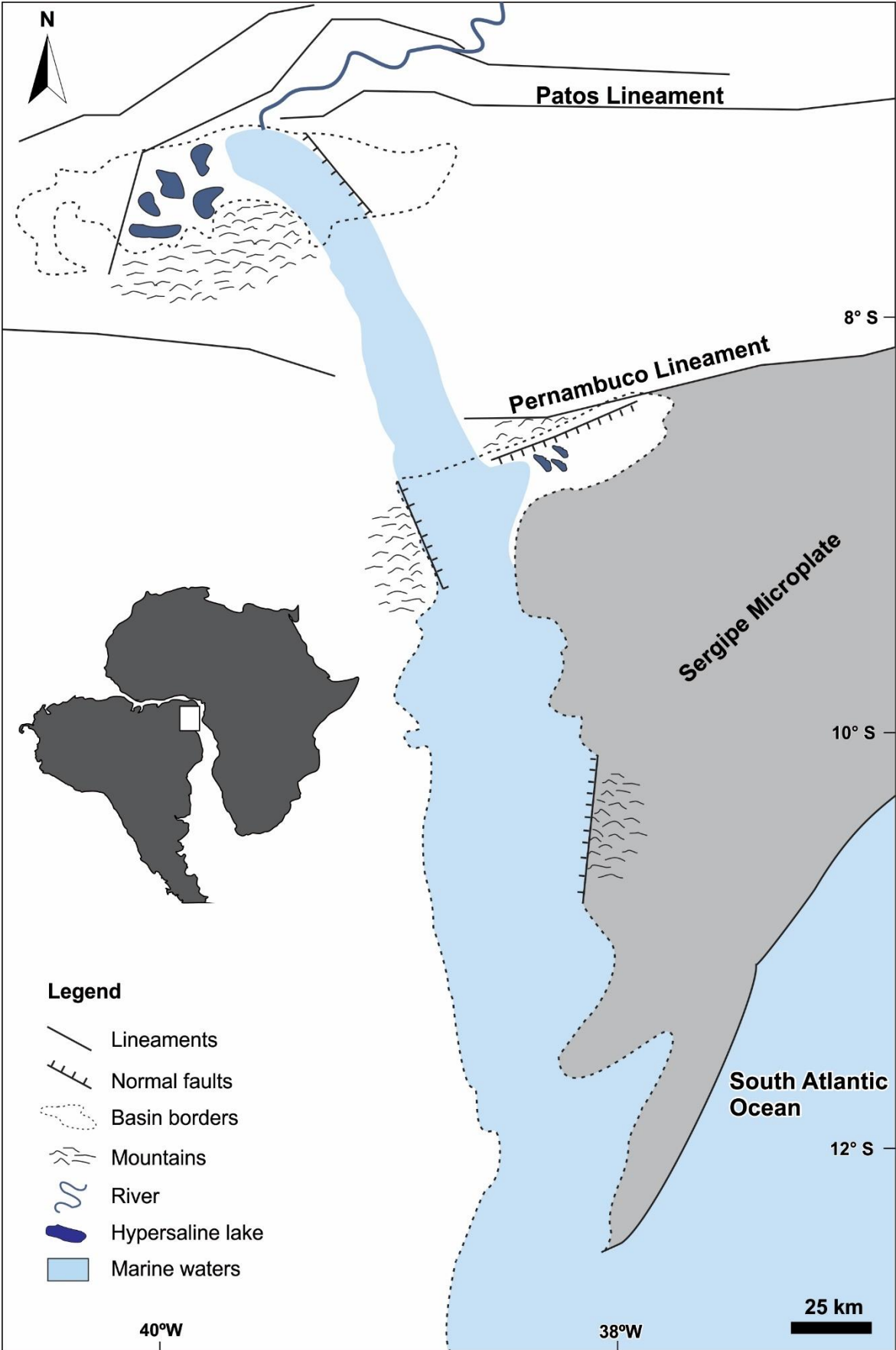


Figure 20 – Paleogeographic reconstitution of the marine ingression in the northeastern Brazil.
Table 1 – Isotopic and organic geochemistry data from the DS-2.

Form ation	Samp les	Lithology	F A	$\delta^{13}\text{C}$ PDB‰	$\delta^{18}\text{O}$ PDB‰	TOC (%)	Sulfur (%)	Phytocla sts (%)	AOM (%)	Palynomor phs (%)
<i>Pedra Branca, Nova Olinda (CE)</i>										
Ipubi	PB-01	Shale	1 2	-	-	0,47	0,03	100	0	0
Ipubi	PB-02	Shale	1 2	-	-	0,16	0,015	95,5	4,5	0
Ipubi	PB-03	Shale	1 2	-	-	0,14	0,7	30,6	69,4	0
<i>SE-19, Ipubi (PE)</i>										
Crato	SE-19-01	Planar laminite	9	-2,41	-2,20	-	-	-	-	-
Crato	SE-19-02	Nodular laminite	9	-1,30	-2,17	-	-	-	-	-
Crato	SE-19-05	Planar laminite	1 1	0,03	-1,65	-	-	-	-	-
Crato	SE-19-06	Wrinkle laminite	1 1	-0,82	-6,86	-	-	-	-	-
Crato	SE-19-08	Planar laminite	1 1	1,85	-7,24	-	-	-	-	-
Crato	SE-19-09	Planar laminite	1 1	-0,54	-2,53	-	-	-	-	-
Crato	SE-19-10	Planar laminite	1 1	1,29	-6,59	-	-	-	-	-
Crato	SE-19-12	Planar laminite	1 1	1,56	-1,81	-	-	-	-	-
Crato	SE-19-15	Planar laminite	1 1	1,82	-4,11	-	-	-	-	-
Crato	SE-19-16	Planar laminite	1 1	1,27	-4,30	-	-	-	-	-
Crato	SE-19-17	Planar laminite	1 1	1,53	-3,72	-	-	-	-	-
Crato	SE-19-18	Planar laminite	1 1	-0,36	-4,42	-	-	-	-	-
Crato	SE-19-19	Wrinkle laminite	1 1	2,61	-2,87	-	-	-	-	-

Crato	SE-19-20	Planar laminite	1 1	-0,21	-2,27	-	-	-	-	-
Três Irmãos Quarry, Nova Olinda (CE)										
Crato	NO-01	Planar laminite	3	-5,76	-4,99	-	-	-	-	-
Crato	NO-02	Loop bedding laminite	3	-7,02	-6,33	-	-	-	-	-
Crato	NO-03	Planar laminite	3	-3,03	-6,66	-	-	-	-	-
Crato	NO-04	Planar laminite	3	-8,77	-3,15	-	-	-	-	-
Crato	NO-05	Wrinkle laminite	3	-1,32	-9,19	-	-	-	-	-
Crato	NO-06	Wrinkle laminite	3	-3,51	-6,22	-	-	-	-	-
Crato	NO-07	Planar laminite	4	0,88	-5,18	-	-	-	-	-
Crato	NO-08	Wrinkle laminite	4	1,13	-3,47	0,12	0	-	-	-
Crato	NO-09	Planar laminite	4	0,62	-4,1	-	-	-	-	-
Crato	NO-10	Wrinkle laminite	4	0,87	-7,41	-	-	-	-	-
Crato	NO-11	Stromatolite	4	1,49	-4,35	-	-	-	-	-
Crato	NO-12	Wrinkle laminite	4	0,83	-7,01	-	-	-	-	-
Crato	NO-13	Planar laminite	4	0,35	-6,4	-	-	-	-	-
Crato	NO-14	Planar laminite	4	1,06	-5,57	-	-	-	-	-
Crato	NO-15	Planar laminite	4	1,17	-5,35	-	-	-	-	-
Crato	NO-16	Wrinkle laminite	4	1,1	-6,46	-	-	-	-	-
Crato	NO-17	Stromatolite	4	0,54	-5,43	-	-	-	-	-
Crato	NO-18	Stromatolite	4	0,46	-6,52	-	-	-	-	-
Crato	NO-19	Planar laminite	4	0,57	-5,31	-	-	-	-	-
Crato	NO-20	Wrinkle laminite	4	0,44	-5,23	-	-	-	-	-
Crato	NO-21	Planar laminite	4	0,45	-6,92	0,08	0,5	-	-	-
Crato	NO-22	Planar laminite	4	0,24	-5,57	-	-	-	-	-

Crato	NO-23	Planar laminite	4	0,37	-6,4	-	-	-	-	-
Crato	NO-24	Planar laminite	4	0,2	-5,76	0,17	0,4	-	-	-
Crato	NO-25	Planar laminite	4	0,48	-4,81	-	-	-	-	-
Crato	NO-26	Rhythmite	4	-0,22	-5,91	-	-	-	-	-
Crato	NO-27	Rhythmite	4	0,31	-6,67	-	-	-	-	-
Crato	NO-28	Rhythmite	4	-0,12	-8,19	0,12	0,3	-	-	-
Crato	NO-29	Rhythmite	4	0,37	-8,1	-	-	-	-	-
Crato	NO-30	Rhythmite	4	0,06	-7,76	-	-	-	-	-
Crato	NO-31	Rhythmite	4	-0,59	-4,59	-	-	-	-	-
Crato	NO-32	SSDS lime mudstone	4	-2,03	-6,85	0,16	0,2	-	-	-
Crato	NO-33	Mudstone	5	-0,6	-6,06	0,1	0,4	-	-	-
Crato	NO-38	Loop bedding laminite	9	-0,39	-5,92	-	-	-	-	-
Crato	NO-39	Loop bedding laminite	9	-1,05	-6,07	0,23	0	-	-	-
Crato	NO-40	Loop bedding laminite	9	-0,68	-5,28	-	-	-	-	-
Crato	NO-41	Loop bedding laminite	9	-1,05	-5,89	-	-	-	-	-
Crato	NO-42	Loop bedding laminite	9	-2,42	-6,32	-	-	-	-	-
Crato	NO-43	Loop bedding laminite	9	-2,17	-4,71	-	-	-	-	-
Crato	NO-44	Loop bedding laminite	9	-0,62	-5,37	-	-	-	-	-
Crato	NO-46	Loop bedding laminite	9	-1,68	-5,05	-	-	-	-	-
Crato	NO-47	Loop bedding laminite	9	-3,95	-4,71	-	-	-	-	-

Crato	NO-48	Loop bedding laminite	9	-0,59	-4,98	0,15	0	-	-	-
Crato	NO-49	Loop bedding laminite	9	-6,39	-4,17	-	-	-	-	-
Crato	NO-50	Loop bedding laminite	9	-2,16	-5,31	-	-	-	-	-
Crato	NO-51	Planar laminite	9	-3,76	-5,38	-	-	-	-	-
Crato	NO-52	Planar laminite	9	0,84	-7,02	-	-	-	-	-
Crato	NO-53	Planar laminite	1 1	-3,03	-3,39	-	-	-	-	-
Crato	NO-54	Planar laminite	1 1	0,60	-4,55	-	-	-	-	-
Crato	NO-55	Planar laminite	1 1	- 12,7 7	-6,30	-	-	-	-	-
Ipubi	NO-56	Planar laminite	1 2	- 10,6 6	-5,81	-	-	-	-	-
Ipubi	NO-57	Planar laminite	1 2	- 10,9 0	-5,42	-	-	-	-	-
Guaribas river, Crato (CE)										
Barbalha	GB-02	Shale	3	-	-	0,3	0,07	78,7	4,6	16,7
Crato	GB-03	Loop bedding laminite	3	-1,04	-7,09	-	-	-	-	-
Crato	GB-04	Shale	3	-	-	0,8	0,2	66,2	24,1	9,7
Crato	GB-05	Marl	3	1,17	-6,8	-	-	-	-	-
Crato	GB-06	Shale	3	-	-	2,01	0,47	91,6	0	8,4
Crato	GB-07	Marl	3	1,83	-4,48	-	-	-	-	-
Crato	GB-08	Shale	3	-	-	0,65	0,07	68,1	0	31,9
Crato	GB-09	Planar laminite	3	0,93	-7,73	-	-	-	-	-
Crato	GB-10	Marl	3	0,72	-7,18	-	-	-	-	-
Crato	GB-11	Marl	3	2,47	-4,55	0,92	0,88	0	100	0
Crato	GB-13	Shale	3	-	-	2	0,51	9,7	85,3	5

Crato	GB-14	Marl	3	2,08	-5,62	-	-	-	-	-
Crato	GB-15	Marl	3	0,41	-5,81	0,63	0,11	0	100	0
Crato	GB-16	Planar laminite	4	-0,71	-4,76	-	-	-	-	-
Crato	GB-16	Planar laminite	4	0,39	-4,85	-	-	-	-	-
Crato	GB-17	Wrinkle laminite	4	0,9	-5,71	-	-	-	-	-
Crato	GB-18	Wrinkle laminite	4	0,45	-5,8	-	-	-	-	-
Crato	GB-19	Wrinkle laminite	4	1,28	-6,39	-	-	-	-	-
Crato	GB-20	Wrinkle laminite	4	-0,35	-6,41	-	-	-	-	-
Crato	GB-21	Wrinkle laminite	4	-	-	0,33	0,05	-	-	-
Crato	GB-22	Wrinkle laminite	4	1,12	-6,21	-	-	-	-	-
Crato	GB-23	Wrinkle laminite	4	0,45	-6,72	-	-	-	-	-
Crato	GB-24	Wrinkle laminite	4	0,14	-6,55	-	-	-	-	-
Crato	GB-25	Wrinkle laminite	4	-2,3	-7,36	-	-	-	-	-
Crato	GB-26	Wrinkle laminite	4	-3,07	-1,25	-	-	-	-	-
Crato	GB-27	Wrinkle laminite	4	0,05	-6,29	-	-	-	-	-
Crato	GB-28	Wrinkle laminite	4	-2,63	0,18	0,38	0,03	-	-	-
Crato	GB-29	Wrinkle laminite	4	-1,2	-8,57	-	-	-	-	-
Crato	GB-31	Wrinkle laminite	6	-1,53	-5,85	-	-	-	-	-
Crato	GB-32	Planar laminite	6	-0,8	-5,04	-	-	-	-	-
Crato	GB-33	Shale	9	-	-	0,3	0,02	84,8	5,4	9,8
Crato	GB-34	Loop bedding laminite	9	-1,68	-4,84	-	-	-	-	-
Crato	GB-35	Shale	9	-	-	0,35	0,01	69,2	4,7	26
Crato	GB-36	Loop bedding laminite	9	-2,02	-7,19	-	-	-	-	-
Crato	GB-37	Shale	9	-	-	0,55	0,01	57,3	23,3	19,4

Crato	GB-38	Wrinkle laminite	9	-3,36	-5,13	-	-	-	-	-
Crato	GB-39	Loop bedding laminite	9	-4,46	-6,71	-	-	-	-	-
Crato	GB-40	Planar laminite	9	-2,1	-6,68	3,11	0,13	0	100	0
Crato	GB-41	Planar laminite	9	-2,07	-6,82	-	-	-	-	-
Crato	GB-42	Shale	9	-	-	1,5	0,28	58	41,6	13,8
Crato	GB-43	Loop bedding laminite	9	-3,45	-6,51	-	-	-	-	-
Crato	GB-44	Breccia	9	-0,57	-6,79	-	-	-	-	-
Crato	GB-45	Wrinkle laminite	9	-0,17	-7,27	-	-	-	-	-
Crato	GB-46	Wrinkle laminite	9	-1,75	-6,62	-	-	-	-	-
Crato	GB-47	Breccia	9	-0,66	-7,33	-	-	-	-	-
Crato	GB-48	Grainstone	9	-1,54	-1,87	1,62	2,24	0	100	0
Crato	GB-49	Grainstone	9	-1,56	-6,66	0,23	0,17	0	97,1	2,9
Crato	GB-50	Shale	1 0	-	-	1,45	0,05	22,4	28,4	49,2
Crato	GB-51	Planar laminite	9	0,14	-8,06	-	-	-	-	-
Crato	GB-52	Planar laminite	9	-0,09	-7,32	-	-	-	-	-
Crato	GB-53	SSDS laminite	9	-4,48	-7,38	-	-	-	-	-
Crato	GB-54	Sandstone	1 0	-	-	0,15	0,01	98	1,6	0,3
Crato	GB-55	Shale	1 0	-	-	1,3	0,35	75,1	9,7	15,2
Crato	GB-56	Planar laminite	1 1	-1,73	-6,62	-	-	-	-	-
Crato	GB-57	Planar laminite	1 1	-5,16	-6,86	-	-	-	-	-
Crato	GB-58	Planar laminite	1 1	-4,54	-4,95	-	-	-	-	-
Crato	GB-59	Shale	1 0	-	-	1,5	0,09	11,6	77,7	10,7
Crato	GB-60	Planar laminite	1 1	-4,61	-3,40	-	-	-	-	-

Crato	GB-61	Planar laminite	1 1	- 10,8 6	-6,62	-	-	-	-	-
Crato	GB-62	Wrinkle laminite	1 1	- 10,7 7	-7,38	-	-	-	-	-
Crato	GB-63	Wrinkle laminite	1 1	-4,33	-6,97	-	-	-	-	-
Crato	GB-64	Wrinkle laminite	1 1	-3,65	-6,87	-	-	-	-	-
Batateira river, Crato (CE)										
Barba lha	RB-01	Sandstone	2	-	-	0,7	0,06	64,9	14,3	20,8
Barba lha	RB-02	Sandstone	2	-	-	0,63	0,07	59,9	13,5	26,6
Barba lha	RB-03	Shale	2	-	-	0,27	0,11	78,5	4,7	16,8
Barba lha	RB-04	Sandstone	2	-	-	0,12	0,03	98,7	0	1,3
Crato	RB-05	Shale	3	-	-	0,89	0,24	50,3	41,6	8,1
Crato	RB-06	Shale	3	-	-	1,26	0,32	40,1	50,6	9,4
Crato	RB-07	Shale	3	-	-	2,24	0,63	0	98,7	1,3
Crato	RB-8	Planar laminite	3	1,06	-9,02	-	-	-	-	-
Crato	RB-9	Planar laminite	3	0,95	-8,82	1,46	0,14	0	100	0
Crato	RB-10	Planar laminite	3	1,21	-8,20	0,51	0,16	0	100	0
Crato	RB-11	Planar laminite	3	0,96	-8,84	0,1	0,01	0	100	0
Crato	RB-12	Planar laminite	3	1,08	-8,51	0,1	0,01	0	100	0
Crato	RB-13	Shale	3	-	-	4,18	0,54	0,3	98,8	0,9
Crato	RB-14	Planar laminite	3	1,67	-8,44	-	-	-	-	-
Crato	RB-15	Wrinkle laminite	3	-0,29	-8,00	-	-	-	-	-
Crato	RB-16	Wrinkle laminite	3	-6,07	-5,50	-	-	-	-	-
Crato	RB-17	Wrinkle laminite	3	-3,14	-3,99	-	-	-	-	-
Crato	RB-18	Planar laminite	4	-0,34	-5,66	-	-	-	-	-
Crato	RB-19	Planar laminite	4	0,84	-3,97	-	-	-	-	-

Crato	RB-20	Planar laminite	4	-0,17	-3,42	-	-	-	-	-
Crato	RB-21	Planar laminite	4	-	-	0,51	0,19	0	97,4	2,6
Crato	RB-22	Planar laminite	4	0,55	-4,37	-	-	-	-	-
Crato	RB-23	Planar laminite	4	-0,75	-5,95	-	-	-	-	-
Crato	RB-24	Planar laminite	4	0,29	-5,62	0,95	0,34	0	98,1	1,9
Crato	RB-25	Planar laminite	4	-1,87	-4,09	-	-	-	-	-
Crato	RB-26	Marl	5	-0,11	-5,79	-	-	-	-	-
Crato	RB-27	Marl	5	-0,04	-5,58	-	-	-	-	-
Crato	RB-28	Marl	5	0,05	-5,48	-	-	-	-	-
Crato	RB-29	Marl	5	-0,09	-4,48	-	-	-	-	-
Crato	RB-30	Marl	6	-0,26	-4,92	-	-	-	-	-
Crato	RB-31	Marl	6	-0,54	-5,70	0,68	0,13	31,1	47,2	21,7
Crato	RB-32	Marl	6	-0,77	-4,84	-	-	-	-	-
Crato	RB-34	Shale	9	-	-	1,32	0,38	1,4	80,6	18
Crato	RB-35	Loop bedding laminite	9	-0,31	-6,31	-	-	-	-	-
Crato	RB-36	Planar laminite	9	-0,78	-7,03	-	-	-	-	-
Crato	RB-37	Grainstone	1 1	0,63	-7,99	-	-	-	-	-
Crato	RB-38	Planar laminite	1 1	0,15	-7,79	0,11	0,02	-	-	-
Crato	RB-39	Planar laminite	1 1	1,52	-7,71	-	-	-	-	-
Crato	RB-40	Shale	1 1	-	-	9,81	0,33	1	95,8	3,2
Crato	RB-41	Planar laminite	1 1	3,00	-0,87	-	-	-	-	-
Crato	RB-42	Planar laminite	1 1	3,72	-0,77	2,87	0,19	-	-	-
Crato	RB-43	Planar laminite	1 1	2,01	-1,22	-	-	-	-	-
Crato	RB-45	Planar laminite	1 1	3,56	-0,49	-	-	-	-	-

Crato	RB-46	Planar laminite	1 1	2,29	-1,06	-	-	-	-	-
Crato	RB-47	Planar laminite	1 1	-3,61	-3,10	-	-	-	-	-
Crato	RB-48	Planar laminite	1 1	-1,61	-6,76	-	-	-	-	-
Crato	RB-49	Grainstone	1 1	- 12,2 3	-6,85	-	-	-	-	-
Crato	RB-50	Planar laminite	1 1	- 14,1 0	-6,70	-	-	-	-	-
Crato	RB-51	Breccia	1 1	-	-	2,34	0,75	-	-	-
Crato	RB-52	Breccia	1 1	- 14,5 3	-6,84	-	-	-	-	-
Crato	RB-53	Shale	1 2	-	-	1,13	0,09	42,9	40,2	16,9
Crato	RB-54	Wrinkle laminite	1 2	- 14,0 2	-5,60	-	-	-	-	-
Crato	RB-55	Shale	1 2	-	-	4,17	0,51	1,3	98,7	0
Crato	RB-56	Planar laminite	1 2	- 13,2 7	-5,78	-	-	-	-	-

Caldas Quarry, Barbalha (CE)

Crato	CA-04	Shale	7	-	-	0,8	0,16	40	45,4	14,6
Crato	CA-05	Shale	9	-	-	0,82	0,1	25,3	66,3	8,3
Crato	CA-06	Planar laminite	9	-	-	1,18	0,18	4,9	83,1	12
Crato	CA-07	Shale	9	-	-	2,22	0,21	2,5	88,6	9
Crato	CA-08	Planar laminite	9	-	-	1,01	0,1	68,5	23,2	8,3
Crato	CA-10	Shale	7	-	-	1,12	0,14	34,6	28,1	37,3
Crato	CA-12	Shale	7	-	-	0,91	0,07	60,2	24,8	15
Crato	CA-13	Shale	7	-	-	1,09	0,11	68,9	19,5	11,6
Crato	CA-14	Shale	7	-	-	0,85	0,17	50,7	25,3	24
Crato	CA-15	Shale	7	-	-	0,22	0,01	90,2	2,6	7,2

Sobradinho river, Porteiras (CE)

Crato	SO-01	Planar laminite	9	-2,21	-8,53	-	-	-	-	-
Crato	SO-02	Planar laminite	9	-3,41	-7,75	-	-	-	-	-
Crato	SO-03	Shale	7	-	-	0,32	0,23	-	-	-
Crato	SO-04	Shale	6	-	-	0,17	0,13	-	-	-
Crato	SO-05	Shale	6	-	-	0,5	0,11	-	-	-
Crato	SO-06	Shale	6	-	-	0,68	0,83	-	-	-
Crato	SO-07a	Grainstone	1 1	-1,13	-3,96	-	-	-	-	-
Crato	SO-07b	Planar laminite	1 1	2,7	-8,28	-	-	-	-	-
Crato	SO-08	Planar laminite	1 1	3,14	1,52	-	-	-	-	-
Crato	SO-09	Planar laminite	1 1	3,02	0,79	-	-	-	-	-
Crato	SO-10	Grainstone	1 1	3,44	-1,18	-	-	-	-	-
Crato	SO-11	Planar laminite	1 1	-	-	-	-	-	-	-
Crato	SO-12	Planar laminite	1 1	2,78	-1,97	-	-	-	-	-
Crato	SO-13	Grainstone	1 1	2,94	-1,89	-	-	-	-	-
Crato	SO-14	SSDS laminite	1 1	-0,19	-3,58	-	-	-	-	-
Crato	SO-15	Planar laminite	1 1	-0,31	-	14,91	-	-	-	-
Crato	SO-16	Planar laminite	1 1	-2,36	-3,91	-	-	-	-	-
Crato	SO-17	Planar laminite	1 1	2,32	-4,33	-	-	-	-	-
Crato	SO-18	Wrinkle laminite	1 1	-0,83	0,33	-	-	-	-	-
Crato	SO-19	Wrinkle laminite	1 1	-6,64	-7,21	-	-	-	-	-
Crato	SO-20	Wrinkle laminite	1 1	-	12,5	-7,03	-	-	-	-
Crato	SO-21	Wrinkle laminite	1 2	-	12,5	-8,04	-	-	-	-
Crato	SO-22	Wrinkle laminite	1 2	-	11,7	-7,49	-	-	-	-

Crato	SO-23	Wrinkle laminite	1	-						
			2	12,13	-7,52	-	-	-	-	-
Apertada Hora (PE)										
Crato	AH-01	Planar laminite	1							
			1	-3,82	-6,73	-	-	-	-	-
Crato	AH-02	Planar laminite	1							
			1	-2,88	-3,74	-	-	-	-	-
Crato	AH-03	Planar laminite	1							
			1	1,67	-1,28	-	-	-	-	-
Crato	AH-03b	Planar laminite	1							
			1	-0,77	-1,92	-	-	-	-	-
Crato	AH-04	Planar laminite	1							
			1	-1,17	-2	-	-	-	-	-
Crato	AH-05	Planar laminite	1							
			1	-3,96	-3,18	-	-	-	-	-
Crato	AH-06	Planar laminite	1							
			1	-5,45	-6,98	-	-	-	-	-
Crato	AH-07	Wrinkle laminite	1							
			1	14,09	-6,39	-	-	-	-	-
Crato	AH-08	Planar laminite	1							
			1	-6,69	-6,45	-	-	-	-	-
Crato	AH-09	Planar laminite	1							
			1	-3,67	-3,33	-	-	-	-	-
Crato	AH-10	Planar laminite	1							
			1	-2,42	-3,13	-	-	-	-	-
Crato	AH-11	Planar laminite	1							
			1	2,7	-1,78	-	-	-	-	-
Crato	AH-12	Planar laminite	1							
			1	-0,09	-2,49	-	-	-	-	-
Crato	AH-13	Planar laminite	1							
			1	-0,83	-2,74	-	-	-	-	-
Crato	AH-14	Wrinkle laminite	1							
			1	12,92	-6,62	-	-	-	-	-
Crato	AH-15	Wrinkle laminite	1							
			1	12,48	-7,91	-	-	-	-	-
Crato	AH-16	Wrinkle laminite	1							
			1	-11,6	-7,38	-	-	-	-	-

III. ESTROMATÓLITOS DO APTIANO DA FORMAÇÃO CRATO, UM SISTEMA LACUSTRE HIPERSALINO NA BACIA DO ARARIPE, NORDESTE DO BRASIL

Os calcários laminados da Formação Crato historicamente foram alvo de grande atenção da comunidade científica devido a sua associação com fósseis tipicamente não-marinhos (*i.e.*, gimnospermas, angiospermas, fungos, artrópodes, peixes, pterossauros, anfíbios, répteis, aves). Desde a descoberta desta assembleia fóssil incomumente bem preservada, a origem desses

calcários tem sido longamente debatida na literatura brasileira e internacional (Martill et al., 2007). Dada sua monótona laminação plano-paralela horizontal, associação com algas do tipo *Botryococcus*, e a existência de pseudomorfos de halita e gipsita, os calcários laminados são interpretados como precipitados pela atividade planctônica de algas em porções distais de um imenso lago hipersalino. Nestas porções da bacia existiram momentos de maior anoxia e salinidade que permitiram a fossilização de elementos alóctones ao lago. No entanto, a descoberta de atividade microbiana muitas vezes associadas a elementos de água rasa em testemunhos de sondagem perfurados no intervalo fossilífero, apontam para interpretação bastante diferente daquela anteriormente defendida. A descrição sedimentológica dos intervalos carbonáticos são restritas a amostras pontuais estudadas apenas em lâminas delgadas e em microscópio eletrônico de varredura (Catto et al., 2016). Dessa forma, faltam critérios macroscópicos que integrem os dados pontuais obtidos e as interpretações paleoambientais e paleodeposicionais existentes. No intuito de averiguar a origem dos calcários laminados do intervalo *Konservat-Lagerstätte* da Formação Crato, foram estudadas seções nas principais ocorrências que estão localizadas na região dos municípios de Nova Olinda (CE) e Santana do Cariri (CE). A descrição detalhada das fácies sedimentares mostra que a laminação aparentemente monótona muitas vezes constitui localmente morfologias decimétricas a métricas características de estromatólitos. A descrição dos microbialitos e as interpretações decorrentes constam no artigo “*Stromatolites from the Aptian Crato Formation, a hypersaline lake system in the Araripe Basin, northeastern Brazil*” publicado no periódico *Facies*, apresentado a seguir.

Referências

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Stromatolites from the Aptian Crato Formation, a hypersaline lake system in the Araripe Basin, northeastern Brazil

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Received: 21 June 2016 / Accepted: 11 November 2016
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Abstract The origin of the Cretaceous laminites of the Crato Formation, Araripe Basin, northeastern Brazil, has been intensely debated since the beginning of the last century. The monotonous, up to 10-m-thick succession composed of very fine fossiliferous laminites in the middle of the unit lacked diagnostic features for assigning a chemically or biologically induced origin for this facies. The presence of a highly diverse and very well preserved allochthonous to parautochthonous fossil assemblage, associated with scattered halite pseudomorphs throughout the succession, led many authors to believe that these limestones were chemically deposited in a highly stressful, evaporitic shallow-water environment, such as a hypersaline lake close to marine environments. Recently, a micro- and ultrastructural analysis of the laminites yielded structures undoubtedly associated with a biological origin. Several examples of lithified in situ preserved coccoid and filamentous cells and extracellular polymeric substances suggest that the deposition of the laminated limestones was, at some levels,

strongly influenced by microbial activity. Here, we record various examples of stromatolite microbialites (mounds, domes, and pseudo-columns) found at distinct stratigraphic levels in the middle part of the Crato Formation. Macro-, meso-, and microscopic features confirm the biologically induced mineralization and the existence of metabolic activity of microbes during the formation of the laminites. Biomat growth may also have played a major role in the excellent preservation of fossils in this famous Cretaceous *Konservat-Lagerstätte* from Brazil.

Keywords Microbialites · Biologically induced carbonates · Santana Group · Lower Cretaceous · Aptian · Araripe Basin

Introduction

Laminated limestones are an intriguing sedimentary facies that occur in the geologic record from the Archean to the Holocene (e.g., Barthel et al. 1994; Sumner 1997; Trichet et al. 2001; Schopf 2006; Wittkop et al. 2009). Modern carbonate stromatolites occur in very different environments, from shallow-marine coastal settings (Dravis 1983; Reid et al. 1995) to high-altitude Andean lakes (Poiré et al. 2010; Farías et al. 2011, 2013). Simple, parallel, thin lamination in carbonate rocks can be formed by both organic and inorganic processes and does not allow to determine the origin of the deposit with certainty (Demicco and Hardie 1994). Furthermore, the usual absence of macroscopic and mesoscopic features, such as wrinkle surfaces and convex forms, make it difficult to define the chemical or biogenic origin of the carbonate (Buick et al. 1981; Riding 1991, 2008; Grotzinger and Knoll 1999). Due to these particularities, micro- and ultrastructural analyses are considered

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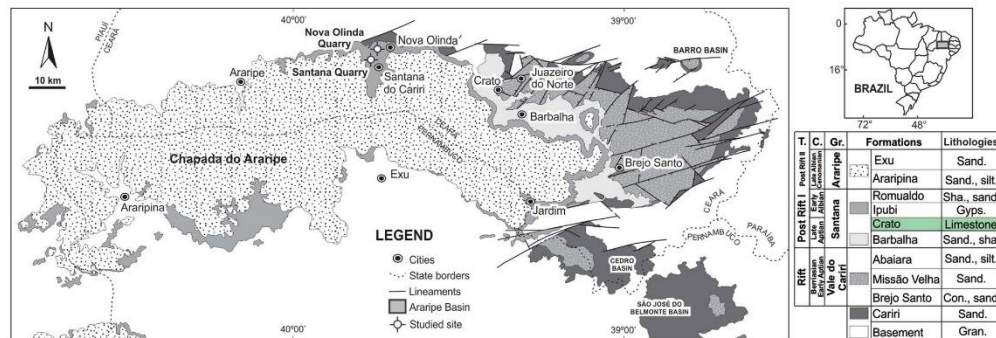


Fig. 1 Geologic map of the Chapada do Araripe area with the location of the studied sites (modified from Assine 2007). The stratigraphic column is summarized at the right. *T* tectono-stratigraphy; *Gr* group; *Sand.* sandstone; *Silt.* siltstone; *Sha.* shale; *Gyps* gypsum; *Con.* conglomerate

a powerful tool to investigate evidence of biomineralization, organomineralization, or chemical mineralization in carbonates (Benzerara et al. 2006; Dupraz et al. 2009). The presence of preserved cells (filaments, coccoids), EPS (extracellular polymeric substances) framework, micro-to nanometer organominerals and organic biomarkers are important evidence to identify the organic-derived origin of carbonates (Défarge et al. 1996; Jahnke et al. 2001; Dupraz et al. 2009).

The laminated facies of the Crato Formation, Aptian, Araripe Basin, northeastern Brazil, was object of several studies (Neumann 1999; Martill et al. 2007a; Heimhofer et al. 2010) mainly due to the presence of its spectacular paleontological archive. Fossil specimens are exceptionally well preserved, including important morphological details and soft tissues (Sayão and Kellner 1998), and define the Crato Formation as a *Konservat-Lagerstätte*. The unusual fossil preservation suggests that the carbonates were deposited in a reducing, hypersaline environment probably under the influence of microbial mats or even authigenic precipitation of calcite (Martill et al. 2007b; Heimhofer et al. 2010; Barling et al. 2015). Recent studies provide new data about the microbial origin of some laminated carbonate beds of the Crato Formation, developed in a saline environment, as indicated by halite hopper and successive gypsum layers (Catto et al. 2016).

Here, several examples of EPS framework, calcified coccoid and filamentous cells, and organominerals are recorded in the laminites of the analyzed stratigraphic interval, revealing the microbial influence during precipitation of such carbonate facies (Catto et al. 2016). In addition, we record and describe, for the first time, various examples of stromatolite structures found in carbonates of the lower Crato Formation (Nova Olinda Member) cropping out in quarries located in the vicinity of Santana do

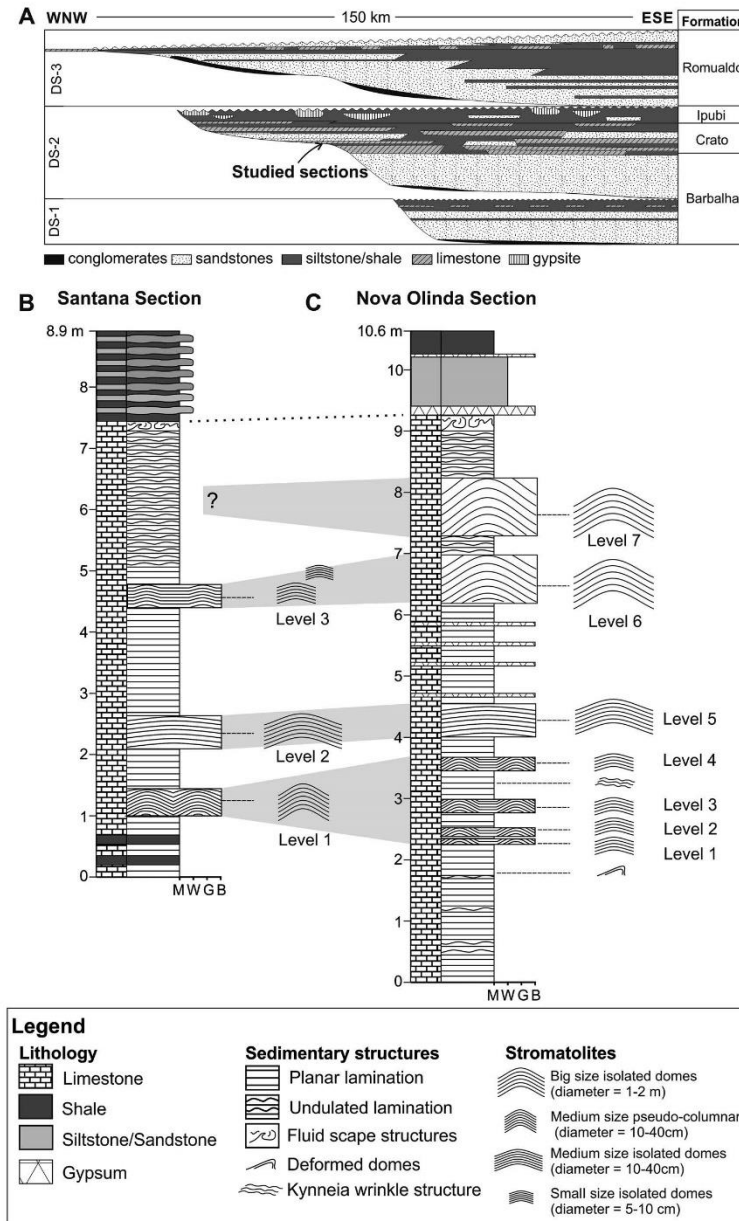
Cariri and Nova Olinda towns, State of Ceará, northeastern Brazil (Figs. 1, 2). The stromatolite structures occur at several stratigraphic levels, which apparently formed under shallow-water conditions, given their association with halite hopper, oncoids, wrinkle structures, and breccias. They constitute bioherms varying in size from 5 to 80 cm with domal and pseudo-columnar shapes, laterally separated by laminites. This confirms the intrinsic relationship between the limestones of the lower Crato Formation and biological activity related to biomineralization of calcium carbonate. It also strengthens the intrinsic relationship between microbialites and stressful environments, as well as the connection between microbial mats and the exceptional preservation of the fossils in this unit.

Geologic setting

The Gondwana breakup triggered the development of several rift basins in Brazil during the Cretaceous. Evidence of this noteworthy event extends from the Brazilian Continental Margin to intracratonic regions (Magnavita and Cupertino 1987; Milani and Davison 1988). The mechanical subsidence tied to the break-up of Africa and South America led to the formation of several hinterland basins at the intersection between the transtensive and distensive branches of the rift system (Matos 1992). The Araripe Basin is one of the most prominent examples of this phase because of its large extension and complex geological evolution (Assine 2007).

The Araripe Basin is limited in the north by the Patos Shear Zone and in the south by the Pernambuco Shear Zone, both oriented in an E–W direction (Castro and Branco 1999; Brito Neves et al. 2000). Besides these ductile shear zones, the structural framework also comprises

Fig. 2 Stratigraphy of the study area. **a** Stratigraphic framework scheme of the Araripe Basin with the location of the studied sections/outcrops. The distance between the two main quarry areas is approximately 20 km. *DS-1* depositional sequence 1; *DS-2* depositional sequence 2; *DS-3* depositional sequence 3 (Assine et al. 2014). This scheme has no vertical scale. **b** Composite stratigraphic section of laminites of the lower Crato Formation in the Santana quarries with positions of the domal and pseudo-columnar microbialite levels. **c** Composite stratigraphic section of laminites in the Nova Olinda quarries showing the positions of the stromatolite levels. The bands in light gray correlate with the microbialite levels in the two localities. *M* mudstone (carbonate/siliciclastic); *W* wackestone; *G* grainstone; *B* boundstone



NE-SW, NW-SE, and E-W normal and reverse faults (Matos 1992; Marques et al. 2014). The reactivation of NE-SW lineaments was responsible for the development of

a horst-graben system in the basin that gave origin to the Feira Nova and Cariri sub-basins, separated by the Dom Leme High (Ponte and Ponte Filho 1996).

Table 1 Information on the five quarries in which stromatolitic structures have been documented

Quarry	County	District	Local name	Coordinates	Present state
Nova Olinda 1	Nova Olinda	—	Três Irmãos	7°06′53.38″S 39°41′48.96″W	Active quarry
Nova Olinda 2	Nova Olinda	—	—	7°07′23.65″S 39°41′53.20″W	Active quarry
Nova Olinda 3	Nova Olinda	—	—	7°06′37.36″S 39°42′23.34″W	Abandoned quarry
Santana 1	Santana do Cariri	Inhumas	—	7°10′40.49″S 39°45′27.71″W	Partially abandoned quarry
Santana 2	Santana do Cariri	Inhumas	—	7°10′41.82″S 39°45′23.52″W	Partially abandoned quarry

Sedimentation started in the Paleozoic and continued during Mesozoic (Jurassic and Cretaceous) times. The rift basin is organized in three major tectono-stratigraphic phases, the pre-rift, syn-rift, and post-rift megasequences (Assine et al. 2014). The pre-rift is characterized by continental siliciclastic units deposited during the Jurassic, while the syn-rift phase, developed in the Berriasian–Early Aptian, was formed in lacustrine and alluvial settings (Assine 2007). The post-rift megasequence is divided into two tectonic events: (1) post-rift I (Late Aptian–Early Albian), characterized by mixed siliciclastic-carbonate-evaporite successions; and (2) post-rift II (Albian–Cenomanian), with fluvial deposits (Assine et al. 2014). The post-rift I megasequence (Santana Group) is represented from base to top by the Barbalha, Crato, Ipubi, and Romualdo Formations, organized in three depositional sequences, encompassing the late Aptian to earliest Albian stages (Fig. 2a; Assine et al. 2014). The second depositional sequence is formed at base by a transgressive stacking of fluvial and lacustrine deposits of the Barbalha Formation followed by the highstand Crato Formation and culminates in the evaporites of the Ipubi Formation (Assine et al. 2014). The Crato Formation is recognized worldwide as a *Konservat-Lagerstätte*, due to its well-preserved fossil content (Martill et al. 2007a). The main fossils are arthropods (i.e., insects, ostracods, crustaceans, and arachnids), small fishes, cheilons, and pterosaurs. The quality of preservation of the flora, including algae and gymnosperms as well as angiosperms in their first diversification phase, is also spectacular (Martill et al. 2007a; Heimhofer and Hochuli 2010).

The Crato Formation comprises a 60-m-thick succession and is composed of metric-scale laminated carbonate units interlayered with equally thick successions of green shales and fine-to-coarse sandstones (Silva and Neumann 2003). The sections exposed in the Nova Olinda and Santana quarries (Fig. 2; Table 1), near Nova Olinda, Ceará, are the most complete ones in this part of the Araripe Basin. The quarries contain a tabular unit of laminites, approximately 10 m thick (Fig. 3a, b), characterized by a monotonous succession of horizontal, sub-millimetric thick layers of pale

to dark carbonate mudstones. The presence of scattered halite pseudomorphs (halite hoppers, Fig. 3c) in distinct carbonate levels suggests that the Crato Formation has been deposited under fluctuating salinity conditions (Martill et al. 2007b; Heimhofer et al. 2010). Despite evidence of microbial activity for the origin of the Crato limestones (Neumann 1999; Catto et al. 2016) diagnostic features, such as domal microbial structures, have never been formally described for the main carbonate bed of this unit.

The rich fossil assemblage of the Crato Formation was originally interpreted as having lived in a non-marine setting (Mabesoone and Tinoco 1973), probably in a saline lacustrine environment close to marine environments (Assine 1992, 2007; Neumann 1999). More recently, several authors (e.g., Mohr and Eklund 2003; Makarkin and Menon 2005; Martill et al. 2007b; Do Carmo et al. 2008; Baez et al. 2009) suggested that the carbonates were deposited in a hypersaline lagoon system with restricted connection to an epeiric sea in the southeast (Assine et al. 2016). Here we regard the earlier view as more likely because of the absence of marine fossils. Episodic freshwater discharges lowered the salinity in the lake and promoted water level fluctuations (Neumann et al. 2003). Anoxic/dysoxic conditions must have prevailed in deeper bottom waters (Martill et al. 2007b). Climate during this period was probably seasonally humid to dry (Makarkin and Menon 2005; Martins-Neto 2006). Despite evidence of a stressful environment, fishes (genus *Dastilbe*) and plant remains are quite common throughout the succession (Fig. 3d). The sedimentary succession is indicative of deposition in a prograding sequence (Assine et al. 2014). Deposition of laminated limestones directly above the basement points to the rapid expansion of the basin (Assine 2007).

Materials and methods

The study area is located at the northern limit of the Araripe Basin in the vicinities of the Santana do Cariri (Santana quarries) and Nova Olinda (Nova Olinda quarries) towns,

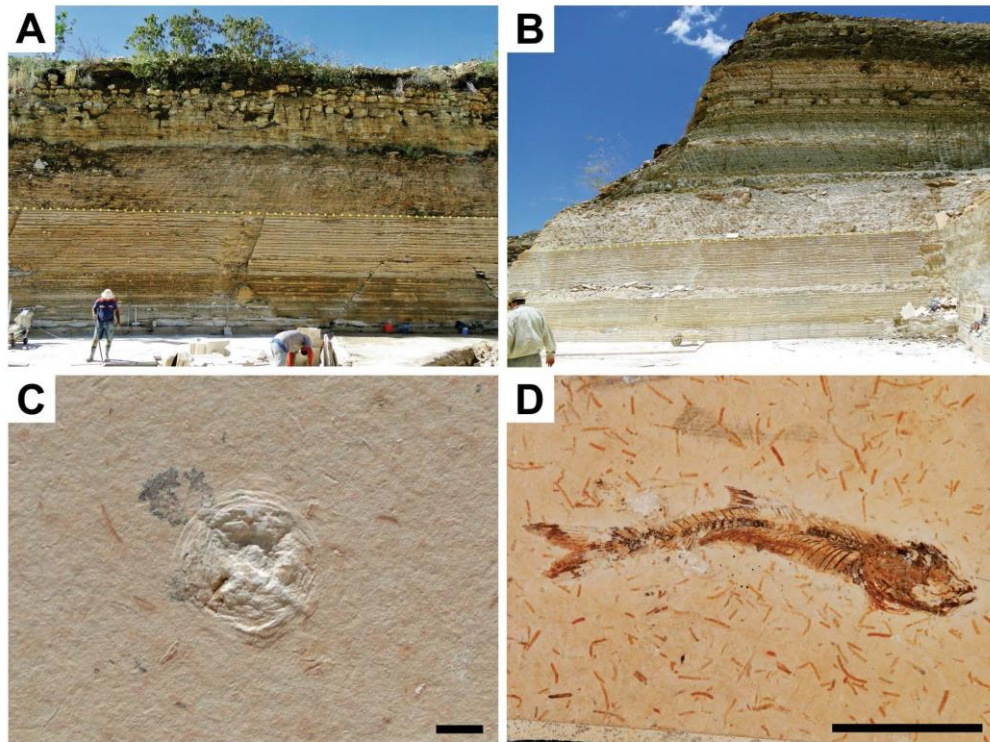


Fig. 3 Sedimentary facies of the Crato Formation in the Nova Olinda Quarry 1. **a** Sedimentary succession of the middle Crato Formation showing the basal laminated carbonates overlain by heterolithic siltstone and shale layers. **b** Thinly laminated carbonates at the base of

Nova Olinda Quarry 1 overlain by a mixed siliciclastic-carbonate succession. **c** Detail of centimeter-sized halite hopper crystal. **d** The small fish *Dastilbe* sp. is a common faunal element of the laminated carbonate facies. The scale bar in **c** and **d** is 1 cm

State of Ceará, northeastern Brazil (Fig. 1). For detailed information on the position of quarries with the stromatolitic structures, see Table 1. Most of the microbialite-bearing outcrops occur in the lower Crato Formation. During the fieldwork, special attention was paid to the detailed measurement of the carbonate succession and description of domal microbialites, including characterization of their composition, associated sedimentary structures, bed thicknesses, contacts and geometry, as well as presence of fossils and salt pseudomorphs. The macroscopic morphometric measurements of the domes included diameter, longest and shortest axes, height, and margin thickness. We also observed the presence (or absence) of collapsed areas, vugs and fenestral cavities, coalescent forms, and other structures suspect of biological origin. We collected ten slabs from the Santana quarries for examination in the laboratory. In addition, 15 petrographic thin-sections of laminated carbonates and domal stromatolites were examined

under both normal and polarized light using a Zeiss Axio Imager A.2 binocular petrographic microscope and a Zeiss Stereo Discovery V.12 binocular magnifying glass, at the Center for Geosciences Applied to Petroleum Geology, São Paulo State University (UNESP-Petro-UNESP). The macro-textures and mineralogical composition of the microbialites were analyzed under a scanning electron microscope (SEM), whereas the micro- and ultrastructural images were acquired with the SEM X-ray energy-dispersive spectrometer (Model Zeiss Evo MA15, operated at EHT 20–30 kV and 40–80 Pa pressure), linked to the system Bruker EDS. The samples were covered with a thin layer of carbon in order to increase the conductivity.

For microbialite classification and description of macro-, meso-, and microstructural features, we used the very comprehensive protocol of Fairchild et al. (2015), complemented by data in Hofmann (1969), Preiss (1972), Walter (1972), and Grey (1989). Rock samples (slabs) and

thin-sections are housed in the Laboratory of Sedimentology of the Institute of Geosciences and Exact Sciences, UNESP.

Stromatolites of the Crato Formation

In the Santana quarries, the stratigraphic section consists of 5-m-thick, very finely planar-laminated limestones interbedded with three levels of stromatolites (Fig. 2b), succeeded by 2.5 m of mudstone with undulated lamination. This succession is covered by about 1.5 m of shales interbedded with undulated beds of massive siltstones/very fine grained sandstones (Fig. 2b). In the Nova Olinda quarries, seven levels of stromatolites occur in an approximately 9-m-thick stratigraphic section (Fig. 2c). The correlation with the stromatolite levels from the Santana quarries are tentatively presented in the Fig. 2b and c. Levels 1–4 in the Nova Olinda quarries stratigraphically correspond to the Level 1 from the Santana quarries, but their morphologies are different (see Fig. 2b, c; Table 2). Level 2 from Santana quarries stratigraphically and morphologically corresponds to Level 5 from Nova Olinda quarries. Level 3 in the Santana succession was correlated with Level 6 in the Nova Olinda succession (Fig. 2b, c), but in the last quarry (i.e., Nova Olinda 3) the stromatolites are considerably larger (up to 100 cm high) and discontinuous with lateral size variation.

In the Santana Quarry 1, the stromatolites occur in the lower part of an at least 7.5-m-thick package located in the lower part of the Crato Formation (Fig. 2c). Microbialite levels have a wide lateral extension (>100 m) and a minimum and maximum thickness of ~20 to 60 cm, respectively. These layers start with horizontal-laminated facies (Fig. 3a) and culminate in small-to-medium domes and low-relief mounds. Each stromatolite bed is formed by domes and pseudo-columns laterally separated by laminites. The contact between the domes/columns and laminites is transitional, marked by the gradual decreasing size of the bioherms until the laminae are again perfectly horizontal.

Microbialites occur as coalescent structures in the basal level (Level 1, Fig. 4) as comparatively steeply inclined structures from 30 cm to up to 46 cm in height, and with a maximum diameter of 170 cm at the base, and 60 cm at the top (Table 2; Fig. 4a, b). The gently inclined, distinctly pseudo-columnar structures are almost contiguous, with lenticular to equidimensional cross-sections (Fig. 4c). Each structure has a symmetric convexity and exhibits internal undulated laminae. Rarely, centimeter-sized elliptic oncoids occur in laminae between domes (Fig. 4d). Pseudo-columns of Level 1 show characteristic pale to dark grey colors, which represent the preserved organic matter

of the EPS (Catto et al. 2016). Analysis of the micromorphology revealed a convex-upward and closely spaced lamination. Each lamina is approximately 0.25 mm thick with a microsparitic texture and occasionally secondarily silicified. Between laminae usually preserved dark organic matter and fenestral porosity occur (Fig. 5). Spherules, around 15 μm in diameter and mainly composed of microcrystalline silica, occur in clusters and dispersed between laminae (Fig. 6).

The intermediate microbialite level of the Santana Quarry 1 (Level 2) occurs ~1.5 m above Level 1 and consists of low discontinuous domes (Fig. 7a–c) of 25-cm height and 50-cm length. Domes are separated (5–25 cm) by horizontal/crinkly laminites intervals (Fig. 7a). All structures have a low relief (Fig. 7c–e) and a faintly curved vertical growth vector towards the S and SE. Domes are slightly asymmetric and locally coalesce. Each structure has a low-to-moderate convexity profile with flat laminae (Fig. 7d) that occasionally grade laterally into horizontal laminites (Fig. 7a–c). Within the domes, vug porosity is quite common, while the most abundant porosity between the laminae is of the fenestral type.

The upper microbialite level (Level 3) occurs 2.2 m above Level 2 and characterizes a discontinuous layer with isolated, domal microbialites. In the quarry face, all analyzed specimens at this level are a few centimeters high (maximum: 5 cm), with growing convexity profile from base to top, and are separated from each other by horizontal laminites. The domes are rounded, discontinuous, and show a straight, vertical growth vector. Each structure observed has a low convexity, composed of continuous, flat laminae that show high symmetry. In one corner of the quarry, this level was exposed as a 6-m-long and 2-m-wide bedding plane where at least nine small mounds, varying in size from 40×30 cm to 100×40 cm were encountered. The tallest mound is 5 cm high. In plan-view, the mounds are parallel to each other, and aligned in a NE–SW direction. Distances between mounds vary from 25 cm to nearly 1 m.

In the southeastern face of the Nova Olinda quarries, five microbial levels occur within a 2-m-thick package of the laminated carbonate unit (Fig. 8a). Level 1 occurs at the base of the exposed quarry face (Nova Olinda 1) and is only poorly exposed (Figs. 2, 9a, b). Level 2 is separated from Level 1 only by 5–6 cm and includes 30-cm-long and 10-cm-high mounds. Most observations come from Level 3 that is ~23 cm above Level 2. The gently convex, more or less symmetric mounds vary between 3–7 cm in height and 14–30 cm in length. Above this interval, *Kinneyia*-type wrinkle structures associated with radial cracks, the first stage of formation of halite crystals, are quite common (Fig. 9c). As in the case of the Santana quarries, the fine lamination does not exhibit internal discontinuities or any other signs of truncation. Laminae thickness increases

Table 2 Description of the macro-, meso-, and micromorphological features of the stromatolite-like microbialites from the Crato Formation

Morphological features		Quarries and microbialite levels			
		Santana 1	Santana 1/Nova Olinda 1	Santana 2/Nova Olinda 1	Nova Olinda 3
		Level 1	Level 2 of Santana 1 (and level 5 from Nova Olinda quarry 1)	Level 3 of Santana 2 (and levels 1–4 from Nova Olinda quarry 1)	Levels 6 and 7
General characteristics	Preservation	Good	Good	Good	Good
Macrostructure	Lateral continuity	Discontinuous	Continuous	Discontinuous	Discontinuous
	Proximity between structures	Close to contiguous	Close	Isolated	Isolated
	Connection between structures	Coalescent	Coalescent	—	—
	Synoptic relief (continuous structures)	—	Low relief continuous domes	—	—
	Shape (discontinuous structures)	Pseudo-columnar	Dome	Dome	Dome
	Section contour	Elliptic to equidimensional, intergrown	Elliptic to equidimensional	Equidimensional	Elliptic to equidimensional
	Branch	No	No	No	No
Mesostructure	Edges	Coalescent	Rounded in plan-view	Rounded in plan-view	Rounded in plan-view
	Vertical growth vector	Straight	Curved	Straight	Straight
	Profile convexity	High	Low to moderate	Low	Moderate to high
	Curvature order	Second	First	First	First
	Laminar inheritance	Moderate to high	High	High	High
	Symmetry	Symmetric	Asymmetric to symmetric	Symmetric	Symmetric
	Internal discontinuities	Absent	Absent	Absent	Absent
Microstructure	Laminae inflection	No	No	No	No
	Mineralogy	Calcite	Calcite	Calcite	Calcite
	Texture	Microsparitic to sparitic	Microsparitic to sparitic	Microsparitic to sparitic or clotted	Microsparitic to sparitic
	Porosity	Fenestral	Vuggy/Fenestral	Vuggy/Fenestral	Vuggy
	Framework	Flat lamination	Flat lamination	Flat/irregular lamination	Flat lamination
Diagenetic features		Recrystallization	Partly recrystallization	Oxidation	Partly recrystallization

List of morphological features modified from Fairchild et al. (2015), with additions from Hofmann (1969), Preiss (1972), Walter (1972), and Grey (1989). The table lists the microbial levels 1–3 from Santana and levels 1–7 in the Nova Olinda quarries. Level 2 from Santana quarry has the same morphology as Level 5 in the Nova Olinda quarry. Level 3 of Santana Quarry exhibits the same morphology as levels 1–4 of the Nova Olinda quarry

towards the top of the mounds, a feature also observed in the mounds at the Santana quarries. For example, a bundle of laminae measuring 10 mm in thickness close to the base of the slope of a mound increases to 19 mm at the top.

The distance between Level 3 and Level 4 is 70 cm. Mounds in Level 4 reach up to 5.5 cm in height and have a lateral extension of 8–16 cm (Fig. 8c), those in Level 3, reach 9 cm in height and 70 cm in length, are elongated, irregular and are arranged parallel to each other. In general, microbialite levels 1–4 observed in Nova Olinda Quarry 1

closely resemble those observed in Level 3 from Santana quarries (Figs. 7, 8a–c; Table 2). An approximately 35-cm-thick unit of horizontal laminites separates levels 4 and 5. Level 5 consists of sparse domes with low relief (Fig. 8d). The lamination has a straight vertical growth (different from Level 2 in Santana Quarry 1) and a low to moderate convexity profile.

In Nova Olinda Quarry 3, in the northeastern part of the outcrop belt of the Crato Formation, there are two levels of gigantic domes (levels 6 and 7) (Fig. 10). The stromatolitic

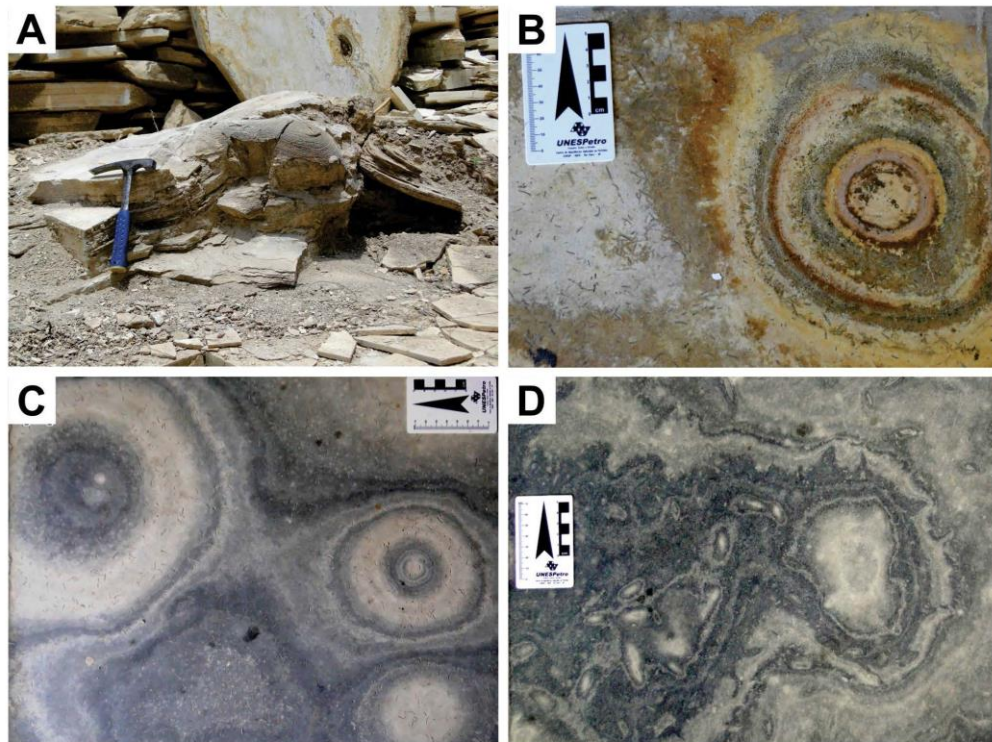


Fig. 4 **a** Small, isolated, and thinly laminated irregular dome located at the base of the exposed laminated limestone unit of the Santana Quarry 1 (level 1). **b–d** Plan-views of polished slabs of domal stromatolitic structures exhibiting thin concentric lamination. Locality unknown. **c** Note the two coalescent domes. **d** Detail of an irregular dome surrounded by centimeter-sized oval oncolites

matolitic structures exhibiting thin concentric lamination. Locality unknown. **c** Note the two coalescent domes. **d** Detail of an irregular dome surrounded by centimeter-sized oval oncolites

mound of Level 6 has a height of up to 80 cm and a length of 140 cm and corresponds to Level 3 in the Santana quarries. The discontinuous domes in Level 7 exhibit a straight vertical growth vector and a moderate-to-high profile convexity, which increases towards the top. The structures are about 100 cm high and 160 cm long (Fig. 10d). It is important to note that Level 7 occurs intercalated between an undulated laminated succession in the Nova Olinda Section and has no stratigraphic equivalent in the Santana succession (Fig. 2c).

Microscopic and ultrastructural features

Microscopic investigations were carried out mainly on samples from the Santana quarries. The main micromorphology seen in thin-sections is parallel and smoothly convex-up lamination (Fig. 11a–d). Lamination consists of alternations of dark and light laminae (each less

than 0.5 mm in thickness; Fig. 11a), reflecting different degrees of calcite crystallization, mostly in the form of microsparite.

Peloids are abundant and occur dispersed in the lamination of the domes. The matrix is formed by euhedral to subhedral calcite micro-rhomboheda associated with filaments with diameter varying between 10 and 200 μm . The individual crystals are between 2 and 14 μm in diameter, surrounded by honeycomb-like structures. Dark-colored organic matter is apparently preserved discontinuously between carbonate laminae (Fig. 11b; Catto et al. 2016). Millimeter- to centimeter-scale fenestral pores follow the lamination. The honeycomb-like internal structures, consisting of calcite, occur as micrometric laminae (Fig. 6a). Each of several individual empty chambers in this structure exhibits a circular shape. Their size ranges from 5 to 30 μm (Fig. 6b). Other spherical calcite objects have also the same size and morphology (Fig. 6c).

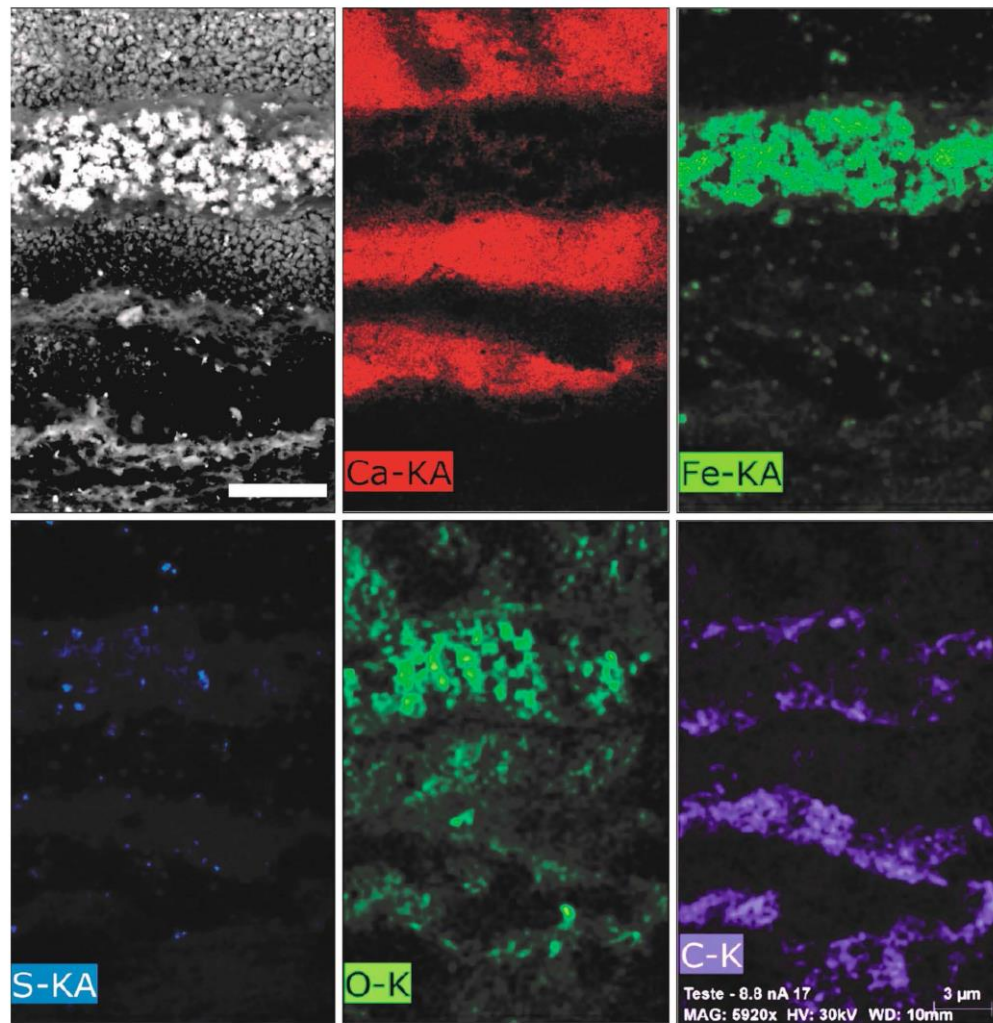


Fig. 5 Microfluorescence map of a microbialite sample from the Crato Formation (see detail of the organic matter in Fig. 6a). Note the high calcium and low carbon content in the light laminae, whereas

in the dark laminae carbon shows high concentrations (27.76 wt%; $C_{\text{organic}} > \text{CaCO}_3$). Scale bar is 5 µm

EDS and micro-fluorescence analysis were carried out in a microbialite sample from Level 2 and reveal a high content of carbon associated with dark organic-rich layers (Fig. 5). These organic layers are associated with oxidized pyrite with low levels of sulfur and higher concentrations of oxygen and iron. The low content of carbon in the calcite layers and high concentration in the organic layers indicate

that 27.76 wt% of carbon in the sample is directly related to organic carbon.

The morphology of these very well preserved microstructures (honeycombs, spherical objects) suggests that they may represent calcified remains of original organic structures associated with benthic microbial communities, most likely EPS layers and coccoidal cells. The rhombohedral

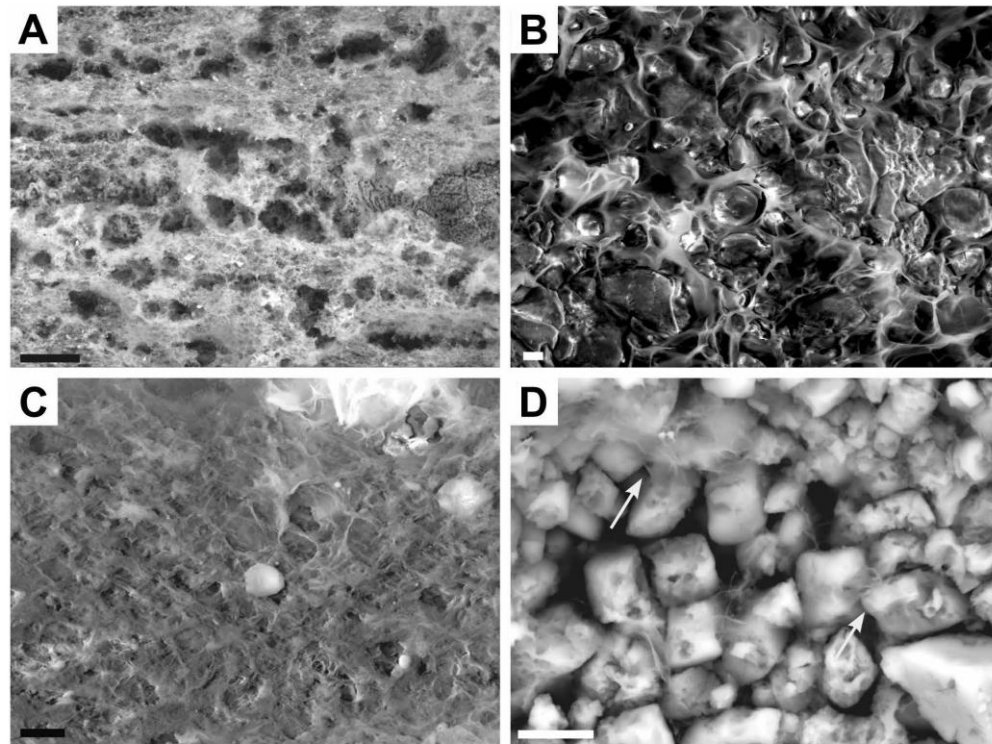


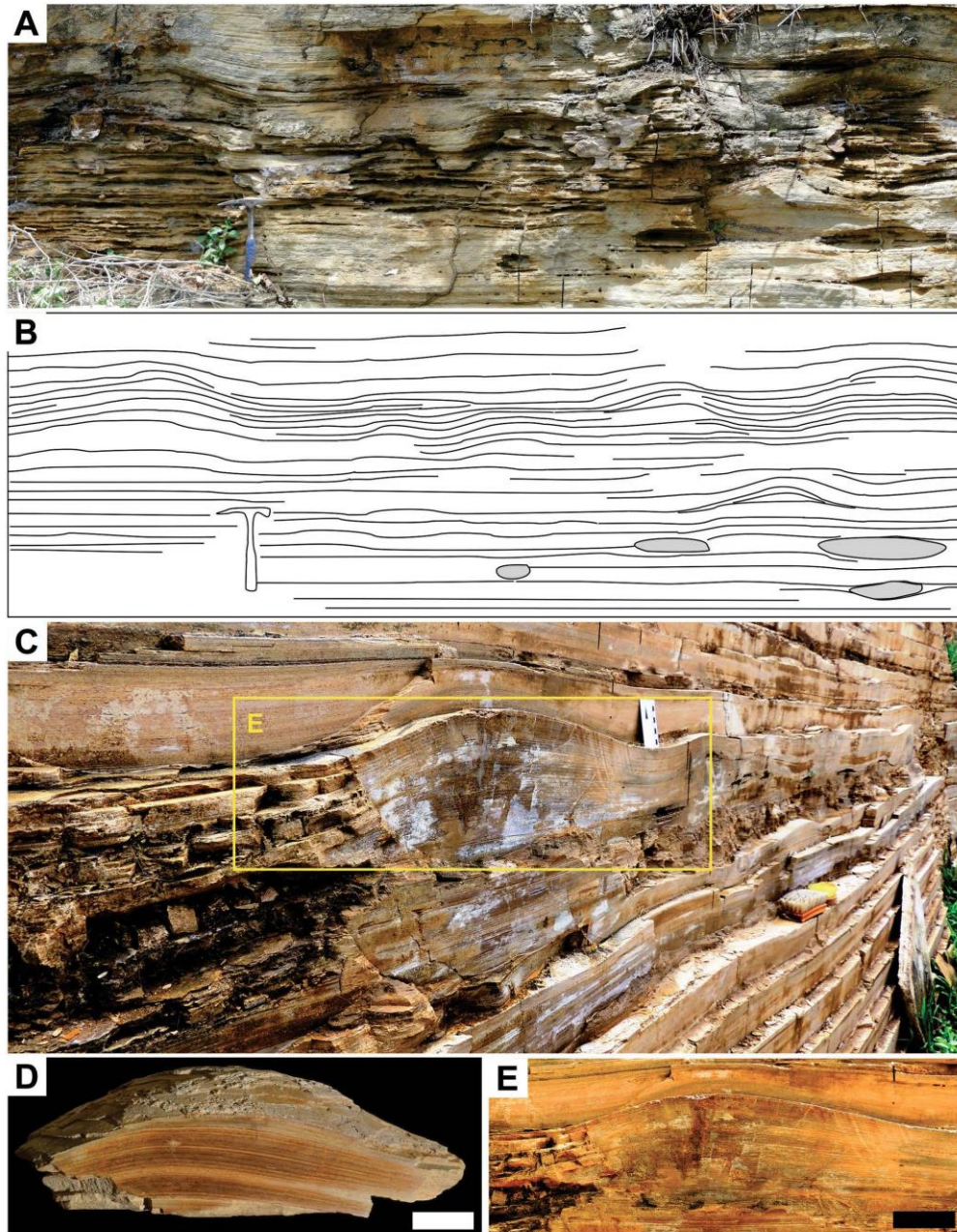
Fig. 6 Scanning electron micrographs of biogenic structures of the domal microbialites from the Crato Formation (from Catto 2015). **a** Sample of laminated carbonate showing multiple layers of calcified presumable EPS matrix. **b** Detail of calcified honey-comb structure interpreted as EPS. Note the spherules which are interbedded within the honey-comb structure and are interpreted as coccoidal bacterial cells. **c** Preserved coccoidal cell within the presumed EPS framework. **d** Calcite rhombohedra showing filaments interpreted as fila-

mentous cyanobacteria cells and silicified EPS matrix between the euhedral crystals (*arrowed*). The smooth rhombs are interpreted as an organomineral product of biologically induced mineralization (sensu Dupraz et al. 2009). This image corresponds to a detail of organic-rich laminae of a domal stromatolite from Level 2 at Santana (see Fig. 2). The scale bar is 100 μm in **a**, and 10 μm in **b–d**. **a–c** are from a core of the laminated carbonate unit at Nova Olinda Quarry 1

crystals are encompassed by what appears to be calcified EPS matrix. The calcareous filaments resemble filamentous bacterial cells and surround the calcite rhombohedra (Fig. 6d). The morphology of the rhombohedra and their association with calcified EPS suggest that the crystals are authigenic and a product of biologically induced mineralization (Dupraz et al. 2009). However, rhombohedral calcite crystals may also form as purely inorganic precipitates (e.g., Reeder 1983; Cizer et al. 2008; Montes-Hernandez et al. 2011; Rodriguez-Blanco et al. 2011). The size of the crystals shown in Fig. 6d is larger than average micrite crystals. Thus, their association with calcified EPS remains and the high-carbon content associated with the dark organic-rich

Fig. 7 Features of the domal microbialites from Level 2, Santana Quarry 1. **a** Note the presence of cavities in the strata bearing the microbialites. **b** Schematic representation of **a**. **c** Lateral view of Level 2 showing at least two medium-sized domes intercalated between flat-laminated carbonates. **d** Polished slab of domal structure. Note the convex-up lamination and the alternation of dark (organic-rich?) and light (more calcareous) laminae packages. **e** Detail of **c** showing a low-relief medium-sized domal structure. The hammer in all pictures is 25 cm long. The scale bar in **c** is 10 cm, in **d** and **e** 5 cm

layers may suggest a microbial origin. The fenestral pores possibly represent gas escape structures from the metabolic activity of benthic microbes living in the domes.



Adaptation of microbialites to high-stress environments

Different types of microbes, including cyanobacteria, play an important role in carbonate production from the Archean to the Present (e.g., Riding 2000). Microbes show a broad environmental tolerance (e.g., Whitton and Potts 2000; Mohr et al. 2011). This tolerance and high adaptability allows them to thrive in environments with high salinity and temperature as well as drastic pH oscillations (Decho 2000). In contrast, such stressful settings are unsuitable for the vast majority of metazoans (Des Marais 1995).

The protection provided by the EPS is essential for microbial communities to attach to the substrate, resulting in generations of micro-domains that allow microbes with different types of metabolisms to coexist (Decho 2000). The EPS also helps the microbialites to resist stressful conditions by stabilizing them against strong hydrodynamic regimes (Decho et al. 2005) and high salinity, alkalinity, and temperature (Kremer 2006). The degradation of EPS plays a key role in the precipitation of carbonate minerals, acting as a mechanism that increases the alkalinity of the environment, due to the metabolism of sulfate-reducing bacteria (Visscher et al. 2002; Braissant et al. 2007). In addition, Reitner (2011) and Arp et al. (2012), while studying hypersaline lakes on Christmas Island (Kiritimati), documented the role of photosynthesis and exopolymer degradation for microbialite formation. The metabolic and photosynthetic activity of some types of microbes also elevate alkalinity in the environment, increasing the inorganic carbon dissolved and calcium carbonate saturation, forcing its precipitation (Dupraz et al. 2009). In the same way, the close relationship between different microbial communities and stromatolite microstructures (Farfas et al. 2011, 2013) was recently documented in Socompa Lake, a high altitude (3570 m), alkaline, hypersaline lake on the Argentine Andean plateau with profuse carbonate stromatolite growth. The microbial communities live in a very shallow lake subject to high chemical and physical stress, such as wide fluctuations in daily temperatures, hypersalinity, alkalinity, and high level of UV radiation.

Depositional and paleoenvironmental implications

Source of carbonates and origin of mounds and domes

In the last decades, the origin of laminites in the Crato Formation was an issue of broad interest for the geological community focusing on this world-famous *Fossil-Lagerstätte*. Based on some inconclusive features, such as vugs, smooth convex-up, ripple-like microbial mats (wrinkle marks?), and slumped and brecciated laminae, some authors suggested a microbial influence for the origin of the

laminated facies (e.g., Heimhofer and Martill 2007; Martill et al. 2007b). The presence of oncoids was noticed also by Heimhofer and Martill (2007, Fig. 4f) in the Crato Formation, but according to these authors, these microbialites are unusual and rare.

The micro-ripple-like lithified structures described by Heimhofer and Martill (2007) and similar structures found by us in several levels of Nova Olinda Quarry 2, corresponding to the stromatolite levels 1–4 of Nova Olinda Quarry 1 (Fig. 9), are indeed best interpreted as of microbial origin. In our opinion, the compatible scale and the presence of elongate and bifurcated crests with flat tops separated by shallow depressions, strongly resemble wrinkle structures such as *Kinneyia* (Porada et al. 2008). Wrinkled surfaces are generally interpreted as irregular surfaces of microbial mats or to have formed by the deformation of mats by currents and waves (Hagadorn and Bottjer 1997).

Contrary to the observations above, Heimhofer et al. (2010) argued that the whole laminated limestone succession was generated by authigenic precipitation of calcite crystals that was induced by biochemical processes without any “significant carbonate contribution from a benthonic microbial community”. The authors interpreted that precipitation of calcite occurred in the hypersaline water column, and was mediated by biochemical processes. Thus, according to these authors microbial-induced carbonate production at the lake floor apparently played only a very minor role. Contrarily, Catto et al. (2016) highlighted the microbial influence in the formation of the laminated limestones of the Crato Formation. His interpretation was based on the presence of (a) abundant calcified coccoid and filament cells, including the cyanobacteria *Spirulina*, (b) calcified biofilms composed of extracellular polymeric substances (EPS), and (c) the occurrence of calcitic filaments and micro-rhombhedra within calcified EPS interpreted as a product of biological-induced mineralization sensu Perry et al. (2007) and Dupraz et al. (2009). In accordance with the evidence presented by Catto et al. (2016), the stromatolite structures described here clearly point to biologically induced mineralization within the limestone interval of the Crato Formation. Our findings suggest that within the main carbonate unit repeatedly favorable conditions existed for the growth of microbial communities at the lake floor. Poor oxygenation and high salinity (attested by abundant pyrite crystals, halite hopper crystals and other salt pseudomorphs) prevailing during the deposition of the Crato Formation (see also Heimhofer et al. 2010) apparently precluded the presence of grazing benthos but not of microbial colonies. The presence of calcified remains of microbial cells of probable cyanobacteria affinity suggests that the microbial levels formed in relatively shallow waters setting within the photic zone.

The microbialites of the Crato Formation strongly resemble the stromatolites occurring in the present-day

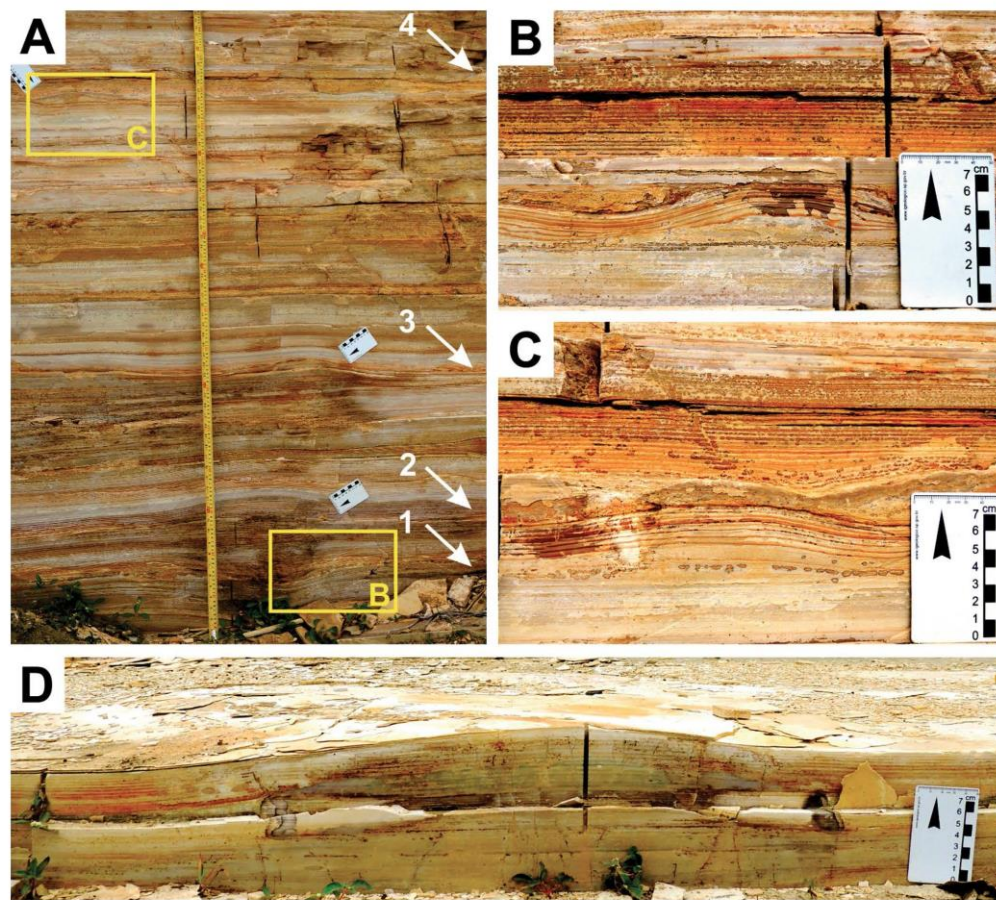


Fig. 8 Microbialites from Nova Olinda Quarry 1. **a** Succession of laminated limestones showing the presence of at least four stromatolite microbialite levels. The white arrows indicate the base of each microbialite level. **b** Detail of small domal structure from Level

1 in **a**. **c** Detail of low-relief domal structure from Level 4 in **a**. **d** 3-D view of domal structure showing the smooth convex-up laminae directly overlying horizontal laminites. The scale bar in **a–d** is 8 cm

Socompa lake of the Andes (Farías et al. 2011), which consist of broad, low domes, rounded to oblong in plant view and are composed of smooth laminae. Neighboring domes tend to coalesce into bigger domes, some of which are also elongated as in the case of the Crato Formation. In several cases the laminae within the mounds and domes can be traced into the neighboring flat lake floor, producing a striking similarity between the lamination of the microbial structures and the remaining lamination of the carbonates. This suggests a common origin of laminae, which might lead to the interpretation that in fact the whole lake floor

was occasionally covered by microbial films. This assumption has far-reaching consequences for the interpretation of the excellent preservation of fossils within the laminated limestones (see below). This hypothesis needs, however, to be substantiated by further detailed investigation of the micro- and nanofacies of the flat-laminated carbonates.

As already mentioned above, Heimhofer et al. (2010) convincingly argued that small calcite rhombohedra originating in the upper water column form the bulk of the finely laminated carbonates. When settling, these grains accumulated on both mounds/domes and on the flat lake floor. The

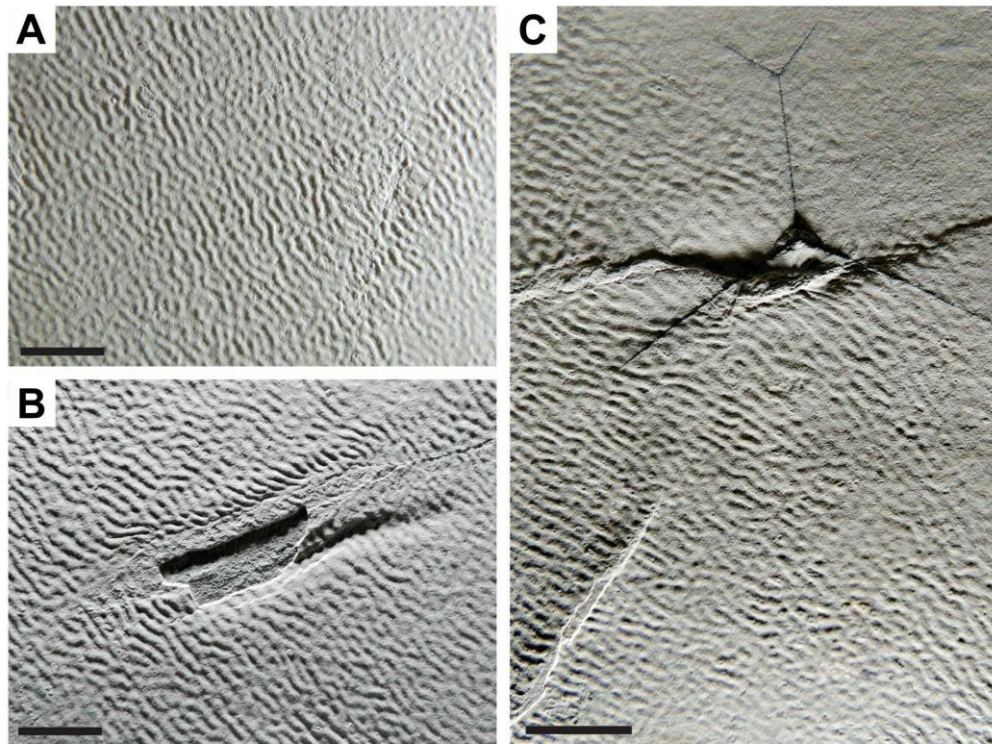


Fig. 9 a–c *Kinneyia*-type wrinkle structures (sensu Porada et al. 2008) at the Nova Olinda Quarry 2. The radial cracks in c have been caused by incipient growth of halite crystals. The scale bar in a–c is 1 cm

difference between the two bottom morphologies (flat versus domal) consists in the greater thickness of the laminae within the latter. The most obvious explanation for this is the binding capacity of the microbial mat, which produced the stromatolite structures, probably associated with microbial-induced early cementation. This cementation may also have prevented compaction of these elevated structures in contrast to the surrounding flat areas. However, it appears that compaction played only a limited role within the lake carbonates judging from the originally high porosity of the regular laminated carbonates (now partly filled with carbonate cements, Heimhofer et al. 2010).

The Crato lake: a Cretaceous analogue of the modern hypersaline lakes of the Kiritimati Atoll?

On the Kiritimati Atoll, Christmas Islands, central Pacific Ocean, several small, very shallow hypersaline lakes exist, the bottoms of which are covered with profuse microbial

mats (Trichet et al. 2001; Saenger et al. 2006; Reitner 2011; Arp et al. 2012). Some of these lakes are connected to a large lagoon (190 km²) (Saenger et al. 2006). The lakes are characterized by a high variability of environmental parameters, such as oxygen, pH, and salinity that strongly restrict the diversity of the biota. The microbial communities were studied in detail by Reitner (2011) and Arp et al. (2012). According to them, the microbialite formation by carbonate precipitation takes place in the lower parts of the mats as a result of exopolymers degradation (see also Défarge et al. 1996).

The position of these lakes close to marine environments and the presence of laminated carbonates, evaporites, abundant benthic microbial communities, lithified microbialites, anomalous and variable salinities (Trichet et al. 2001; Saenger et al. 2006; Reitner 2011; Arp et al. 2012), as well as events of fish mass-mortality (Reitner 2011) closely resemble features that are characteristic of the Crato lake carbonates. However, there are also key differences

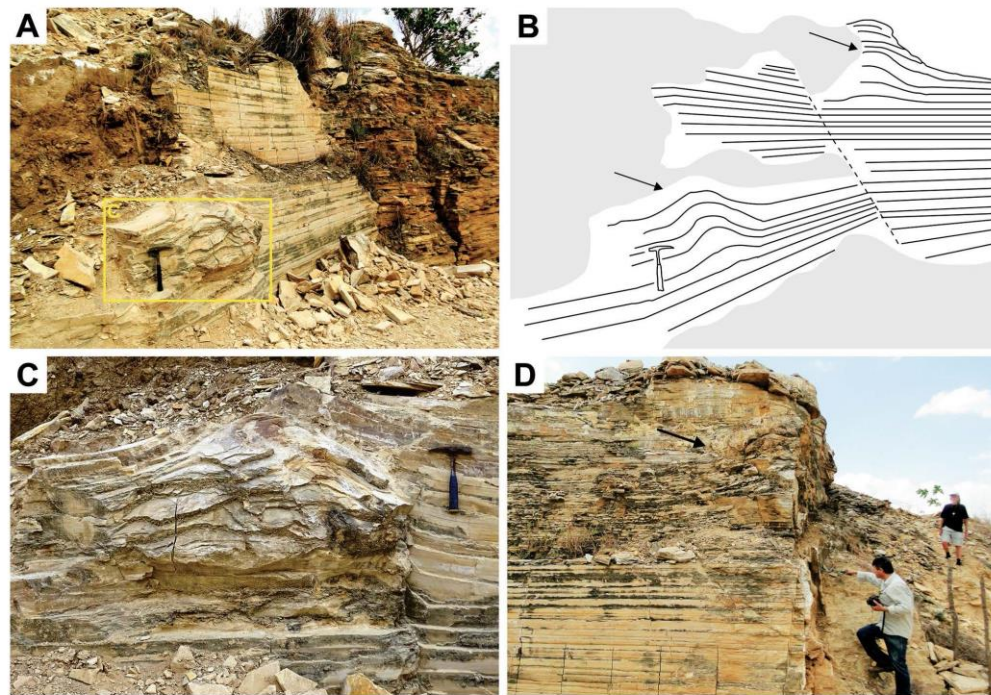


Fig. 10 a–d Giant stromatolite domes from levels 6 (a–c) and 7 (d) at Nova Olinda Quarry 3. **b** Sketch of the structure in **a**. **c** Detail of the stromatolite in **a**

between the fossil and the modern analogue. For example, microbial mats were not as prominent in the Crato lake. Moreover, the precipitated carbonate minerals in the Crato lake apparently were calcitic, rather than aragonitic, as in the case of Kiritimati lake. Finally, the investigated Crato sediments (especially the limestones) do not exhibit any signs of intertidal to supratidal environments. Nevertheless, it appears that in both lake systems many environmental parameters were similar and characterized by microbial communities, even though in the Crato lake microbialites occurred only locally at certain levels.

The role of microbialites for excellent fossil preservation

The presence of microbialites in the Crato Formation raises the possibility that microbial mats played a decisive role in the excellent preservation of the fossils of this unit (Martill 1988; Martill et al. 2008; Barling et al. 2015). In the main carbonate unit of this formation (~10 m of fossil-bearing laminites; Martill and Bechly 2007), fossils are preserved

in two distinct modes: (1) as goethite/limonite replacement, and (2) as phosphatized remains (Menon and Martill 2007). Martill et al. (2008) argued that occasional mass mortality events were a prerequisite for the formation of the *Konservat-Lagerstätte*. According to them, these drastic events occurred in response to changes in water oxygenation and salinity, poisoning of the water by H_2S released from reducing bottom sediments, or by cyanobacterial blooms. The best-preserved organisms are phosphatized (Menon and Martill 2007; Barling et al. 2015). The origin of the phosphorous is still controversial, but this compound may be derived from microbial degradation and concentration in the water column (Wilby et al. 1996).

Regardless of the origin of organic phosphorus, the confirmed microbial-influenced/induced carbonate mineralization most likely played a key role in fossil preservation (Martill 1988; see also Wilby et al. 1996; Iniesto et al. 2013; Raff et al. 2014). The presence of microbial mats covering the bottom would have prevented the carcasses from floating in the water column. Furthermore, the rapid growth of the microbial mats would have protected them

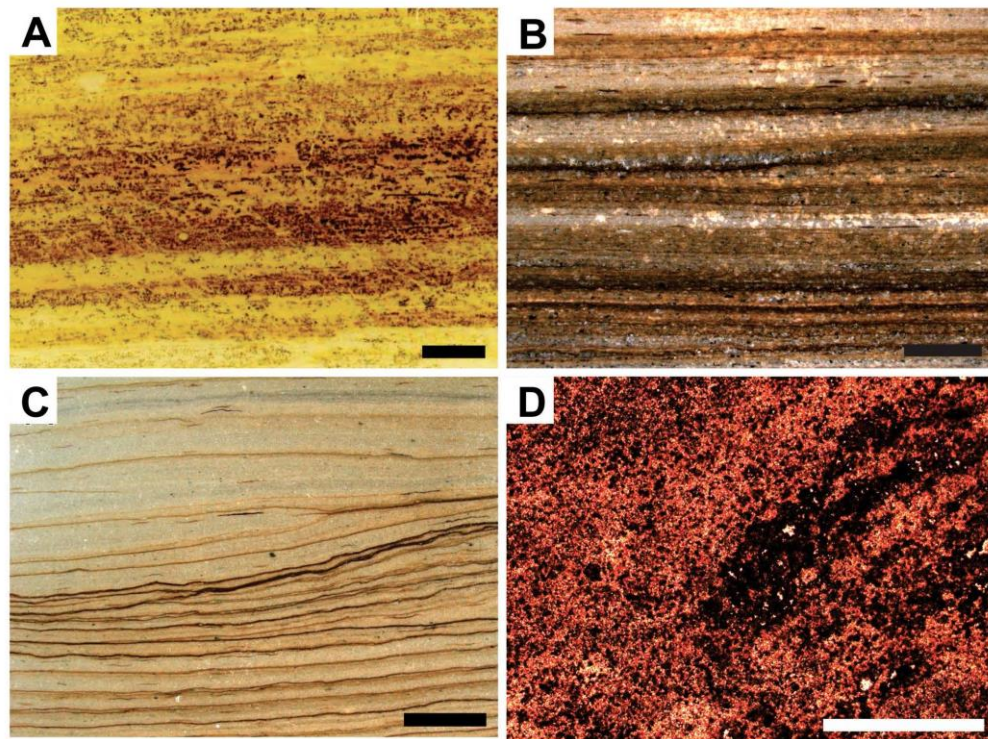


Fig. 11 Thin-section micrographs of the microbialites from the Crato Formation. **a** Detail of the alternation between yellow and brown laminae, Level 2, Santana Quarry 1; $\times 50$, parallel polarizers. **b** Close-up of the thin lamination; $\times 25$, crossed polarizers. **c** Convex up lamination of low-relief dome, Level 3, Santana Quarry 1, and detail of

truncated laminae; $\times 25$, parallel polarizers. **d** Detail of **c**; note the presence of several small ($<30\ \mu\text{m}$ in diameter) circular objects, which may represent the remains of original organic structures; $\times 50$, crossed polarizers. The scale bar is 2 mm in **a–c** and 0.5 mm in **d**

from scavengers and bioturbators (Wilby et al. 1996). The fact that microbial mats are sites of rapid mineralization also may have accelerated this process (Chafetz and Buczynski 1992). Another important factor for the preservation of organic material is the absence of oxidizing conditions a few millimeters below the surface of the mats caused by the degradation of cells and EPS.

The preservation of organisms with organic skeletons (arthropods, plants etc.), and the complete absence of bottom-dwelling benthos and bioturbation structures is a prominent feature of the Crato *Lagerstätte* (Maisey 1991). The lack of grazing benthos, such as gastropods in this stratigraphic interval may have contributed to the proliferation of the microbial mats. Hence, the microbial communities may have played direct and indirect roles in the exceptional preservation of the Crato fossils, which arrived at the lake bottom from the water column.

Barling et al. (2015) recorded microfabrics (i.e., microspheres, hollow micro-spheres and aggregates) in insect fossils of the Crato Formation, which may represent bacterially mediated Fe mineral growths. According to these authors, some may even represent auto-lithified bacteria (Barling et al. 2015). Indeed, the high preservational fidelity of the Crato fossils, which is comparable to that of typical Ediacaran fossil embryos where the microbial activity promoted the direct replication of tissues by apatite, may be linked to substrate microbial fabrics (Briggs and McMahon 2016). Thus, biogeochemical processes involving mineralization of organic remains by microbial colonies seem to be essential for the preservation of Crato fossils. The lack of bacterial decay of organic skeletons and tissues in the laminated limestones of the Crato Formation could be associated with microbial communities that thrived on an anoxic, hypersaline bottom, since these conditions can contribute

to slowdown of decay (Fürsich et al. 2007). This process is common in hypersaline lakes (e.g., Maisey 1991). Additionally, microbial films may have had the direct effect of sealing the substrate, protecting organisms from any disturbance and from rapid, complete decay, in a manner similar to that described by Gehling (1999) for large Ediacaran body fossils (Briggs and McMahon 2016, p. 5). Indeed, this feature appears to have played a major role in the excellent preservation of fossils in a number of other laminated *lagerstätten*, such as the Upper Jurassic Solnhofen plattenkalks of southern Germany (Keupp 1977), and the Early Cretaceous lake deposits of northeastern China (Fürsich et al. 2007).

Concluding remarks

This contribution provides evidence for biologically induced carbonate mineralization in the most important South American Cretaceous *Fossil-Lagerstätte*. During the Aptian, microbial mats locally thrived in quiet, shallow-water, hypersaline, and oxygen-deficient settings at the margins of the Araripe lacustrine system, and were responsible for the origin of stromatolite mounds and domes. This finding, together with macro-, meso-, and microscopic evidence (in situ coccoidal, filamentous, and spiral cyanobacteria cells and fossilized extracellular polymeric substances, see Catto et al. 2016) indicate that the genesis of the well-laminated limestone, corresponding to the main fossil-bearing interval of the Crato Formation, was indeed strongly influenced by microbial activity. The extreme paleoenvironment accounted for the absence of bottom-dwelling benthos, favoring the profuse development of microbial mats and preservation of the organic remains.

The discovery of stromatolitic microbialites in the finely laminated limestones of the lower Crato Formation provides a unique opportunity to address the direct and indirect roles of the microbial communities in the exceptional preservation of the Crato fossils, and would be an important new research avenue for future taphonomic investigations of this *Konservat-Lagerstätte*.

Acknowledgements We are deeply indebted to Pablo Suarez-Gonzalez, Universidad Complutense de Madrid, for his very constructive comments on an earlier version of this manuscript. The reviews by Eduardo Roemers-Oliveira and an anonymous reviewer are also gratefully acknowledged. The authors thank Suzana Aparecida Matos da Silva for assistance in the field and photography. Financial supported by CNPq (Grants 444070/2014-1, 401039/2014-5, 30017/2015-3), FAPESP (Grant 2014/27337-8, 2004/15786-0) and Petrobras (0050.0023165.06.4) is gratefully acknowledged. We also thank the Center for Geosciences Applied to Petroleum Geology, São Paulo State University (UNESP/Petro-UNESP), for the laboratory facilities for Scanning Electron Microscopy, petrographic macroscopy and magnifier stereoscopy. This research was conducted with institutional

support of the São Paulo State University-UNESP, Brazil. Assine, M.G. Simões and L.V. Warren are fellows of the CNPq.

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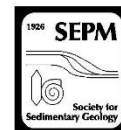
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IV. O KONSERVAT-LAGERSTÄTTE DA FORMAÇÃO CRATO E O PAPEL DAS ESTEIRAS MICROBIANAS NA PRESERVAÇÃO DE ASSEMBLEIAS FÓSSEIS EXCEPCIONAIS

As evidências macro, meso e microscópicas de atividade microbiana influenciando a sedimentação dos calcários laminados do intervalo *Konservat-Lagerstätte* da Formação Crato apontam para deposição em ambiente lacustre hipersalino e raso. A alta salinidade do meio dificulta a existência de grande diversidade de metazoários, ao passo que facilita a proliferação de comunidades microbianas resistentes a ambientes ecoestressantes. Além do mais, os reconhecidos intervalos anóxicos, antes interpretados como pertencentes às porções profundas e distais do lago Crato (Neumann et al., 2003; Heimhofer et al., 2010), são condizentes com atividade biológica em níveis específicos constituídos por esteiras microbianas de águas rasas. Nesse sentido, é bastante improvável que os fósseis da Formação Crato sejam resultantes de processos de fossilização em condições de águas profundas. No intuito de averiguar os processos tafonômicos que permitiram a preservação dos tecidos moles de fauna e flora tão diversa, foi conduzido estudo detalhado na principal ocorrência fossilífera da unidade, a pedreira Três Irmãos próxima a cidade de Nova Olinda (CE). Deste modo, os principais níveis de ocorrência de cada grupo fóssil foram identificados e associados à suas respectivas fácies sedimentares. Em função da preservação morfológica 3-D de crustáceos da Formação Crato, estes foram selecionados para estudar a interação rocha-fóssil e averiguar os diferentes mecanismos de fossilização. Os dados obtidos durante esta pesquisa integram o manuscrito “*Exceptional preservation of soft tissues by microbial entombment: insights into the taphonomy of the Crato Konservat-Lagerstätte*” submetido ao periódico *PALAIOS*. Este trabalho propõe um novo modelo de preservação de assembleias fossilíferas excepcionalmente preservadas e discute a importância da preservação associada a atividade microbiana ao longo do registro geológico. O texto submetido ao referido periódico consta integralmente a seguir.

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EXCEPTIONAL PRESERVATION OF SOFT TISSUES BY MICROBIAL ENTOMBMENT: INSIGHTS INTO THE TAPHONOMY OF THE CRATO KONSERVAT-LAGERSTÄTTE

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ABSTRACT: The Aptian Crato Konservat-Lagerstätte is renowned for its exceptionally preserved fossils in lacustrine laminated limestones. Although previous works on this site include numerous taxonomic studies, its taphonomy remains a subject of debate. Herein, we present new data on the taphonomy of decapod crustaceans preserved in wrinkle laminites, highlighting the role of microbial mats in enhancing fossil preservation. Our results suggest that benthic microorganisms may have promoted protection and organic mineralization of some of the allochthonous to parautochthonous organic remains within the microbial laminites of the Crato lake. Overall, this work provides the first empirical evidence that the preservational pathways of the fossils in the Crato Konservat-Lagerstätte involved microbial mats.

INTRODUCTION

The fossil record is inherently biased and incomplete, and because of these intrinsic natural properties, its adequacy is a primary concern in large-scale fossil-based studies (Paul and Donovan 1998; Muscente et al. 2017). In addition, the completeness of the fossil record of organisms with biomineralized tissues (e.g., shells, bones) differs dramatically from that of soft-bodied organisms (Paul and Donovan 1998; Foote and Sepkoski 1999; Kowalewski 2007) as soft and non-mineralized tissues are only preserved under unusual environmental and/or taphonomic conditions (Allison and Briggs 1993; Schiffbauer and Laflamme 2012; Muscente et al. 2017). Deposits where exceptionally preserved soft-tissues are present are called Konservat-Lagerstätten, in contrast to Konzentrat-Lagerstätten that preserve quantity rather than quality (Seilacher et al. 1985). In addition to soft tissue preservation, Konservat-Lagerstätten usually contain remains of articulated multi-element skeletons, offering relatively complete snapshots for exploring the ecology and dynamics of ancient ecosystems (Conway Morris 1986; Muscente et al. 2017). Such archives are regarded as windows into the paleobiology and evolution of metazoans (Butterfield 2003; Nudds and Selden 2008; Xiao et al. 2014), supporting a variety of studies in taphonomy, systematics, and paleoecology (e.g., Vinther et al. 2008; Ma et al. 2012; McNamara et al. 2012a; Maldanis et al. 2016; Pan et al. 2019; Muscente et al. 2019).

In such conservation deposits, animal and plant tissues are finely preserved, often in high-quality details and occasionally at the cellular (Knoll and Barghoorn 1977; Xiao et al. 1998; Briggs 2003a; Cohen et al. 2009; Pang et al. 2013), and sub-cellular (Schiffbauer et al. 2012; Muscente et al. 2015b) levels. Consequently, organic structures such as internal organs (Ma et al. 2012; Maldanis et al. 2016; Hawkins et al. 2018; Pan et al. 2019), integument (Walossek et al. 1993; Müller et al. 1995; Pinheiro et al. 2012), feathers (Vinther et al. 2008; Carvalho et al. 2015), muscle fibers (Schultze 1989; Martill 1990; Osés et al. 2016), and cells with nuclei (Knoll and Barghoorn 1977; Xiao et al. 1998; Cohen et al. 2009; Pang et al. 2013; Osés et al. 2017) can be fossilized, providing key

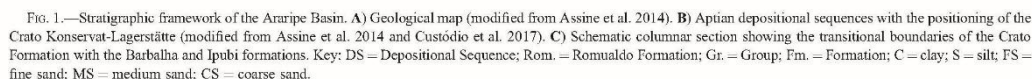
elements for unraveling and understanding the evolution of metazoans (e.g., Butterfield 2003; Xiao et al. 2014; Carvalho et al. 2015; Martill et al. 2015; Maldanis et al. 2016; Pan et al. 2019).

Preservation of soft tissues is rare and only occurs when mineralization processes are faster than degradation (Briggs 2003a). Silicification, phosphatization, pyritization, aluminosilicification, and preservation by carbonate minerals are among the main taphonomic processes leading to exceptional preservation (see Muscente et al. 2017 and references therein). These processes are recorded in well-known fossils assemblages (Butterfield 2003) that may undergo a variety of taphonomic pathways depending on the environmental conditions and particularities of each organism (Cai et al. 2012). Different processes can be identified within a single specimen (McNamara et al. 2009; Cai et al. 2012), among specimens from a single assemblage (McNamara et al. 2012b; Schiffbauer et al. 2014), or among assemblages located closely in space and time (Muscente et al. 2015b, 2017). This means that favorable microenvironments can induce to different taphonomic processes under similar global and regional circumstances, providing evidences for a single unifying conceptual model, rooted in sedimentary geology and geomicrobiology (see Muscente et al. 2017, fig. 3).

Microbes play both constructive and destructive roles in the preservation of organisms within all types of sediments (Muscente et al. 2017). Advances in the study of biofilms and microbial mats suggest that these microbial communities play key roles in the preservation of soft tissues (Martill 1988; Briggs and Wilby 1996; Wilby et al. 1996; Briggs 2003a; Darroch et al. 2012; Iniesto et al. 2016). Microbial mats rapidly entomb dead organism, protecting the organic remains rather than decomposing them (Iniesto et al. 2013, 2015, 2016). Thereby, this mat-derived coverage provides sarcophagus-like conditions (i.e., a woven microbial layer that covers dead organisms; Iniesto et al. 2013), and ideal steep geochemical gradients (e.g., pH, oxygen, phosphate), acting as sites of authigenic organic mineralization (Briggs 2003b; Schiffbauer et al. 2014; Tomescu et al. 2016) and/or allowing the replication of tissues by bacterial cells

Published Online: July 2019

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The Lower Cretaceous Crato Konservat-Lagerstätte (Fig. 1) is renowned for its fossils, including abundant and exceptionally preserved insects (Barling et al. 2015), early flowering plants (Mohr and Friis 2000), gymnosperms with evidence of insect-plant interactions (Santos Filho et al. 2017), the oldest gilled mushroom (Heads et al. 2017), a Gondwanan basal serpentiform snake (Martill et al. 2015), birds with preserved feathers (Carvalho et al. 2015) and melanosome cells (Vinther et al. 2008), pterosaurs with fossilized head crests (Pineiro et al. 2012), as well as many other vertebrates, invertebrates, and plants preserved in a lacustrine environment (e.g., Martill et al. 2007a). However, besides relevant efforts (see Martill et al. 2007a; Barling et al. 2015; Osés et al. 2016, 2017), the processes that led to the exceptional preservation of allochthonous faunal and floral elements in the laminated limestones is still poorly understood. Herein, new data on the fossils and laminated limestones of the Crato Formation are presented, supporting the hypothesis that microbial mats significantly contributed to the exceptional preservation of the fossils.

The Araripe Basin preserves the most complete record of the Northeast Brazilian rift basins (Assine 2007), encompassing the extensional processes that led to the break-up of Gondwana and opening of the South Atlantic Ocean (Chang et al. 1988; Matos 1992) (Fig. 1A). The basin is structurally confined in a Precambrian shear zone located in the Borborema

Currently, the Araripe Basin constitutes a remarkable, > 900 m high geomorphological structure known as Araripe Plateau, surrounded by steep and erosional scarps (Morales and Assine 2015), where Lower Cretaceous (Aptian) strata are exposed. The Aptian transitional phase is represented by the Barbalha, Crato, Ipuí, and Romualdo formations that comprise the Santana Group (*sensu* Assine et al. 2014). In this succession, the Crato Formation contains exceptionally preserved fossils, constituting an outstanding Cretaceous Konservat-Lagerstätte worldwide. Notably, the absence of true marine fossils indicates that the interval was deposited under lacustrine conditions (Neumann et al. 2003; Heimhofer et al. 2010).

The Crato Formation encompasses a 90 m thick mixed carbonate-siliciclastic succession best exposed in the eastern part of the Araripe Basin (Assine et al. 2014). The unit has transitional contacts with the underlying

Barbalha Formation and the overlying Ipubi Formation, and may also have an unconformable (erosional) boundary with the Romualdo Formation (Fig. 1B, 1C). In the Nova Olinda region, the Crato Formation lies unconformably on the Brejo Santo Formation, and in some regions, it may rest directly on basement rocks (Fig. 1A). The most widely accepted model for the deposition of the mixed carbonate-siliciclastic succession proposes that the transgressive-regressive cycles record periods of lacustrine system expansion and retraction coupled with changes in the sedimentary supply (Neumann et al. 2003). The carbonate facies purportedly reflect authigenic precipitation in distal parts of the lake, supposedly induced by biochemical processes (Heimhofer et al. 2010). The presence of halite pseudomorphs in the limestone beds are direct evidence that the basin experienced climatic variations, including periods of increasing arid/evaporitic conditions (Martill et al. 2007b; Heimhofer et al. 2010; Warren et al. 2017).

The recent discovery of widespread microbialites in the laminated limestones of the Crato Formation in association with well-preserved fossils indicates that microorganisms mediated carbonate precipitation (Catto et al. 2016; Warren et al. 2017). The morphologies of the microbialites and microbially induced sedimentary structures (MISSs; Noffke et al. 2001) vary with the vertical stratigraphic position in the Crato Formation, suggesting that the bottom of the hypersaline lake was frequently covered by biofilms and microbial mats, and that deposition of the laminated limestones was influenced by microbial activity in shallow-water settings (Catto et al. 2016; Warren et al. 2017). Although some stratigraphic intervals contain allochthonous fossils of terrestrial organisms (e.g., pterosaurs, angiosperms, and clam shrimps) in limestone beds, the unit may not consist entirely of lacustrine strata. Indeed, the presence of possible marine (or brackish) bivalves (see Bruno and Hessel 2006) and micro-foraminiferal linings (Goldberg et al. 2019) in the Crato Formation suggests deposition in transitional environments.

MATERIAL AND METHODS

The sedimentological and stratigraphic archives of the Crato Konservat-Lagerstätte were investigated by measurement of detailed columnar sections in the Três Irmãos quarry (UTM, Zone 24M/422,955E/9,213,344S), Nova Olinda region, Ceará State, northeastern Brazil (Figs. 1, 2). Analogous to the Solnhofen limestones (Seilacher et al. 1985), the Crato laminites are only considered a Konservat-Lagerstätte with extraordinarily preserved fossil assemblages due to the existence of excellent exposures in open quarries. The mining activities near the Nova Olinda and Santana do Cariri regions reveal diverse and well-preserved fossil assemblages (Martill et al. 2007a). Almost all fossils specimens were accidentally collected by local workers as the mine front advanced precluding a detailed bed-by-bed analysis in most of the published studies.

Considering this particularity, a detailed investigation of the stratigraphic distribution (relative abundance) of the main fossil groups (i.e., tetrapods, fishes, arthropods, and plants) in this deposit was done by the careful observation of exposed bedding planes, revealing that the preservation of particular groups of fossils are tied to changes in sedimentary facies (see below). Two exceptionally preserved specimens of shrimp were chosen to be studied in detail. These samples were found by local miners while excavating the limestones, thus the stratigraphic position is not well-constrained regarding a particular bedding plane. However, the stratigraphic position of those shrimp specimens was determined with both the help of local quarry miners and the careful analysis of its host rock (microfacies) and association with other fossils. All specimens are housed at the scientific collections of the Institute of Geosciences, University of São Paulo, São Paulo, southeastern Brazil, under the code GP/1E 10863 and GP/2E 9490.

The samples of the fossiliferous laminated limestone (Fig. 2) were sectioned as slabs for macroscopic description and classification in the laboratory. Petrographic thin-sections previously prepared from the rock

slabs were analyzed under both normal and polarized light using a Zeiss Axio Imager A2 binocular petrographic microscope and a Zeiss Stereo Discovery V.11 binocular magnifying glass, at the Center for Geosciences Applied to Petroleum Geology, São Paulo State University, Brazil (UNESPetro-UNESP). The fossil diagenesis was investigated based on the microtextures and general geochemical composition of the samples and both host rock and fossils were analyzed under Scanning Electron Microscope (SEM), using standard techniques (see Muscente and Xiao 2015 for all the parameters that one must consider in electron imaging).

The resulting SEM images were generated using an electron microprobe JEOL JXA 8230 equipped with five WDS spectrometers and a solid-state EDS detector, at the Department of Petrology at São Paulo State University, Brazil. Images of the microbial textures and microstructural fabric of fossils were made in variable-pressure mode, using secondary electron images operated at EHT 5–30 kV and 40–80 Pa, without metal coating. The working distance used for rock fabrics was 7 mm, while fossil microtextures varied from 10 to 20 mm. All the elemental analyses were performed simultaneously, using the EDS detector operated under constant conditions using 20 kV and 20 nA with a step size of 4 μ m and a dwell time of 10 ms.

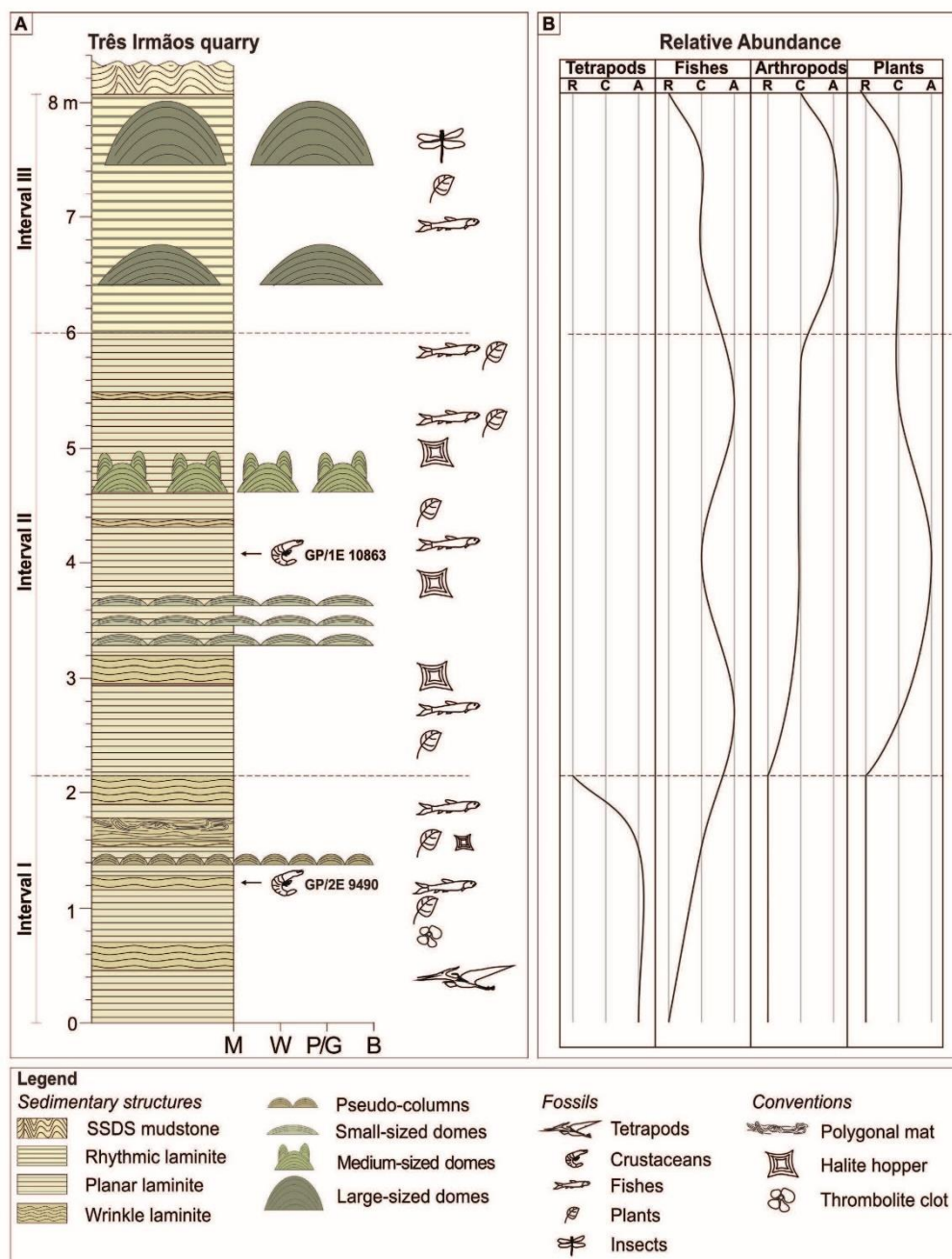
RESULTS

Stratigraphic Position of the Main Fossil Groups

The exceptionally preserved fossils are not widely distributed within the Crato Formation, but confined to an 8 m thick, basal carbonate unit in the Nova Olinda region (Fig. 2), nearly 12 m above the unconformable boundary with the Brejo Santo Formation (Fig. 1A). However, within this unit, the abundance of fossils varies notably. Fishes and plants occur throughout the entire interval, but the vertical distribution of other fossil groups seem to be constrained to some particular sedimentary facies (Fig. 2). Therefore, during this study three fossil-bearing intervals with distinct sedimentary characteristics were identified (Figs. 2, 3A).

The first interval (Interval I) encompasses a 2 m thick finely interbedded succession of wrinkle laminites, planar laminites, thrombolites, oncoids, and stromatolites (Figs. 2A, 3A–3E). Wrinkle laminites are very common in this interval and are characterized by 0.1 to 0.5 mm thick microsparry calcite with occasional intervals of discontinuous organic films inter-laminated with up to 0.25 mm thick wrinkled organic laminae (Fig. 4A, 4B). Wrinkle laminites form up to 0.2 m thick beds that are commonly associated with equally thick intervals of planar laminites. Also, they can occur as cm-thick layers with frequent convoluted lamination, due to the rupture of organic material produced by microbial communities during desiccation events (i.e., polygonal mats, *sensu* Lokier et al. 2017) (Fig. 3B). The planar laminites of this interval are characterized by 0.5 to 2 mm thick microsparry calcite laminae interbedded with micrite laminae. These planar laminites commonly present MISSs in the bedding planes (Fig. 3C). Also, 5 to 30 cm high coalescent pseudo-columnar stromatolites and oncoids are present in this interval (Fig. 3D, 3E), forming layers that are laterally continuous for dozens of meters. Pterosaurs, snakes, frogs, lizards, and turtles have been collected from Interval I (Fig. 2B) along with relatively rare decapod crustaceans, which are preserved in the wrinkle and planar laminites (Figs. 2A, 4B, 4C, 5A).

The second interval (Interval II) is about 4 m thick and constitutes the thickest succession of the Konservat-Lagerstätte (see Fig. 3A). It is characterized by dm-thick layers of planar laminites interbedded with rare, cm-thick layers of wrinkle laminites (Fig. 2). The planar laminites are the most common sedimentary facies and are characterized by mm- to cm-thick alternations of organic-rich micrite and microsparry calcite, very similar to those from Interval I (Fig. 4C). Up to 2 cm thick laminae of vertical needles of gypsum commonly occur segregating thin laminae of micrite in this interval (Fig. 4D). Also, bedding planes with well-preserved



halite hoppers are abundant. An important feature in this middle succession is the occurrence of discontinuous levels of 5 to 40 cm high symmetric and asymmetric domal stromatolites. These domes increase in size towards the top and are laterally separated by planar and wrinkle laminites. Porosity increases in proximity to domes due to the occurrence of fenestrae and vugs, which caused the percolation of fluids and the diagenetic growth of concretions at several levels. Domes also occur with complex overgrowth features separated by intervals of probable erosion events. These may culminate at the top in smaller domes representing a very specific branching pattern (Fig. 3F). In this interval, fishes and plants are the most abundant fossils (Fig. 2B) and occur associated with both, wrinkle laminites and, most commonly, planar laminites (Figs. 2, 4C). Shrimps are sparsely preserved in Interval II with planar laminites that contain halite hoppers, impressions of plant fragments, and evidence of fish mass-mortality events (Fig. 5B–5E).

The upper 2 m of the Konservat-Lagerstätte succession (Interval III) is characterized by finely laminated rhythmic laminites, having a distinct papery look when deeply weathered (Fig. 3A). The lamination consists of very fine (0.25–0.5 mm) intercalations of dark micrite and light microsparry calcite and discontinuous films apparently rich in organic matter (Fig. 4E). Meter-sized domal stromatolites also occur in this interval (Fig. 3G). These are scattered 0.7 to 1.2 m high, flat-based domal structures. Gypsum layers are also found between micrite laminae, mostly in the first 50 cm. Micro-deformational soft-sediment structures (i.e., micro-slumps and loop-beddings) are also observed in this interval. Most of the recorded insects come from Interval III, but fishes and plants are also present (Fig. 2B). Caridean shrimps are rare in this interval, but occur as exceptionally preserved specimens associated with insects. The upper interval culminates in an unfossiliferous, flat-based and irregular-topped mudstone bed with several soft-sediment deformation structures including breccias and fluid escape structures that completely obliterated the original lamination (Martill et al. 2008, fig. 6B).

Exceptional Preservation of Decapod Crustaceans in Microbial Mats

Two specimens of exceptionally well-preserved shrimps associated with the main microfacies within the Crato Konservat-Lagerstätte were investigated in detail: (1) specimen GP/2E 9490 from the wrinkle laminites of Interval I and (2) specimen GP/1E 10863 from the planar laminites of Interval II (Figs. 2A, 3A). The two decapod specimens here analyzed are referred to the sole known shrimp species in the Crato Formation, *Beurlenia araripensis* Martins-Neto and Mezzalana, 1991, an *incertae sedis* Caridea (Schweigert et al. 2007, but see Maisey and Carvalho 1995). *Beurlenia araripensis* was a freshwater shrimp that lived in the Crato lake bottom community. The specimen GP/2E 9490 was preserved in dorsal aspect (i.e., the dorsal surface is parallel to the substrate; Fig. 5A, 5B), an extremely uncommon position in shrimp preservation (Schweitzer et al. 2014). On the other hand, specimen GP/1E 10863 (Fig. 5C, 5D) is preserved as a laterally disposed individual, a condition interpreted as the “normal” lateral attitude in shrimp preservation (see Schweitzer et al. 2014). The specimens are preserved as complete, true-body fossils (i.e., they are corpses, not molts). The carapace of both shrimps is devoid of signs of predation, scavenging, and/or infestation by epibionts.

The microstructural analyses reveal that the wrinkle laminite where the specimen GP/2E 9490 occurs consists of mm-thick microsparry calcite and a mesh network of alveolar structures characteristic of microbial mats (Fig. 6A). The thicker microsparry laminae are composed of < 10 µm sized

rhombic calcite crystals with several discontinuous patches of organic structures. Also, some of these laminae are replete with microspheroids that can reach up to 200 µm in diameter (Fig. 6B). In some parts the laminae exhibit a peloid-microclotted fabric, a distinguishing feature of microbialites (see Theisen and Sumner 2016 for similar features). The alveolar structures are characterized by 10 to 60 µm sized apertures, forming an intricate pattern resembling honey-combs (Fig. 6C). In some parts, these polygonal voids are filled with iron-rich microspheres (Fig. 6D).

The caridean shrimp specimen GP/1E 10863 is preserved in a planar laminite of Interval II. The microstructural analysis on this facies reveals mm-scale microsparry calcite laminae segregated by thin (~ 0.05 mm) organic-rich dark films (Fig. 6E). Organic patches are also recognized in the microsparry laminae (Fig. 6E). There, an alveolar network of amorphous organic matter occurs interspersed with rhombic calcite crystals (Fig. 6F).

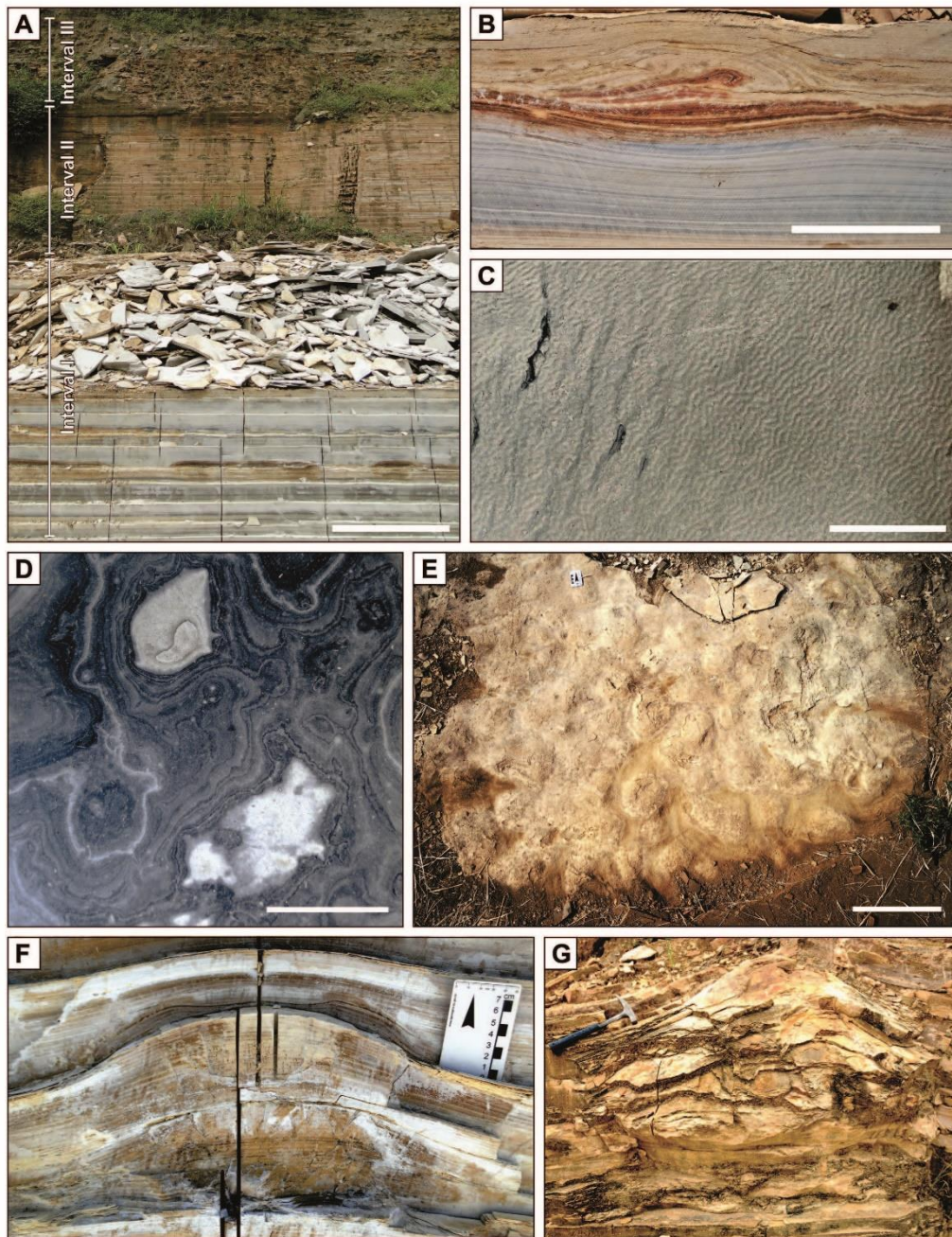
The studied specimens are very well-preserved in 3D and occur in wrinkle and planar laminites. The specimens also show complete articulation of antennae, pereopods, pleopods, abdominal somites, telson, and rostrum (Fig. 5) and are preserved parallel to the bedding, with appendages apparently attached to the host rock by fine-grained subbedded calcite needle-like structures similar to filaments (Fig. 7A; see also fig. 11 in Iniesto et al. 2016). Fine sheets of calcified biofilms also coat most parts of the multilayered shrimp cuticles (Fig. 7B). The internal tissues of the pereopods, revealed by openings generated by curled biofilms (Fig. 7C), are enveloped by honey-combed structures (Fig. 7D) with the same morphology as the alveolar structures from the matrix (Fig. 6C, 6D), albeit smaller (each polygon has a diameter of about 1 µm). The host rock also exhibits similar cracked and wrinkled features, characterized by thin and curled microbial lamination covered by very thin subbedded calcite (Fig. 7E). The hard parts of the shrimps, such as appendages, antennae, and carapace, are mostly preserved as calcium phosphate (Fig. 8A–8D), while the internal tissues and other soft parts are preserved by a calcium-phosphate free and iron-rich phase (Fig. 8E). Due to the overall oxidation of the sample, sulfur is not observed in association with iron where soft tissues occur (see Fig. 8E, 8F). Isolated, small crystals of pyrite also occur disseminated in the sample (Fig. 7F). Siliceous cylindrical structures resembling diatom frustules (Fig. 7F) are also found in aggregates between pleopods and abdominal somites.

DISCUSSION

Three distinct features document microbial activity during deposition of the carbonates of the Crato Konservat-Lagerstätte: (1) the presence of stromatolitic crusts, oncoids, pseudo-columns, domes, MISS, thrombolites and preserved microbial mats (Catto et al. 2016; Warren et al. 2017; this work) directly associated with the macrofossils; (2) the widespread casting of soft parts by mineralized bacteria in fishes and arthropods (Barling et al. 2015; Osés et al. 2017), including formation of microbial-related pyrite (Catto et al. 2016; Osés et al. 2016), and coating of shrimps (Fig. 7) and insects (Barling et al. 2015; Osés et al. 2016) by extracellular polymeric substances (EPS); and (3) presence of bacteria autolithification (*sensu* Wuttke 1983) in insects (see Barling et al. 2015, fig. 15C).

By combining taphonomic, sedimentologic, and stratigraphic data, the association of EPS and shrimp specimens within microbial laminites was detected. Therefore, we critically discuss this association and a new taphonomic pathway for soft-tissue preservation of the Crato Konservat-

Fig. 2. Sedimentological, stratigraphic and paleontological aspects of the Crato Konservat-Lagerstätte. A) Detailed columnar section of the Crato Konservat-Lagerstätte in its main outcrop area, Nova Olinda county, State of Ceará, northeastern Brazil, indicating the stratigraphic position of the main fossil groups and the positions of the shrimp specimens analyzed. B) Relative abundance of the main fossil groups based on qualitative data. Key: M = lime mudstone; W = wackestone; P/G = packstone/grainstone; B = boundstone; R = rare; C = common; A = abundant.



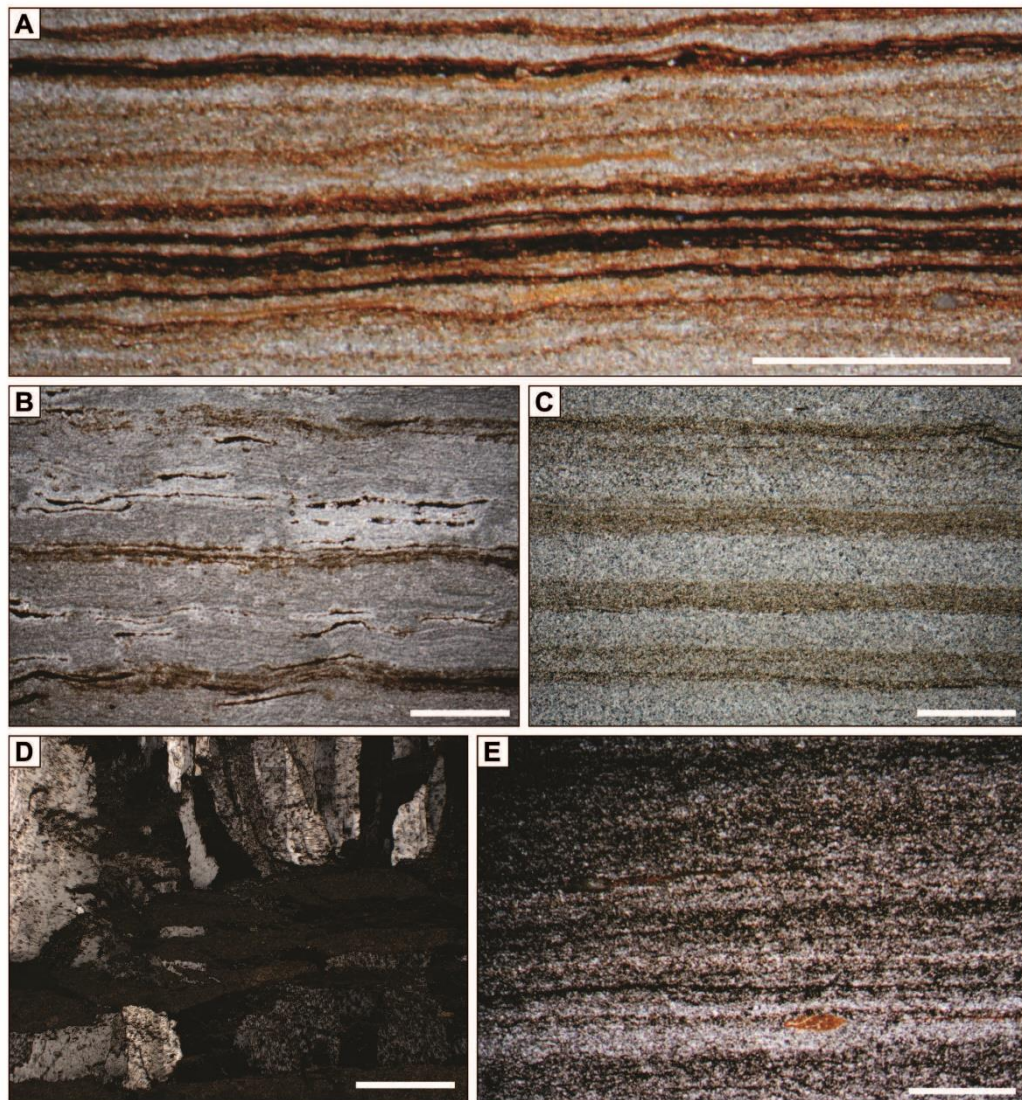
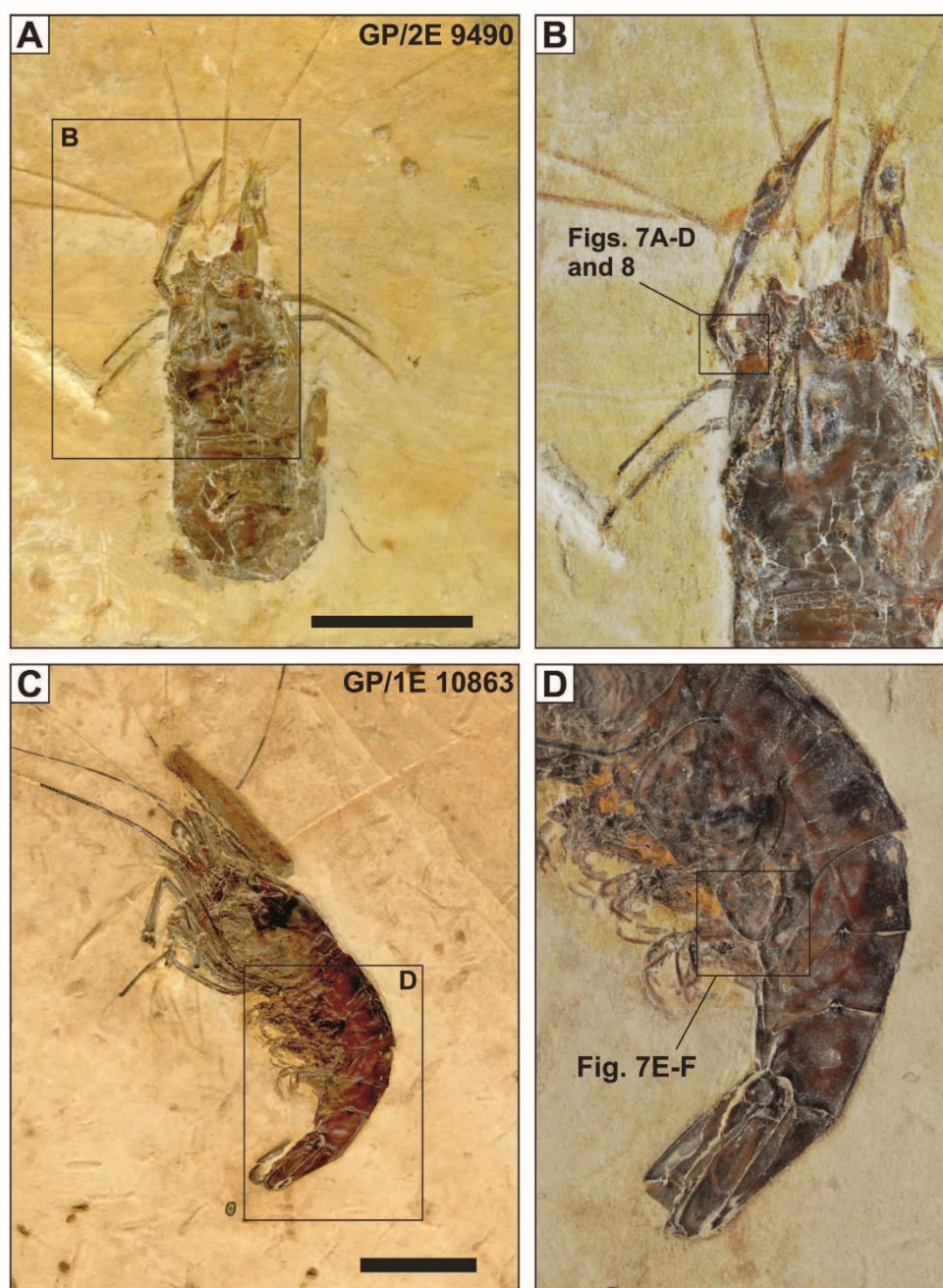


FIG. 4.—Petrography of the different laminite facies within the Crato Konservat-Lagerstätte. **A)** Intercalation of organic-rich micrite and microsparry calcite in wrinkle laminites; scale bar = 1 mm. **B)** Wrinkle lamination showing alternation of dark organic laminae and microsparry laminae with discontinuous biofilms; scale = 1 mm. **C)** Planar laminite showing < 1 mm thick micrite and microsparry alternations; scale bar = 1 mm. **D)** Needles of gypsum segregated by micrite laminae; scale = 1 mm. **E)** Rhythmic laminites characterized by thin alternations (0.01 to 0.05 mm) of organic-rich micrite and sparry calcite lending the rock a papery look; scale bar = 1 mm.

FIG. 3.—Microbial facies of the Crato Konservat-Lagerstätte. **A)** General view of the intervals II and III; scale bar = 1 m. **B)** Deformed wrinkle laminites resembling polygonal mats (*sensu* Lokier et al. 2017); scale bar = 1 cm. **C)** *Kinneya*-like MISS on the surface of planar laminites; scale bar = 1 cm. **D)** Polished slab of coalescent pseudo-columnar stromatolite and oncoids in plan-view; scale = 15 cm. **E)** Plan view of pseudo-columnar stromatolite field; scale = 50 cm. **F)** Stacked layers of a domal stromatolite showing branching at the top. **G)** Isolated large-sized domal stromatolite; 30 cm hammer for scale.



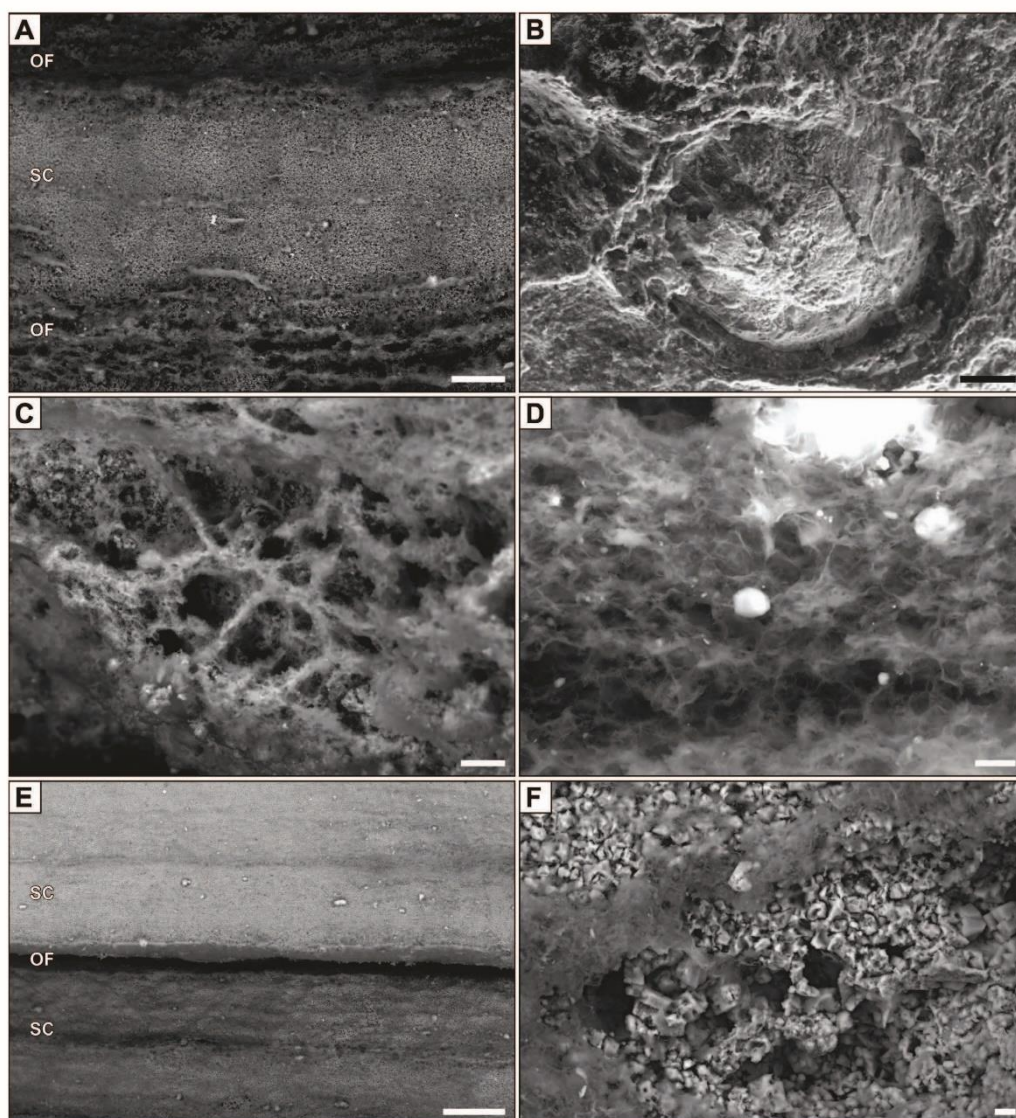


FIG. 6.—SEM images of wrinkle laminites. **A)** Cross-sectional view of alternating microsparry calcite and organic-rich laminar; scale bar = 100 μm . **B)** Round peloid in a microspar lamina; scale bar = 50 μm . **C)** Detail of organic-rich lamina, revealing an alveolar network (EPS); scale bar = 50 μm . **D)** Mineralized coccoid cell associated with EPS; scale bar = 10 μm . **E)** Cross-sectional view of planar laminites showing an organic biofilm separating microsparry laminar. **F)** Detail of the microsparry laminar in E with interspersed alveolar structures. Key: SC = microsparry calcite; OF = organic film; scale bar = 10 μm .

FIG. 5.—Exceptionally preserved shrimps with 3D morphology from the Crato Konservat-Lagerstätte. **A)** Shrimp specimen GP/2E 9490 preserved in wrinkle laminites (Fig. 4B). **B)** Detail of specimen GP/2E 9490; the area analyzed by SEM (Figs. 7A–7D, 8) is highlighted. **C)** Shrimp specimen GP/1E 10863 preserved in planar laminites associated with carbonized plant. **D)** Detail of the abdominal somites of specimen GP/1E 10863; the area analyzed by SEM (Figs. 7E, 7F) is highlighted.

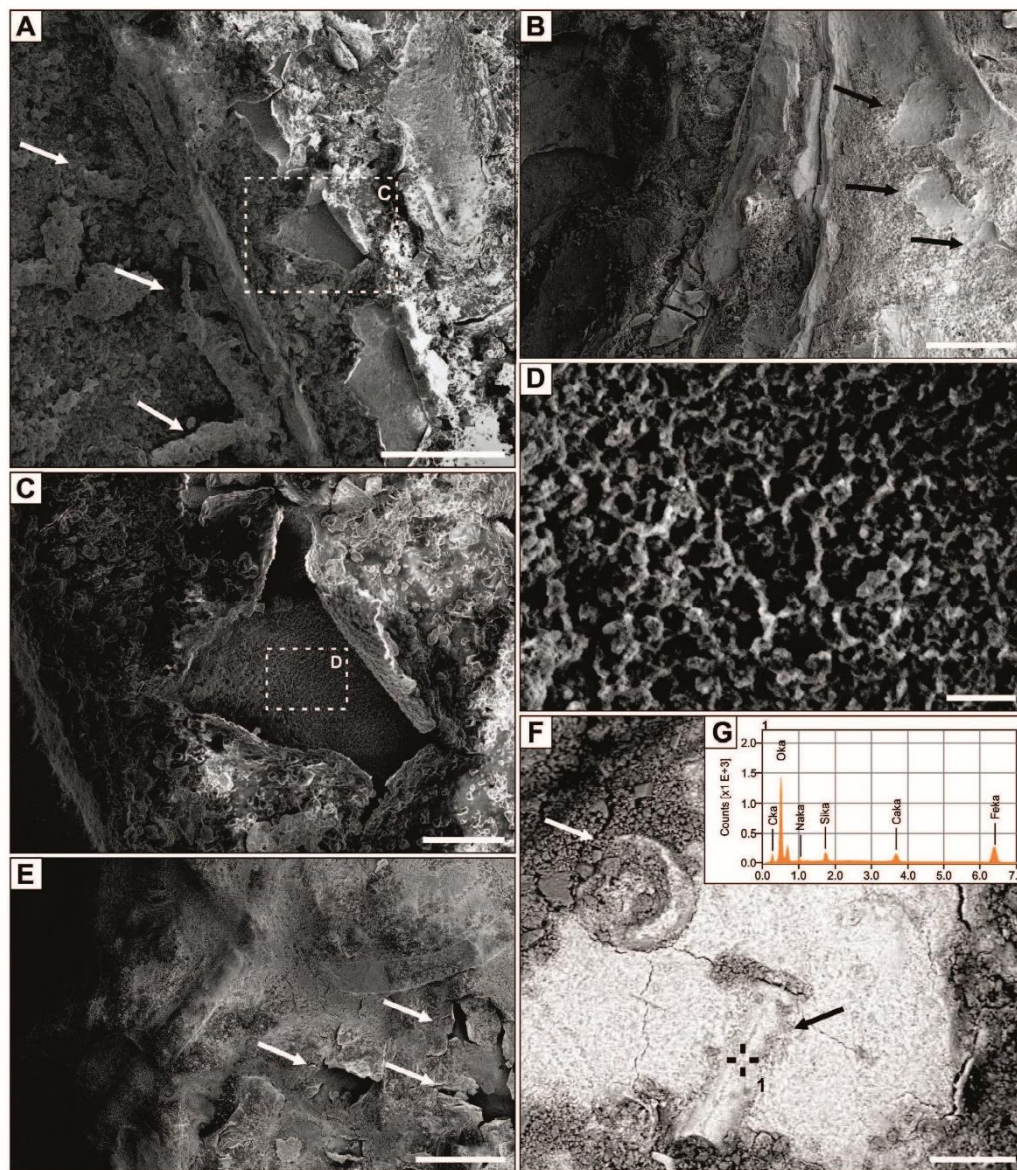


FIG. 7.—SEM images of shrimps from microbial laminites. **A**) Detail of a walking leg of shrimp specimen GP/2E 9490 preserved in 3D attached to the rock by calcified EPS filaments (arrowed); scale bar = 200 μ m. **B**) Exoskeleton with very fine coating of a probable calcified biofilm (specimen GP/2E 9490); scale bar = 500 μ m. **C**) Cracked integument revealing a 3D structure inside the carapace that was enveloped by EPS coating (specimen GP/2E 9490); scale bar = 50 μ m. **D**) Detail of internal tissue coated by mineralized EPS (specimen GP/2E 9490); scale bar = 5 μ m. **E**) Cracked thin film of the host rock near the abdominal area (specimen GP/1E 10863); scale bar = 500 μ m. **F**) Diatom frustules between abdominal somites (specimen GP/1E 10863); scale bar = 50 μ m. **G**) Energy dispersive X-ray spectroscopy point (point 1 in F) spectra.

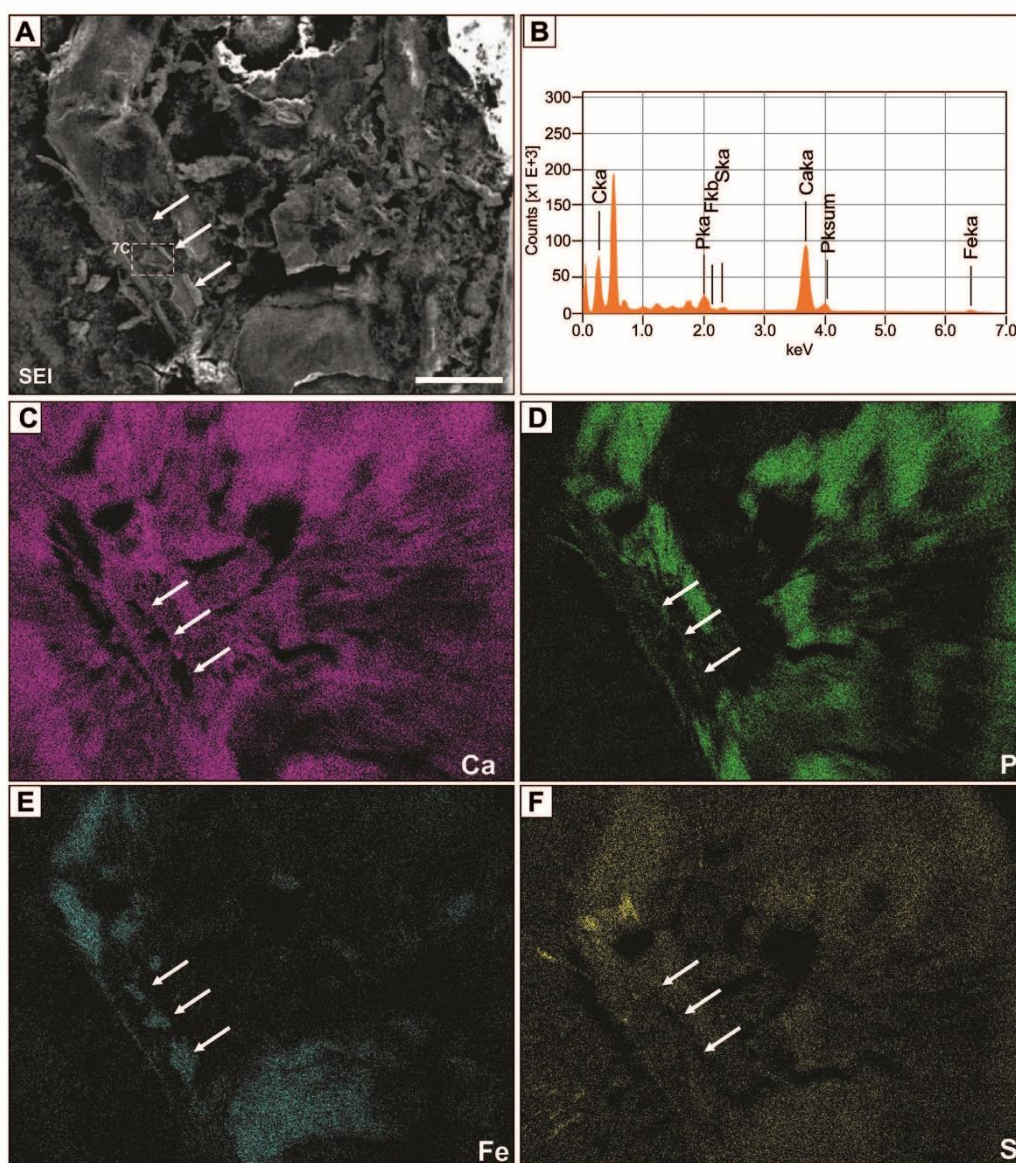


FIG. 8.—EDS analysis of shrimps highlighting the preservation by phosphatization and pyritization. Arrows point to the cracked integument revealing internal soft tissues. A) General view of the shrimp specimen GP/2E 9490 showing the cracked exoskeleton revealing soft tissues (also note the highlighted area with magnification in Fig. 7C). B) EDS spectrum of the area shown in A. C) EDS elemental map compositional map showing calcium in both host rock and shrimp. D) Phosphate associated with calcium in the shrimp specimen. E) Iron-rich EPS coating of internal tissues preserved (see also Fig. 7c). F) Sulfur concentrated in pyrite framboids.

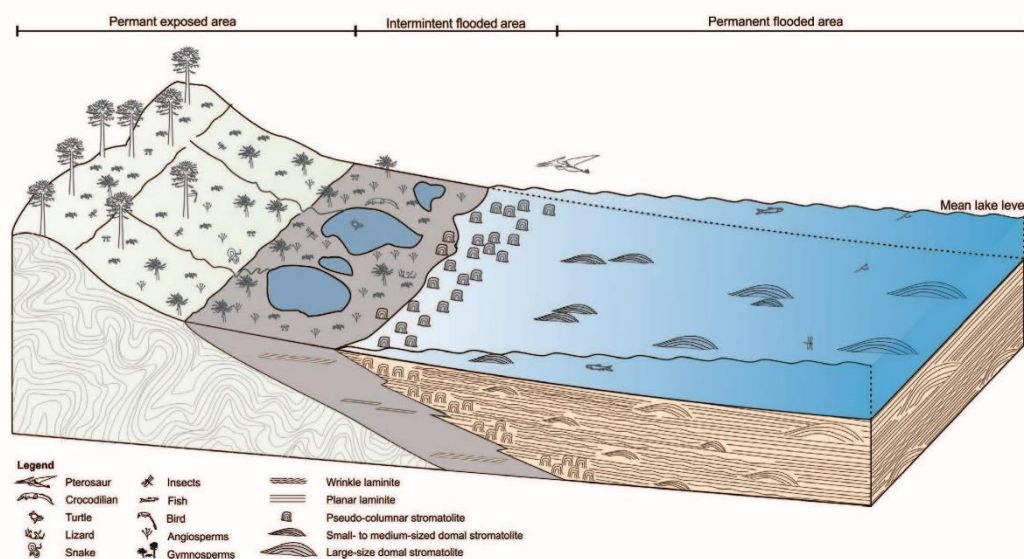


FIG. 9.—Block diagram of the depositional environment of the Crato Konservat-Lagerstätte.

Lagerstätte is suggested under the light of the distinct types of microbial-related structures.

Paleoenvironmental Conditions Influencing Microbialite Morphologies

The co-occurrence of microbialites and metazoans in the same setting is unusual in the Phanerozoic Eon, thus unique physical (e.g., temperature) and geochemical (e.g., high salinity and high/low pH) environmental conditions must have existed (Myshrall et al. 2014) during the deposition of the Crato Konservat-Lagerstätte. Indeed, the extreme variations in environmental parameters may have influenced the development of microbialites and the conditions to exceptional fossil preservational (Warren et al. 2017). The Crato lake developed under high alkalinity, high salinity, and probably oxic conditions as suggested by the abundant microbialites, occurrence of halite pseudomorphs, and the apparent absence of bioturbation (Heimhofer et al. 2010; Downen et al. 2016; Warren et al. 2017).

In the first interval of the Konservat-Lagerstätte succession, the presence of typical microbial polygonal mats (*sensu* Lokier et al. 2017) formed in wrinkle laminites (Fig. 3B), as well as the occurrence of MISSs in the top of planar laminites (Fig. 3C), dm-high and closely spaced to coalescent pseudo-columnar microbialites (Fig. 3E), and thrombolites are interpreted to have formed in hypersaline shallow waters (Warren et al. 2017) (Fig. 9). Polygonal mats are interpreted as desiccated and curled microbial mats (Lokier et al. 2017) and indicate that the lower interval was punctuated by brief intervals of subaerial exposure. As verified by Kaźmierczak et al. (2015), the alternation of micrite and sparite in both planar and wrinkle morphologies is a common feature of modern microbial mats. In addition, the existence of microbial mats is reinforced by the preservation of alveolar structures interpreted as EPS secreted by microbes (Dupraz et al. 2009) in both the wrinkle and planar laminites facies (Fig. 6). This is also revealed by the nature of alveolar structures preserved interspersed with rhombic calcite crystals (Fig. 6F) that is highly

suggestive of EPS secretion by benthic microbes (see examples in Kaźmierczak et al. 2015). The occurrence of interbedded planar and wrinkle morphologies suggests pronounced lake water level variations, typical of coastal areas, and the association of these microbial mats with oncoids, thrombolites, and stromatolites resembles those that occur in the margins of the Great Salt Lake (Bouton et al. 2016) and high-altitude hypersaline lakes from the Andes in Argentina (Fariás et al. 2011).

The middle carbonate interval is also characterized by planar and wrinkle laminites, but they are less abundant than in the lower interval. Salinity is interpreted to have been very high as indicated by occasional early diagenetic gypsum laminae (Fig. 4D) within laminites, by abundant halite hopppers, and also by the predominantly flexed leg of spiders (see Downen et al. 2016). The size of the stromatolites corroborates an increase in water depth towards the top of the succession, where up to 40 cm high domes replaced the smaller ones present in the lower parts of the Konservat-Lagerstätte (Fig. 2). The presence of dichotomies in domes and intervals with ripple cross-laminated grainstones are also typical of somewhat turbulent waters. Overall, the facies association in Interval II is still representative of shallow waters, although evidence of subaerial exposure is apparently lacking. In fact, this situation is expected in a system with benthic photosynthetic communities, constituting potential evidence to support the presence of microbial mats in the lake.

Papery planar laminites with slumps and loop-beddings indicate a more distal environment of the shallow lacustrine system, where seismic pulses probably induced the formation of soft-sediment deformation structures (Martill et al. 2008) by slumping. Previous studies (i.e., Catto et al. 2016) indicate that planar and rhythmic laminites contain several biofilms with preserved EPS and filamentous bacteria, showing that, although apparently monotonous, the laminated limestones can be formed by direct metabolic activity of benthic microbial communities. In addition, the existence of up to 1.2 m high isolated domal stromatolites in this association also characterizes more distal waters, analogous to living stromatolites from the Great Salt Lake (Della Porta 2015).



FIG. 10.—Reconstruction of the lacustrine Crato Konservat-Lagerstätte. Illustration by Julio Lacerda.

The microbial facies and the morphology of microbially induced structures in the Crato Konservat-Lagerstätte limestones are typical of a shallow hypersaline lacustrine system recording a distinct deepening-upward pattern (Fig. 9). This interpretation is supported by the occurrence of terrestrial fossils, polygonal mats, and the presence of wrinkle morphologies in its basal part, which decrease in abundance towards the top. Also, stromatolite morphologies vary from base to top both in size and morphology. Indeed, while wrinkle laminites are abundant and pseudo-columns exist in Interval I, up to meter-sized domal stromatolites occur in the upper intervals (Fig. 2). The lake likely developed in an arid to semi-arid climate under closed conditions, favoring moderate to high levels of evaporation, which are attested by gypsum and halite hopper, and growth of microbial mats, thrombolites, and stromatolites (Fig. 10). The predominant carbonate fabric produced directly by microbially induced organomineralization (*sensu* Dupraz et al. 2009) was favored by the overall conditions of high salinity and high alkalinity of the lake water, which precluded the presence of grazing benthos but not of microbial colonies (see also Warren et al. 2017). The presence of *Spirulina* and other microbial cells of probable cyanobacteria affinity (Catto et al. 2016) suggests conditions of relatively shallow waters within the photic zone.

Fishes in this hypersaline lake system were the most abundant macro-organisms, most of them belonging to the genus *Dastilbe*. This cosmopolitan taxon probably tolerated hypersaline conditions and was subject to frequent mass mortality events (Davis and Martill 1999), possibly linked to algal blooms (Heimhofer et al. 2010). With the exception of fishes and shrimps, the preserved macrofossils of the Crato Konservat-Lagerstätte are allochthonous to the basin (*sensu* Kidwell et al. 1986), and probably lived in neighboring environments (freshwater rivers/ponds) of the hypersaline shallow lake where they finally came to rest (Martill et al. 2007a) (Fig. 10). Most of the pterosaurs were toothless herbivores (Pêgas et al. 2016) and probably fed on the abundant gymnosperms and angiosperms that thrived along the lake's margins. In this riparian forest, insects and other arthropods were abundant (Heads et

al. 2008) and even mushrooms were present (Heads et al. 2017). Frogs, turtles, lizards, and crocodiles are rarely preserved and occur either disarticulated or articulated with rarely preserved soft-tissues (Salisbury et al. 2003; Fielding et al. 2005; Carvalho et al. 2019). These organisms lived in the riparian forest, nearby rivers, and/or shallow lakes around the main Crato lake, which suggest post-mortem drifting of the carcasses prior to final burial (Salisbury et al. 2003; see also Selden and Nudds 2012). While large tetrapods are found in coastal facies (i.e., wrinkle laminites), small insects and plants probably floated offshore, which explains why they are common in the upper part of the Crato Konservat-Lagerstätte. Differences in the articulation and soft-tissue preservation mainly reflect different degrees of carcass reworking (Martill et al. 2007a). In any case, microbial mats may have rapidly covered carcasses (Iniesto et al. 2013, 2015, 2016), protecting them from abiotic (e.g., bottom currents) and biotic processes (e.g., microbial degradation).

Shrimp Biostratigraphic History

The studied shrimps occur as disperse, isolated individuals in some bedding planes of the laminated limestones of the Crato Formation (Fig. 11), suggesting that they are non-gregarious organisms. Indeed, shrimps interpreted as gregarious in the literature are found in large numbers and in relatively close proximity from each other in some bedding planes (Schweitzer et al. 2014). The presence of fossilized soft tissues indicates confidently that our specimens of *Beurlenia araripensis* are not molts, instead they are corpses of individuals that were preserved in their original life habitat. As most caridean shrimps, *Beurlenia araripensis* was a benthic organism, having a chelate second pair of pereopods which the outline points to a detritus-feeding lifestyle (Schweigert et al. 2007). As highlighted by these authors, the antennae and antennules are moderately long, and the stalked eyes are well-developed, therefore *Beurlenia araripensis* either lived in a shallow lake, littoral zone, or they inhabited algal mats close to the water surface (Schweigert et al. 2007, p. 134).

However, since their fossils are preserved as individuals with clean corpses (i.e., without epibionts), this may indicate that they had efficient cleaning mechanisms and/or were natant (see Schweitzer et al. 2014).

The causes of death of *Beurlenia araripensis* are very difficult (or even impossible) to determine, but their preservation on discrete bedding planes of the laminated limestone of the Crato Formation (Fig. 11) suggests that this might be associated to some short-lived, variation of environmental conditions. Given the isolate paleogeographic nature of Crato lake in the continental interior, abrupt variations in salinity, pH, oxygen content as well as algal blooms, among others, may account for the shrimp death in some stratigraphic intervals.

Upon death, the individuals were rapidly recovered by microbial mats, and were not subsequently disturbed by scavengers or bioturbation that seems to have been minimal or absent in the lake bottom. In fact, decay experiments with caridean shrimps indicate that rapid disarticulation of the carapaces will take place soon after death (Plotnick 1986). When bacterial decomposition dominated in association to major soft tissue disintegration, the disassociation of some anatomical elements, such as the antenna, pereopods, pleopods, carapace and abdominal segments will occur within a few days (i.e., two weeks; Plotnick 1986). In addition to bacterial decay, this author also argued that bioturbation and scavenging of buried decaying shrimps are key bioturbation processes to skeletal disassociation. As already commented, evidences of predation or scavenging were not observed in the studied shrimps. Thus, preservation of these decapods with nearly intact corpses indicates that soon after death they were recovered by microbial mats and were not subsequently disturbed by physical or biological agents.

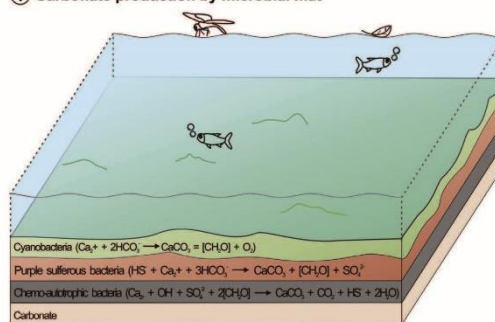
The specimen GP/1E 10863 came to rest lying on the left side (Fig. 5B, 5C), but the specimen GP/2E 9490 were oriented with the dorsal surface parallel to bedding (= sediment/water interface) (Fig. 5A, 5B). This unstable orientation is rarely observed in the shrimp fossil record (see Schweitzer et al. 2014 for some examples). Although the presence of well-developed scaphocerites extending laterally may contribute to shrimp stabilization in this unstable posture (Schweitzer et al. 2014), the absence of strong bottom currents and scavengers into the Crato lake bottoms, as well as the presence of microbial mats may have contributed to the stabilization of shrimp corpse in such dorsal attitude. Yet, the pereopods extending laterally may have also assisted in the dorsal shrimp stabilization (Fig. 5). Finally, as soon as the individuals were recovered by the microbial mats the early fossil diagenesis began due to the peculiar physico-chemical conditions provided by this type of coverage and the depositional environment. These are detailed discussed below.

Main Taphonomic Processes Associated with Microbial Mats

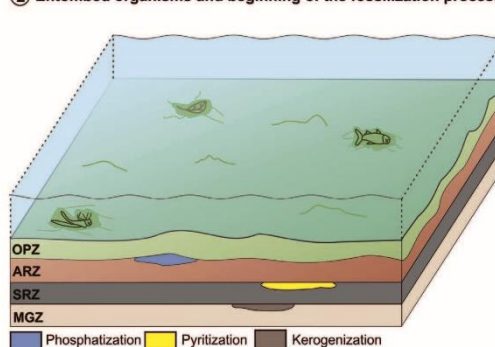
The role of microbial mats and biofilms in the preservation of exceptional fossil assemblages has been debated since the seminal work of Seilacher et al. (1985), who proposed that it represented one of the key factors leading to soft tissue preservation, along with stagnation and obrution. Regardless of their importance, microbial mats may have played a crucial role in the preservation of fossils in numerous Konservat-Lagerstätte, such as the Solnhofen and Messel (Allison 1988 and references therein), Hvar (Seilacher et al. 1985), Santana (Martill 1988), Cerin (Wilby et al. 1996), Monte Bolca (Marramà et al. 2016), Lebanon (Wilby and Briggs 1997) and Wattendorf (Fürsich et al. 2007).

Various lines of evidence suggest that microbial entombment (i.e., the encapsulation of organic remains by microbial mats after the death of the organism; Iniesto et al. 2013) may, in some cases, contribute to the preservation of soft tissues (Wilby et al. 1996; Wilby and Briggs 1997; Briggs 2003b; Tomescu et al. 2016). Complex communities of microorganisms can generate pseudomorphing biofilms with steep geochemical gradients that may favor soft-tissue preservation (Briggs 2003a; Raff et al. 2014; Briggs and McMahon 2016; Iniesto et al. 2016).

① Carbonate production by microbial mat



② Entombed organisms and beginning of the fossilization process



③ Burial and formation of new mat

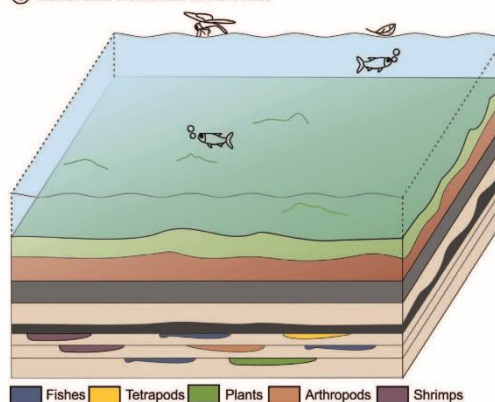


Fig. 11.—The microbial entombment model based on data from Dupraz et al. (2009), Schiffbauer et al. (2014), Muscente et al. (2015a), Iniesto et al. (2016), and Osés et al. (2017). Key: OPZ — oxygenic photosynthesis zone; ARZ — aerobic respiration zone; SRZ = sulfate reduction zone; MGZ = methanogenic zone.

Microbial metabolisms contribute to exceptional fossil preservation through phosphate and sulfide mineralization as well as the binding of sediments around impressions (Callow and Brasier 2009; Schiffbauer et al. 2014; Muscente et al. 2015a, 2017; Tomescu et al. 2016). The Crato Konservat-Lagerstätte contains fossils representing a variety of preservational modes (Butterfield 2003; Xiao and Schiffbauer 2009; Muscente et al. 2017): (1) pyritized insect cuticles, fish scales and soft tissues (Barling et al. 2015; Osés et al. 2016, 2017); (2) carbonaceous remains of plants (Mohr and Friis 2000) and fish (Osés et al. 2017); (3) phosphatized soft tissues of tetrapods, fishes, and insects (Fielding et al. 2005; Pinheiro et al. 2012; Barling et al. 2015); and (4) impressions of soft tissues and skin of anurans (Carvalho et al. 2019).

Phosphatization can lead to high-fidelity soft-tissue preservation (Martill 1988; Briggs and Wilby 1996; Wilby et al. 1996; Wilby and Briggs 1997; Briggs 2003b; Pinheiro et al. 2012; Wilson et al. 2016), potentially at the sub-cellular scale (Xiao et al. 1998; Schiffbauer et al. 2012; Muscente et al. 2015b). Microbial mats may help to facilitate this process due to the existence of strong gradients in pH that favor the precipitation of phosphate over carbonate when the carcass is fully entombed and not in direct contact with the photosynthetic layers (Sagemann et al. 1999; Iniesto et al. 2015; Muscente et al. 2015a). In addition, the sulfur-oxidizing bacteria within microbial mats make a major contribution to the storage and release of phosphorus, which is prevented to escape from the sediment by the aid of the sealing effect (Muscente et al. 2015a). In this context, the microorganisms present in the microbial mats contribute to remineralization of organic phosphorus, producing phosphate that may precipitate within soft tissues (Briggs 2003a; Muscente et al. 2015a). This process is responsible for the spectacular preservation of fish muscle-fibers in the Crato Konservat-Lagerstätte (Martill 1988; Osés et al. 2017).

The two caridean shrimp specimens analyzed here are lying between EPS and microsparry calcite laminae in both wrinkle and planar morphologies (Fig. 5A–5C), suggesting a close relationship between the fossilization process and the presence of microbial mats (Figs. 4A, 4B, 6). Extensions of calcite crystals emerging from the rock matrix (Figs. 7A, 8A) are very similar to mineralized microbial filaments (Iniesto et al. 2016, fig. 11 for an analogous example). This suggests that the existent microbial mats may have helped to fix the dead organism to the substrate by coating it (Fig. 7B), providing a type of sarcophagus that preserved the carcass against physical disaggregation and biological degradation (Iniesto et al. 2013). A very similar fossilization mechanism was also suggested for the preservation of anurans in the lower part of the Konservat-Lagerstätte succession (Carvalho et al. 2019). The phosphorus for the mineralization of the exoskeleton probably was derived from its original composition, but mats may have contributed as an additional phosphorous source (Briggs 2003b; Muscente et al. 2015a), delaying decomposition, and inducing replication by Ca compounds (Iniesto et al. 2013), with fossilization starting at the early moments of microbial entombment when the carcass was completely covered by the photosynthetic microbial layer (Fig. 11).

Pyritization is another common soft-tissue mineralization process that results from the precipitation of iron with sulfide by anaerobic sulfate-reducing microorganisms (Briggs et al. 1991, 1996; Schiffbauer et al. 2014; Guan et al. 2016; Tomescu et al. 2016). This process is usually accountable for the delicate fossilization of insects and fishes from the Crato Konservat-Lagerstätte (Barling et al. 2015; Osés et al. 2016, 2017). In these cases, framboidal pyrite is associated with EPS (Catto et al. 2016; Osés et al. 2016), suggesting that fossils rested for a prolonged time interval within the anoxic layers of microbial mats (Schiffbauer et al. 2014). The internal tissues and other soft parts of the analyzed shrimps are mainly preserved by hematite/goethite, common products of the oxidation of pyrite, which in this case was likely produced as a consequence of microbial sulfate reduction (Barling et al. 2015; Osés et al. 2016, 2017). As described from the Lower Cretaceous Jehol Biota, northeastern China (Pan et al. 2013, 2014), if the precipitation of pyrite occurs during the decay of

soft-tissues, the newly formed crystal would fill the empty space created by degradation allowing the preservation of the 3D morphology. Framboidal pyrite is a common bacterially induced mineral (Folk 2005; Maclean et al. 2008), and the preserved iron-rich (weathered early diagenetic pyrite) EPS coating supports the fossilization of the soft tissues of the shrimp in the sulphate-reducing zone of the microbial mat prior to its degradation (Fig. 11). Hence, the coating of internal soft-tissues by EPS secreted by microbes from the mats and biofilms was most probably responsible for the high-fidelity 3D preservation of the studied shrimp specimens, in a similar way described for insects and fishes of the Crato Konservat-Lagerstätte (Barling et al. 2015; Osés et al. 2016, 2017).

The Microbial Entombment Taphonomic Model

The recognition of microbial activity facilitating preservation of soft tissues in the Crato Konservat-Lagerstätte is not entirely new (e.g., Barling et al. 2015; Osés et al. 2017; Carvalho et al. 2019). However, the previous proposed taphonomic models of preservation assume that this sedimentary unit originated: (1) under anoxic conditions and probably rapid deposition in the presence of sulphide-rich waters (Martill et al. 2007a); (2) by microbially induced mineralization without covering by benthic microbial communities (Barling et al. 2015); or (3) by bacterial EPS secretion in the dead carcasses, which facilitated the balance of ion diffusion rates and nucleation rates (Osés et al. 2016, 2017). These models assumed that the laminated limestones were the product of authigenic precipitation by biochemical processes (as previously proposed by Heimhofer et al. 2010) with variable sedimentation rates mostly controlled by small scale transgressive-regressive climatic cycles (i.e., varves; Neumann et al. 2003) in a deep lacustrine system (Martill et al. 2007a). Despite of the high quality of the data generated by previous ultrastructural taphonomy-based studies (e.g., Barling et al. 2015; Osés et al. 2016, 2017), the proposed models are far off the track, because they do not take into consideration the widespread occurrence of microbial mats in the host rocks of the Crato Konservat-Lagerstätte.

Considering the ubiquitous presence of microbial mats that thrived due to the existent hypersaline conditions and absence of grazing benthos (Warren et al. 2017), the preservation of soft-tissues was favored by the rapid entombment of allochthonous to parautochthonous organisms. As soon as the dead organisms reached the boundary between the oxygenic photosynthesis and the aerobic respiration zones of the living matting ground of the Crato lake bottoms, the fossilization process started (see also Iniesto et al. 2015). In this situation, different types of taphonomic processes took place due to the presence of geochemically stratified microbial layers within the living mats (Fig. 11). This means that the dead organisms were accommodated successively within different zones, passing throughout distinct post-burial histories according to its residence time in each zone (see also Schiffbauer et al. 2014 and Muscente et al. 2015a).

Phosphatization was probably the first taphonomic process to take place under redox conditions (below the oxygenic photosynthetic zone of the mats) where PO_4^{3-} was concentrated due to the presence of sulfur-oxidizing bacteria and the sealing effect of the EPS (Muscente et al. 2015a). As mats continued to grow, the dead organisms were kept encapsulated in different taphonomic zones where distinct reactions occurred during the fossilization process (Fig. 11). In this context, pyritization probably took place by prolonged residence time of internal soft-tissues in the sulphate reduction zone, while the preservation of carbonaceous remains may have occurred in the methanogenesis zone (Schiffbauer et al. 2014).

CONCLUSIONS

The recent identification of benthic microbial communities in the Crato Konservat-Lagerstätte as true microbial mats allowed a different

taphonomic approach to the formation of this spectacular fossil site. The association of exceptionally preserved shrimps and microbial textures points to the role of microbial mats in the fossil preservation in the Crato Konservat-Lagerstätte. The evidences of EPS attaching and coating specimens of decapod crustaceans reveal that the dead bodies were completely covered by the mats, promoting protection against disarticulation and scavenging, but most importantly providing the key geochemical gradients that favored exceptional fossilization. The residence time of shrimps in the distinct microbial zones, with subsequent different microbial metabolisms, was essential to the occurrence of different types of taphonomic processes (i.e., phosphatization and pyritization). This fact also accounts for the preservation of the distinct fossil assemblages entombed in the Crato Konservat-Lagerstätte, where carbonaceous remains are also well-preserved in association to pyritized and phosphatized organisms. Consequently, stressful environments with preserved microbial mats are potential settings for the exceptionally preservation of allochthonous to parautochthonous fossil assemblages.

ACKNOWLEDGMENTS

We thank D. Muscente and M. Iniesto for their careful review of the manuscript and very useful comments and corrections, which substantially improved the final version of this paper. We also thank the PALAIOS associate editor, and M. Zischin (Coeditor) for their insightful comments that improved the quality of this contribution. We are deeply indebted to J. de Moraes Leme Basso, curator of the Crato fossil collections of the Institute of Geosciences, University of São Paulo, and I. Cardoso Gonzales, technician of the same institution, for providing access to some exceptionally preserved shrimp specimens. F.G. Varejão and S.A. Matos are fellows of FAPESP, grants 2016/13214-7, and 2017/20803-1, respectively. Partial financial support was also offered by CNPq (401039/2014-5), and Petrobras (2014/00519-9). This work was made with institutional support of the São Paulo State University. M.L. Assine, M.G. Simões and L.V. Warren are fellows of CNPq.

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Received 1 May 2019; accepted 13 June 2019.

V. REINTERPRETANDO AS ESTRUTURAS LOOP BEDDING

“*Loop bedding*” são usualmente descritas como estruturas sin-sedimentares bastante comuns no registro geológico, caracterizadas por lâminas rompidas com aspecto de um *boudin* (Calvo et al., 1998). Essas estruturas são comumente encontradas em sedimentos inconsolidados, finamente laminados, e rítmicos, depositados em sistemas lacustres e marinhos modernos e antigos (Calvo et al., 1998; Rodríguez-Pascua et al., 2000). A associação de “*loop beddings*” com outras estruturas sin-sedimentares, como microfalhas e *slumps*, é usado como evidência para sustentar a interpretação de que tais estruturas são geradas por atividade sísmica sin-deposicional em ambientes extensionais (Rodríguez-Pascua et al., 2000). Neste trabalho é apresentada interpretação alternativa para a origem de estruturas “*loop bedding*”. Na Formação Crato, essas estruturas ocorrem diretamente associadas a gretas de sinérese em calcários com laminação rítmica depositados em sabkhas costeiros. As gretas de sinérese são formadas pela nucleação de cristais de gipsita e ocorrem juntas à outras estruturas evaporíticas, tais como *hoppers* de halita, dobras enterolíticas e fácies nodulares em folhelhos escuros. Durante a cristalização sin-sedimentar da gipsita, a laminação do sedimento inconsolidado foi localmente encurtada e rompida originando os “*loop beddings*”. Desta forma, essa estrutura classicamente interpretada como oriunda de abalos sísmicos é aqui ineditamente atribuída a processos inerentes à dinâmica de ambientes evaporíticos em que ocorre a precipitação de carbonatos, sais e sulfatos. Assim, ainda que pesem as interpretações clássicas para a gênese desta estrutura, o uso da estrutura “*loop bedding*” como evidencia inequívoca de sismicidade sin-deposicional deve ser considerada com parcimônia. Os dados desta pesquisa constituem o manuscrito intitulado “*Loop bedding structures: evidences of seismic activities, salt nucleation or both?*”.

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LOOP BEDDING STRUCTURES: EVIDENCES OF SEISMIC ACTIVITIES, SALT NUCLEATION OR BOTH?

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Abstract: Loop beddings are soft-sediment deformation structures characterized by mm-scale bundles of laminae with boudin aspect interpreted as the result of microseismic activity. Herein, we present an alternative interpretation to the origin of these structures. We describe loop bedding structures in rhythmically laminated limestones in close association with syneresis cracks deposited in coastal sabkha deposits preserved in the Cretaceous Crato Formation (Araripe Basin, Brazil). Syneresis cracks were formed by nucleation of gypsum and they are associated with other evaporitic structures as halite hoppers, enterolithic folds and nodular facies. During syndimentary gypsum growth, lamination was locally disrupted originating loop structures while the sediment was not lithified. The close association with evaporitic features and the absence of soft-sediment deformation structures related to any tectonic activity in the studied interval, indicates that the origin of these structures admits an alternative interpretation. Thus, their use as unequivocal evidence of syndepositional seismicity has to be considered with parsimony.

INTRODUCTION

Loop bedding is a well-known soft-sediment deformation structure (SSD; deformations in shallowly buried, water-saturated and unconsolidated sediments; see Owen and Moretti, 2011) characterized by mm-scale bundles of laminae with boudin aspect, like links in a chain (Calvo et al., 1998). These structures are commonly developed in not lithified rhythmically laminated sediments deposited in modern and ancient lakes (Calvo et al., 1998; Rodríguez-Pascua et al., 2000; Törő and Pratt, 2016). Similar structures were also described in lagoons (Hasselbo and Trewin, 1984), open marine deposits (Beck et al., 2007, Martín-Chivelet et al., 2011), peritidal platforms (Su and Sun, 2012), tide-dominated estuaries (Bhattacharya et al., 2016), fan deltas (Liu et al., 2016), and playa lakes (Berra and Felletti, 2011). In these cases, the structures mainly differ in size (millimeter- to meter-scale), and in designation (pinch-and-

swell, boudinage or pull-apart structures), but they are all defined as boudin-like structures developed in finely laminated sediments.

The contrasting composition and rheology of laminae is the main reason why non-consolidated sediments form loops (Hasselbo and Trewin, 1984; Calvo et al., 1998; Törő and Pratt, 2016). Deformation may be simple, formed by symmetrical to asymmetrical bundle necks; or complex, with boudin necks bounded by microfaults (Calvo et al., 1998). This intricate morphology variability is attributed to the different stages of lithification, with simple loops related to deformation on unconsolidated sediments and complex loops on poorly lithified sediments (Calvo et al., 1998). The association with nearby faults and other non-liquefaction structures, such as microfaults and slumps, are the main elements used to assign loop beddings to low magnitude seismic activity in extensional settings (Rodríguez-Pascua et al., 2000). Coincidentally, these structures were also formed in high energy environments like deltas, turbidites, and tidally-dominated systems (Rodriguez-Pascua et al., 2000; Bhattacharya et al., 2016; Liu et al., 2016). In these depositional settings the shear stress due to gravitational, wave or tide action are a relevant process and fluctuations of salinity can be expected. Additionally, loop beddings are always defined in cross section and description of these structures in plan view are never presented.

In the upper part of a laminite-turbidite succession of the Devonian Achanarras Fish Bed, Rayner (1963) recognized striking structures that were described as 0.05- to 0.5-m-long T-shaped and Y-shaped ridges and depressions without any preferred orientation. These features were observed disrupting and clearly bending the lamination upwards, forming pull-apart or loop bedding structures (Rayner, 1963; Trewin, 1986). An important observation was made by Trewin (1986), that recognized that the cracks were not filled by sediments prior to compaction, so the loops may have formed within the unconsolidated sediment. Rayner (1963) interpreted these structures as incipient desiccation cracks that formed in very shallow waters of a lacustrine system. However, Trewin (1986) reinterpreted the loops as formed beneath turbidites, producing associated microfaults, folds and flame structures that resulted in the shrinkage of the sediments originating syneresis cracks. Similar combination of structures is discussed by Cole and Picard (1975) that interpreted them as secondary sedimentary features produced during compaction and dewatering.

Subaqueous sedimentary cracks formation may be triggered by (see McMahon et al. 2016): (1) fluctuations in salinity; (2) loading, burial or wave-induced stress; (3) seismic shocks; (4) microbial processes; and (5) authigenic mineralization. Reported syneresis cracks in the

Gale crater, Mars are suggestive of gas production (Siebach et al., 2014), and constitutes an additional way of formation of this subaqueous sedimentary structure. Unlike desiccation cracks, these structures are not originated in the same way in every setting, and additional information may always be presented to suggest a plausible interpretation (McMahon et al. 2016).

To our knowledge, the association between syneresis cracks and loop bedding was never investigated before, which constitutes a gap in the sedimentary literature due to their abundance and importance in the geological record. Considering this, we present unprecedented data on the origin of combined syneresis cracks and loop bedding structures in laminated limestones of the Aptian Crato Formation, Araripe Basin, Brazil, and propose an alternative model for the formation of loop bedding structures other than seismic.

GEOLOGIC SETTING

The Cretaceous Araripe Basin is located between two major Neoproterozoic shear zones in the Borborema Province that were reactivated during the opening of the southern and equatorial branches of the Atlantic Rift System (Matos, 1992). The first marine connection between Central and South Atlantic waters occurred in the Aptian (Koutsoukos et al., 1991). The propagation of the stresses related to the opening of the equatorial margin implicated in a new subsiding event in the Araripe Basin, culminating in an important epicontinental marine ingression that reached the basin from the south during the post-rift phase (Assine et al., 2016; Custódio et al., 2017; Fürsich et al., 2019). During this event, mixed carbonate-evaporite-siliciclastic depositional successions were deposited (Assine et al., 2014; Fig. 1B), emphasizing the Crato Formation, an up to 90-m-thick succession of interbedded limestones, shales, mudstones and sandstones (Fig. 1C).

After an initial transgressive lacustrine phase, brackish-water bivalves with marine affinity (see Bruno and Hessel, 2006) preserved in grey/green mudstones attest to the first marine ingression in the basin and mark the maximum flooding surface in the basin. The regressive phase starts with a muddy to mixed intertidal flat characterized by up to 8-m-thick interval with interbedded shales with flaser bedding, sandstones with wavy and linsen bedding, sigmoidal cross-bedded sandstones with mud drapes (tidal bundle), and ripple cross-laminated sandstones draped by fluid mud (Fig. 1D). The entire succession is burrowed by *Skolithos*, *Lockeia*, *Ophiomorpha*, *Diplocraterion*, *Arenicolites* and *Planolites*, which are considered compatible with the *Skolithos* ichnofacies (see Buatois and Mangano, 2011). The upper part of

the succession representative of this regressive cycle is marked by shales and evaporitic limestones in a supratidal sabkha environment (Fig. 1D). This succession is characterized by the presence of enterolithic folds delineated by gypsum, anhydrite and calcite folded layers in shales (Fig. 2A), by nodules of carbonate in black shales (Fig. 2B), and by evaporitic planar laminites with abundant halite hoppers, lens-shaped gypsum, syneresis cracks and loop bedding structures (Fig. 2 C-H).

MATERIAL AND METHODS

The study area is located at the eastern part of the Araripe Basin, where Aptian post-rift strata from the Crato Formation are fully preserved (Figure 1A-C). There, a total of four columnar sections with up to 15 m were measured (i.e., Três Irmãos, Estiva, Batateira, and Caldas) with detailed facies description (Fig. 1D). Several samples of laminites were collected for further laboratory analysis, preferentially those with good bed surface exposure. During the fieldworks, special attention was given to the detailed measurement of the carbonate succession and description of the limestone beds, including characterization of their composition, associated sedimentary structures, bed thicknesses, contacts and geometry, as well as presence/absence of fossils and evaporitic fabrics. The macroscopic morphometric measurements of the loop beddings and syneresis cracks included longest axes, height, and thickness. We also measured the orientation of the syneresis cracks, and consequently the loop bedding structures, as they are coincident with the direction of the main crack axis. Nine petrographic thin-sections were examined under both normal and polarized light using a Zeiss Axio Imager A.2 binocular petrographic microscope and a Zeiss Stereo Discovery V.12 binocular magnifying glass, at the Center for Geosciences Applied to Petroleum Geology, São Paulo State University.

LOOP BEDDING STRUCTURES IN THE CRATO FORMATION

Detailed sections measured in four sites in the middle part of the Crato Formation, revealed the presence of typical evaporitic deposits characteristic of a sabkha environment (Fig. 1C-D; 2). This succession comprises up to 10-m-thick interbedded planar laminites, black shales with calcite and gypsum nodules and evaporitic paleosols with enterolithic folds. The 0.25- to 1.5-m-thick tabular beds of brownish/reddish colored planar laminites are characterized by rhythmic millimetric alternation of dark and light laminae presenting soft-sediment

deformation structures (e.g., loop bedding) in close association with syneresis cracks. Single loops vary in size from 2 to 10 mm and are laterally discontinuous for few decimeters, with vertical recurrence in the entire succession (Fig. 2). Loop bedding are commonly formed in sparite laminae that are disrupted and encapsulated by micrite lamina and in few cases by microbial biofilms and gypsum (Fig. 3A, D).

The presence of gypsum between laminae is noteworthy, and commonly occur segregating entire loops (Fig. 2D). Halite pseudomorphs crystals are also observed in the nuclei of the loops, clearly promoting thickness increasing of the sparite laminae (Fig. 3A). In these cases, loops are completely encapsulated by thin microbial biofilms (Fig. 3A). Ductile deformed valves of ostracodes are also common in the micrite laminae, showing that the sediment was unlithified during the deformation. In all analyzed samples, the loops are constrained to single laminae and are bounded upwards by undeformed sediments and downwards by bended laminae (Fig. 3). This slightly folded lamination is locally associated to phosphatic and iron nodules that deform the lamination (Fig. 2C and 3A), suggesting early diagenetic origin (Lash and Blood, 2004). This condition also occurs when calcite nodules are present (Fig. 3B). However, in the absence of nodules the bended lamination is clearly linked to shrinkage of lamination due to the presence of syneresis cracks (Fig. 2G-H), and nodules only grow because of the local increase of permeability.

Loops are mostly simple structures characterized by horizontally to obliquely disrupted laminae (Fig. 2E), that occasionally truncate the underlying laminae. Complex loops are absent, but microfaults may be laterally disrupting several laminae. The fact that these microfaults are not constrained to the loop interval, but affects laminae above and below it, suggests that they occurred after deposition and lithification. In all analyzed examples the loop beddings are associated to syneresis cracks (Fig. 2G-H, 4) that occur as abundant features in the surface of the planar laminites. When observed in profile, the cracks are responsible for disrupt the lamination exactly at the bended termination of the loops. Is important to note that the expression of the syneresis cracks in profile is only noted by the discontinuity of the lamination, without any other characteristic feature associated, as syphon-like or v-shape structures.

The cracks are filled by low Mg calcite after gypsum and occur in four different morphologies (Fig. 4): (1) simple; (2) lenticular; (3) y-shaped or “bird’s foot”; and (4) fusiform. Simple cracks are 1- to 3-cm-long and may be oriented parallel to each other (Fig. 4A) or randomly organized (Fig. 4D). These simple morphologies (type 1) are associated to halite hoppers and other evaporite pseudomorphs (see Fig. 4B, E). Up to 2-cm-long lenticular cracks

(type 2) forming small ridges and troughs are the most common cracks associated to the planar laminites. These structures occur in more numerous concentrations than simple cracks and are not oriented in any preferred direction (Fig. 4C). The y-shaped cracks (type 3) generally occur associated with lenticular cracks and are similar in size and morphology to the lenticular ones, albeit geometrically more complex (Fig. 4F). The main axis of these cracks is oriented in a predominant direction (in each sedimentary surface and not in the entire stratigraphic interval), but its secondary small branches may be oriented in any direction (Fig. 4F). Fusiform cracks (type 4) may vary in size between less than 1 cm to more than 5 cm and are very rare in the studied succession. They are complex morphologies without an orientation parameter, albeit they are apparently randomly organized. Despite of the existence of different syneresis crack types, it was not observed any relation between different morphologies and possible variations in geometry and size of the loop beddings. This means that in all cases loops are simple and originated by syneresis cracks disruption of lamination independent of any possible preferred orientation.

AN ALTERNATIVE MODEL FOR THE ORIGIN OF THE LOOP BEDDING STRUCTURES

We summarize in the Table 1 the representative works that mention the presence of loop bedding structures in the sedimentary record, which totalize 21 Pre-Cambrian to Quaternary occurrences. The loops are commonly related to successions developed in fault-bounded basins, although they also occur in crater lakes, as the Foulden Maar crater at New Zealand (Fox et al., 2016). Loops develop in well-laminated rhythmites, oil shales, laminated gypsum, and in limestones (including microbialites) deposited mostly in lacustrine environments, and subordinately in marine settings. In both cases, loop bedding structures are linked to high-energy environments (i.e., delta progradation, tide waves and turbidite currents) where slumps and microfaults are commonly associated structures. Loops mostly occur as simple features (11 occurrences, see Table 1), but simple/complex morphologies are also common (7 occurrences). These features vary in height from 2 to 500 mm, but loops smaller than 10 mm are considered the most frequent (see Table 1).

It is noteworthy that the vast majority of works that recognized loop bedding structures in the geologic record (about 75%, or 16 occurrences) were published after the seminal work of Calvo et al. (1998). In almost all of these cases, loops are interpreted as product of stretching of laminated sediments associated with extensional fault reactivation related to low magnitude

seismicity (Rodriguez-Pascua et al., 2000). In some cases, evidences for seismic activity producing loop beddings and associated structures are undoubtful (e.g., Törő and Pratt, 2016). Notwithstanding, it is interesting to note that the seismic hypothesis is almost always considered, even in situations where the depositional setting is predominantly evaporitic and no soft-sediment deformation, sin-sedimentary faults and/or seismites were observed (e.g., Ortí et al., 2003).

In addition, there is also some confusion with the usage of the term “loop bedding” in the case of meter-sized bed-parallel lenticular structures (e.g., Knaust, 2002; Zheng et al., 2015; Ko et al., 2017; Zeng et al., 2018). The production of such features differs drastically from those defined by Calvo et al. (1998), as they are associated to flame structures and ball-and-pillows, although produced in more distal settings from the epicenter of the seismic shock (see Zeng et al., 2018). In this way, the use of the loop bedding term should be only used for millimeter- to centimeter-thick soft-sediment deformational structures in unlithified to poorly lithified rhythmically laminated sediments, as previously defined by Calvo et al. (1998).

Despite the unquestionable association of loop bedding and seismites present in the literature, this is not true for the here reported investigated interval. Otherwise, the presence of evaporitic facies and syneresis cracks in the sabkha laminites from the Crato Formation strongly suggest a cause and effect relationship between the origin of these structures and the formation of loops. In addition, the absence of typical features produced by seismic activity, as folded, loaded, faulted and rotated crack-hosting beds and the typical pygmatic folding deforming more than one lamina bellow or above the surface of syneresis cracks (see Pratt 1998), reinforce the non-tectonic origin for the loops.

Other mechanisms that could generate loop bedding structures are related to subaerial exposure of microbial mats. It is true that some dried cyanobacterial mats originate a pinnacle-like structure with soft disruption of lamination that after compaction would be very similar to loop bedding (see fig. 7 of Cuadrado and Pan 2018). Microbial mats are also involved in the formation of sedimentary cracks - a common feature associated to loop beddings in the studied section – by intrastratal degradation of biofilms (Harazim et al., 2013). However, these post-depositional situations are unlikely in the case of the sabkha laminites from the Crato Formation. Most of loops are formed in interlaminated micrite and sparite and not in microbialite facies, as is the case of syneresis cracks.

The most striking feature associated to loop bedding structures un the Crato laminites are syneresis cracks. In general, syneresis cracks are defined as sharp-walled, nearly planar

cavities formed predominantly by brittle failure (McMahon et al. 2016). The formation of these sedimentary cracks requires that the sediment must be unlithified and have sufficient adhesion to crack rather than deform (McMahon et al. 2016). Thus, the occurrence of such features related to ductile deformed loop bedding structures (*sensu* Calvo et al. 1998) in the laminites of the Crato Formation is completely viable. Also, these laminites were partially produced under microbial influence in shallow and quiet waters, and it is expected that early soft lithification was very quick. This means that these structures are surely syn-depositional and indicates that they formed in sediments that were not completely lithified, even in the main occurrences of evaporitic precipitated laminites.

The penetration of the surficial cracks in the rock lamination is not well marked in the laminites, except by its disruption (Fig. 2 G-H). This may suggest that: (1) the fissure was not filled by sediments prior to the deposition of the upper laminae (Hasselbo and Trewin 1984); or that (2) the fissure was filled by a more ductile material (i.e., salt, gypsum) that during early diagenesis was solubilized or substituted. Lens-shaped gypsum filling syneresis cracks suggest that they grew during moments of large salinity fluctuations (see Aref et al 1997), in the substrate-water interface or even within the sediment, similarly to what occurred in the Achanarras Fish Bed, Old Red Sandstone, Scotland (see Trewin 1986). This situation is common in the rock record, as also is the case of the Devonian Orcadian Basin, where lenticular cracks were produced in response to gypsum crystal growth, acting as nuclei for cracking and controlling syneresis morphology (Astin and Rogers 1991).

In the Crato laminites, the morphology of the cracks - mostly lenticular and y-shaped in upper view - and its close association with halite hopper and gypsum, are indicative that they were surely formed by evaporite crystal growth. Lenticular gypsum is commonly interpreted to be a diagenetic product, but it also occurs subaqueously as in the case of the Monegros basins, Spain (Mees et al., 2012). Despite the occurrence of diagenetic features (i.e., enterolithitic and nodular facies), all evidences point to a synsedimentary origin for the lens-shaped gypsum. Also, the replacement of gypsum by low Mg calcite is characteristic of highly porous zones that are usually traced to the surface as a series of cross-cutting polygonal furrows (Warren, 1982; Mees et al., 2012). This situation is the same of that observed in the bed surfaces of the studied laminites.

Despite the apparently chaotic distribution of the different types of syneresis cracks throughout the succession, it is striking that simple cracks can be oriented in single bed surfaces, conditioning orientation of loop bedding necks (see Fig. 4). This behavior was already observed

in the Green River oil shales, where linear cracks are oriented parallel to the strikes of ripple cross-laminated sandstones (Picard 1966). An alternative view for this situation is that related to seismic action, where the orientation of cracks is interpreted to reflect the propagation of seismic waves (Pratt 1998). Notwithstanding, none of these situations are expected for the sabkha laminites from the Crato Formation, as ripple marks are absent and seismic activity is unlikely. In this case, the orientation of cracks in single bed surfaces may be the response to internal anisotropies (e.g., wrinkled microbial surfaces).

Finally, we interpret the loop bedding structures to be originated by syndimentary gypsum growth. As gypsum starts to nucleate at the water-sediment interface or even within the unlithified sediment, there is an increase in the sediment volume producing an extensional strain that disrupt lamination (Fig. 5). Thus, the loop bedding structures, similarly to syneresis cracks (see McMahon et al., 2016) may have several triggers of formation and may not be easily assigned to seisms or other processes without a proper and detailed investigation of the sedimentary succession where they occur.

CONCLUSION

Loop bedding structures originated in unlithified finely laminated siliciclastic and carbonate sediments are common in both lacustrine and marine settings and are associated to microseismic activity. Nevertheless, the occurrence of these structures in close association with syneresis cracks produced by different stage of gypsum growth in sabkha laminites under quiet tectonic activity suggests an alternative model for the formation of the loops. In evaporitic environments, the salt crystallization cause increase in volume and produce local compression and distention in the plane of the sedimentary bed. The distensive effect cause the formation of micro faults and punctual boudinage of the lamina, forming the loop bedding structures. Thus, considering this alternative hypothesis, all interpretations of seismicity contemporary to the sedimentation based on the occurrence of loop bedding should be carefully reviewed. In this way, seismically- or salinity-produced, loop bedding in rhythmically laminated unconsolidated sediments need to be closely examined to verify (or refute) one interpretation or another. In other words, in disagreement with the previously thought, the loop bedding is not necessarily a sedimentary structure exclusively indicative of syndimentary seismicity.

ACKNOWLEDGEMENTS

The authors would like to thank the São Paulo State Research Foundation - FAPESP (2016/13214-7) for F.G.V Ph.D. scholarship. Partial financial support was also offered by PETROBRAS (Sigitec 2014/00519-9). This work was made with institutional support of the São Paulo State University. We are also indebted with the Center for Geosciences Applied to Petroleum Geology, UNESPetro, IGCE/Unesp/Rio Claro, for providing laboratory facilities. L.V.W is fellow of the CNPq.

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FIGURES AND TABLE

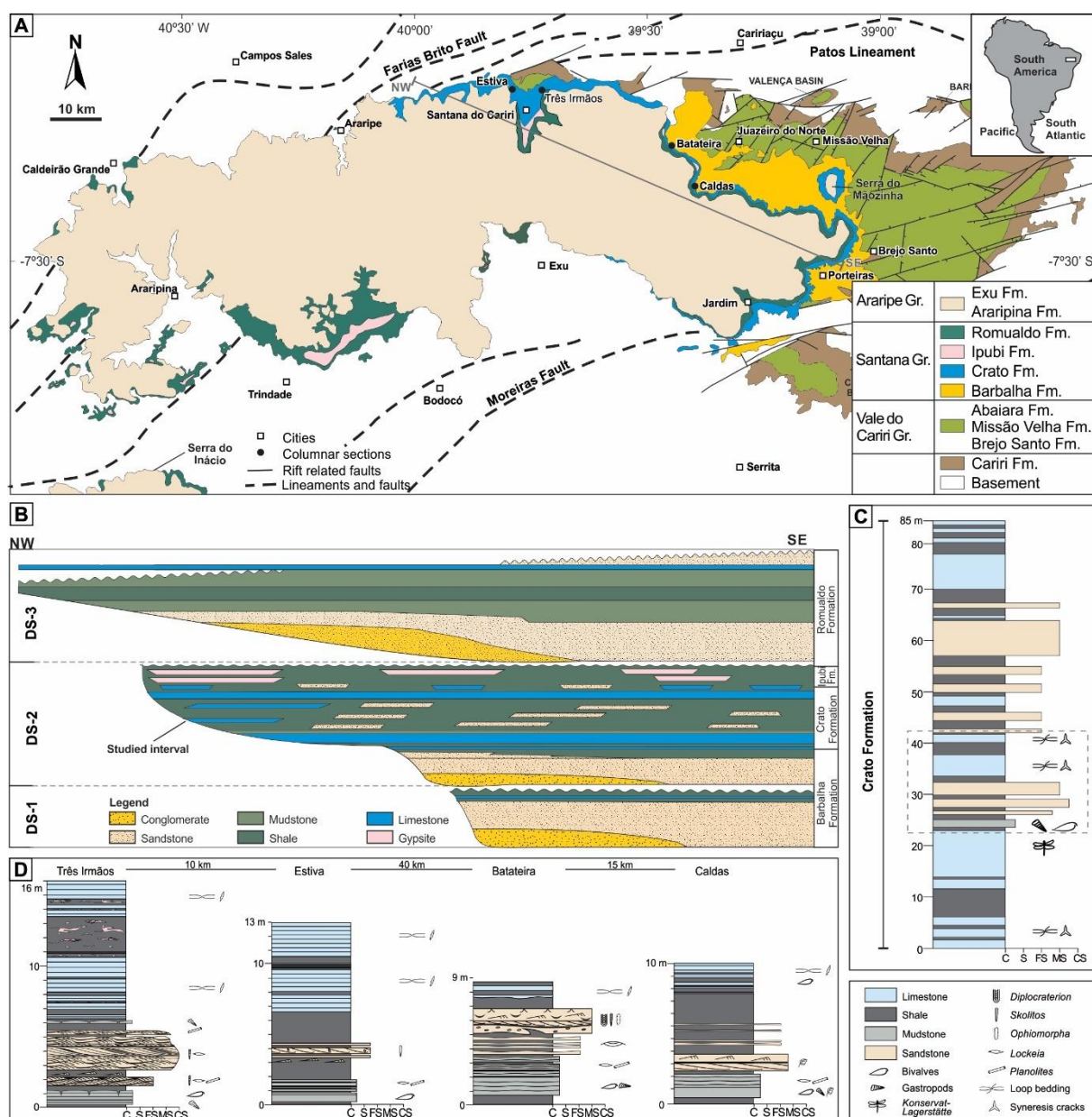


Fig. 1 – (A) Geologic map of the Araripe Basin with location of the measured columnar sections (modified from Assine et al., 2014). (B) Aptian depositional sequences of the Araripe Basin (modified from Assine et al., 2014 and Custódio et al., 2017). (C) Schematic columnar section of the Crato Formation with the positioning of the studied interval. (D) Detailed columnar section of the interval with loop bedding structures and syneresis cracks.

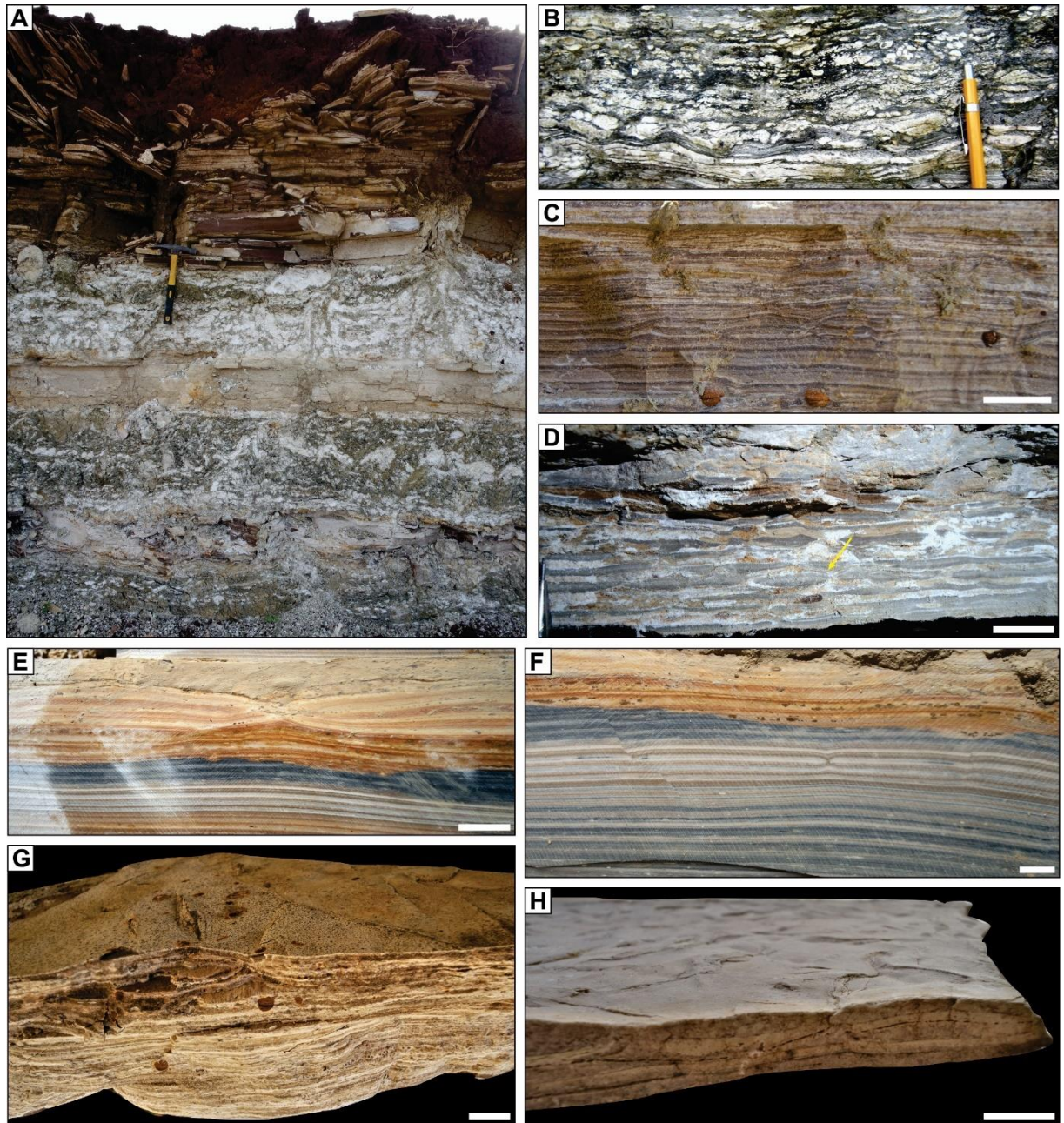


Fig. 2 – Supratidal sabkha facies of the Crato Formation. (A) Succession of interbedded evaporitic paleosols with enterolithic folding and limestones. Hammer is 30-cm-long. (B) Nodular facies in black shale. Pencil is 12-cm-long. (C) Several laminae with simple loops associated with diagenetic nodules. (D) Looped laminae separated by millimeter-thick gypsum laminae. (E) Simple loop. (F) Associated loop bedding and microfault. (G-H) Syneresis cracks forming loop bedding. Scale bars in C-H are 1 cm.

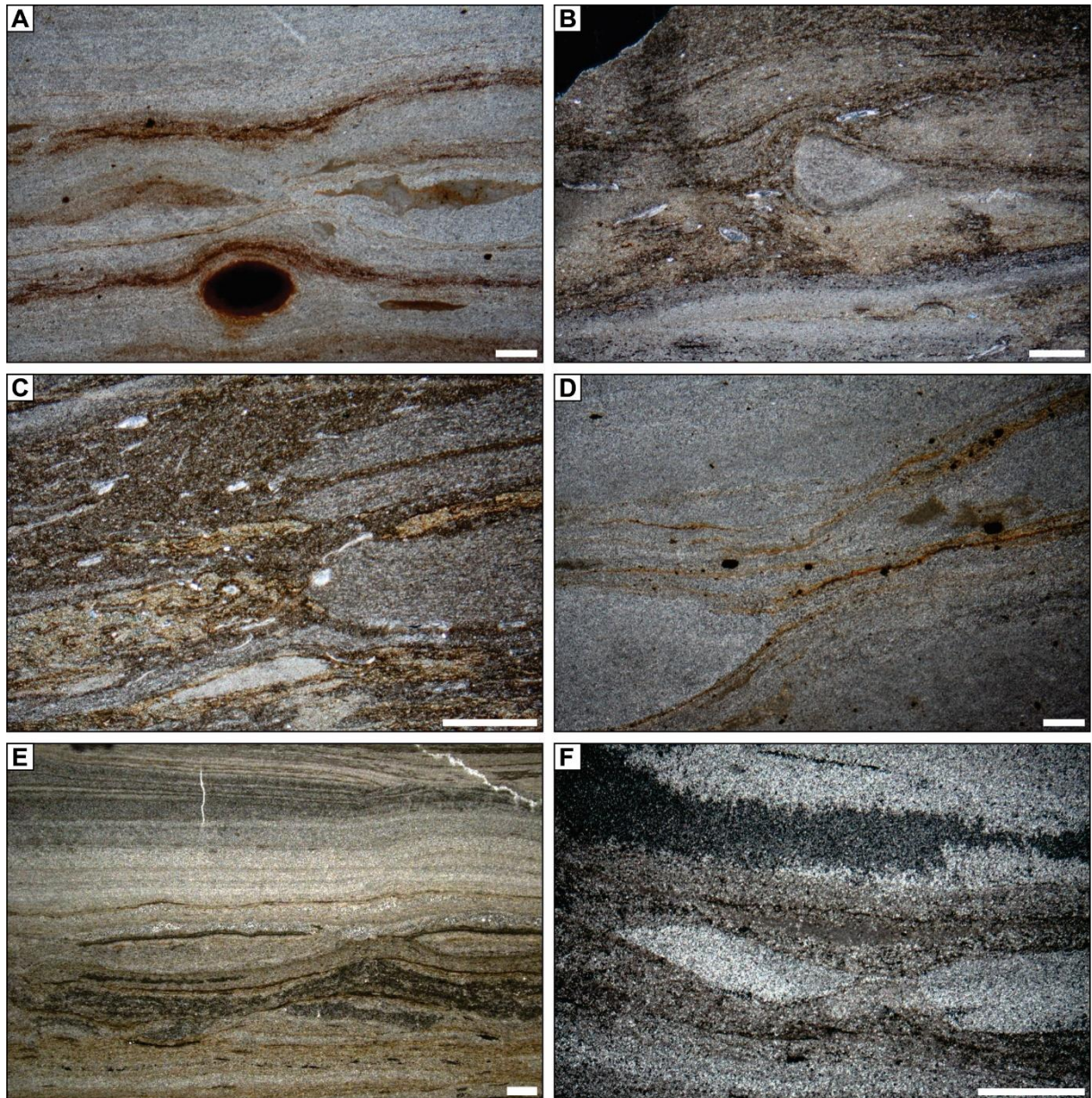


Fig. 3 – Petrographic thin sections. (A) Loop bedding formed in association with microbial biofilms, gypsum and phosphatic nodule. (B) Carbonate nodule deforming loop bedding. (C) Compressed ostracodes in association with loops. (D) Loop bedding formed in microbialite facies. (E-F) Loops formed in rhythmic laminated limestone. Scale bars in A-F are 1 mm.

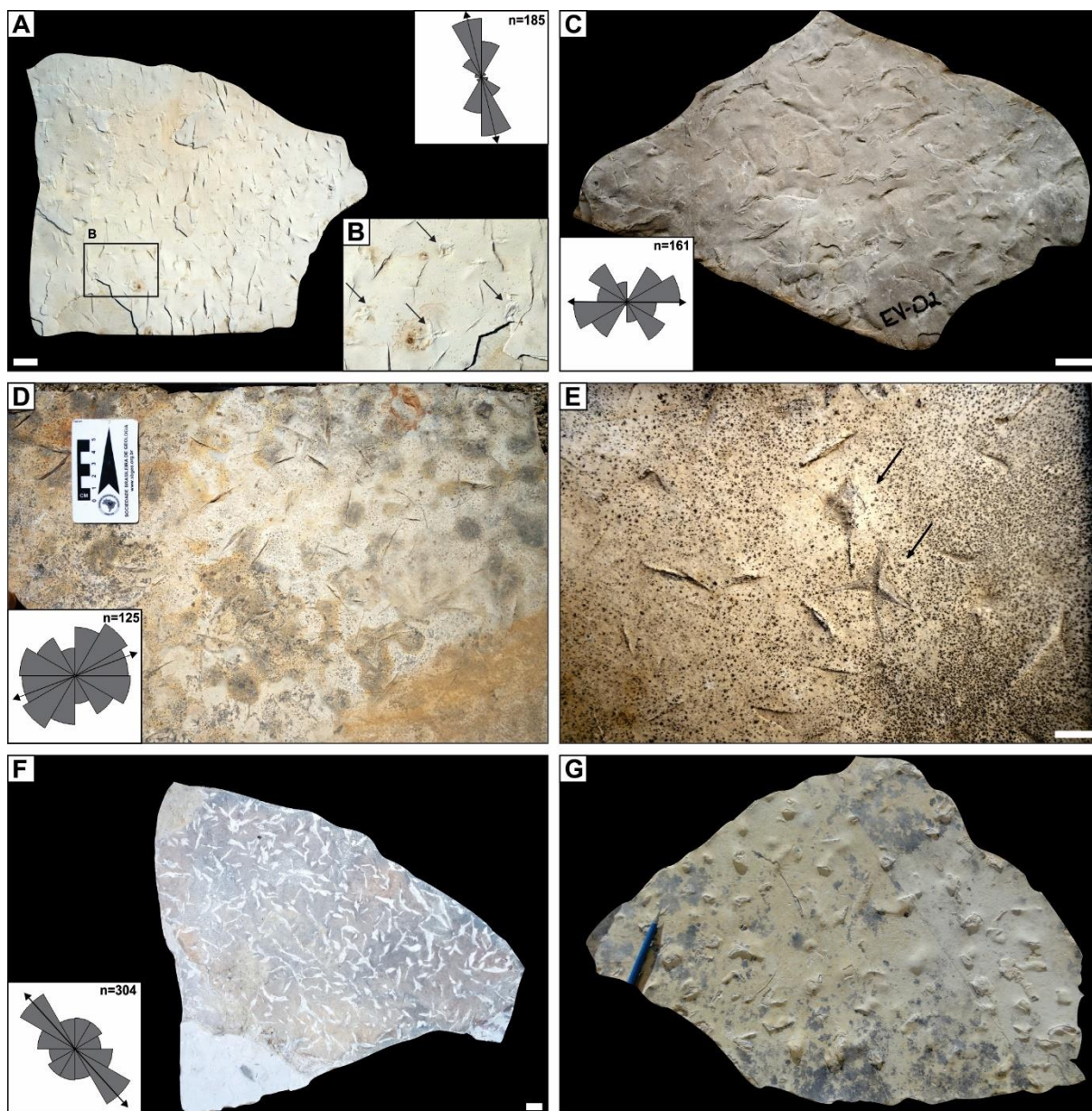
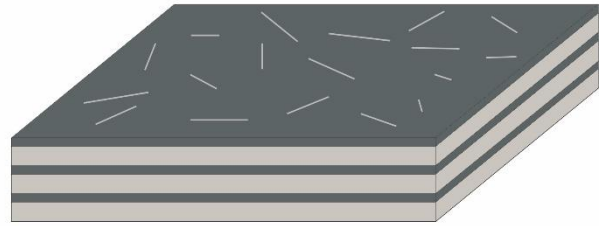


Fig. 4 – Syneresis cracks. (A) Polygonal cracks. (B) Lenticular cracks. (C) Y-shaped cracks. (D) Oriented linear cracks. (E) Detail of D showing associated halite hopper pseudomorphs. (F) Chaotic distribution of linear to lenticular cracks. (G) Linear to lenticular cracks associated to salt pseudomorph.

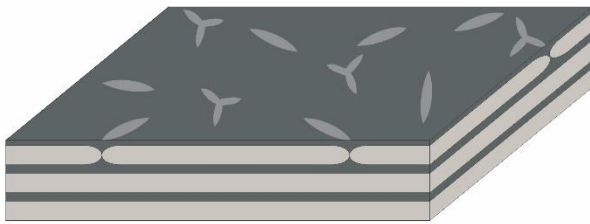
(1) Laminite deposition



(2) Evaporite nucleation



(3) Gypsum crystals originate syneresis cracks and disrupt lamination



(4) New phase of gypsum growth after burial and new sedimentation event

**Fig. 5** – Evaporitic model for the origin of loop bedding structures.**Table 1** – Occurrences of loop bedding structures.

Age	Site	Rock	Depositional Environment	Basin type	Loop type	Width (mm)	Extension	Associated structures	Trigger mechanism	Reference
Quaternary	Sea of Marmara	Marlstone	Marine	Pull-apart	Simple	15	-	Dewatering veins	Earthquake disturbance	Beck et al. (2007)
Neogene	Libros Gypsum	Rhythmic gypsum	Lacustrine	Rift	Simple	30	Few centimeters	Slumps	Instability of sediment on a lake slope	Ortí et al. (2003)
Neogene	Hijar and Elche de la Sierra	Laminite	Lacustrine	Transfer zone	Simple and complex	7 to 15	Decimeter scale	Slumps, microfaults, neptunian dykes	Extensional stretching of laminated sediments due to minor seismic shocks	Rodríguez-Pascua et al. (2000)
Neogene	Hijar Basin	Rhythmite (diatom/)	Turbidite lake	Transfer zone	Simple and	8 to 15	Decimeter scale	Slumps	Extensional stress	Calvo et al. (1998)

		calcite/c lay)			comple x				associat ed to low magnitu de seisms Extensi onal stress due to subsidi nce in the absence of basin margin faults	
Neogen e- Paleoge ne	Foulden Maar	Diatomi te	Turbidit e lake	Crater	Comple x	8	-	Slumps		Fox et al. (2016)
								Ball- and- pillow, flame, convolu te, faults, folds, sand dykes, breccia	Load structur e produce d by seismic shock	Liu et al. (2016)
Paleoge ne	Liaodon g Bay	Sand- mud	Fan- delta	Rift	Simple	10	Centime ter scale			
Paleoge ne	Green River	Oil shale	Lacustri ne	Arch between basins	Comple x	< 10	Few millimet ers	Microfa ults	Dewater ing by compact ion Interstra tal ductile deforma tion due to tensile stresses	Cole (1985)
Paleoge ne	Green River	Oil shale	Lacustri ne	Fault- bounde d	Simple and comple x	2 to 5	< 10 mm	Microfa ults		Toro and Pratt (2016)
Paleoge ne	Shaheji e	Carbona te mudsto ne	Turbidit e lake	Half- graben	Simple	3 to 10	100 mm	Sedime ntary dykes, diapirs, convolu te laminati on, load- flame, faults	Earthqu ake- induced slump	Liu et al. (2007); Zheng et al. (2015)
Cretace ous	Las Hoyas	Limesto ne	Turbidit e lake	Rift	Simple	1 to 2	-	Slumps	Gas bubble leakage	Fregena l- Martine z and Melend ez (1994)

Cretaceous	Beolgeumri	Sandstone	Lacustrine	Strike-slip fault system	Simple	10 to 50	Decimeter scale	Folds, load, water-scape, rip-down, faults	Volcanic - tectonic	Ko et al. (2017)
Cretaceous	Crato Fm.	Rhythmite (clay/calclite)	Lacustrine	Intracontinental rift basin	Simple	1 to 5	Centimeter scale	Slumps, microfaults	Synsedimentary deformation	Neuman et al. (2003)
Cretaceous	Amargosa	Limestone	Lacustrine	Aulacogen	Simple and complex	1 to 5	Centimeter scale	Slumps	Tectonic destabilization Seismic activity under	Varejão et al. (2016)
Jurassic	Amarillas Bed	Microbialites	Marine	Back-arc	Simple and complex	150	Decimeter scale	Faults, breccias, folds, slumps	extensional stress field	Martín-Chivelet et al. (2011)
Triassic	Muschelkalk	Limestone	Marine	Intracratonic basin	Simple	100 to 500	Meter scale	Load casts, pseudonodules, ball-and-pillows, convolute bedding, slumps	Synsedimentary earthquakes associated to tsunamites and seismites	Knaust (2002)
Permian	Pizzo del Diavolo	Fine sand and Silt	Playa lake	Fault-bounded	Complex	5 to 25	Few centimeters	Ball-and-pillow, convolute lamination, slumps, dykes, breccias	Low angle normal micro faulting associated to low magnitude seisms	Berra and Felletti (2011)
Permian	Barakar	Sand-mud heteroliths	Tide-influenced estuary	Half-graben	Simple	12 to 25	Few meters	Convolute lamination, folds, faults, pseudonodules, water-scape structures	Reactivation of basin marginal faults	Bhattacharya et al. (2016)
Carboniferous	St Louis Mb.	Dolomites	Marine	Forebulge	Simple	100 to 500	Meter scale	Flame structures,	Expulsion of fluidize	Zeng et al. (2018)

								dykes, folds, faults, ball-and-pillow Interstratal folds, thrust faults, injection structures	d mddy sediments due to seismic activity	
Carboniferous	Cheese Bay	Shale/Dolomite	Lake / Lagoon	Under influence of volcanism	Simple and complex	5 to 10	Few centimeters		Volcanic - tectonic	Hassellbro and Trevin (1984)
Devonian	Achanar ras	Laminite	Turbidite lacustrine	Post orogenic closed continental basin	Simple and complex	1 to 3	Centimeter scale	Load and flame structures, folds, microfaults	Syneresis cracks formed under effect of shear stress	Rayner (1963) and Trevin (1986)
Mesoproterozoic	Wumishan	Limestone	Shallow peritidal	Aulacogen	Simple	20 to 100	Centimeter scale	Brecia	Extensional stress due to fault reactivation	Su and Sun (2012)

VI. CONCLUSÕES

Na presente tese foi abordada de forma integrada a sedimentação mista carbonática-siliciclástica aptiana da Formação Crato, tendo como meta: (1) caracterizar a arquitetura deposicional e a evolução paleogeográfica da unidade; (2) identificar e interpretar os controles na sedimentação mista; (3) estabelecer critérios de correlação nas diferentes áreas de ocorrência da unidade; (4) estudar a gênese dos calcários laminados do intervalo Konservat-Lagerstätte; e (5) identificar os controles de preservação fossilífera excepcional.

A Formação Crato das bacias do Araripe, Jatobá e Tucano Norte, destaca-se pela deposição de microbialitos e evaporitos análogos aos que ocorrem no Pré-Sal. O intervalo dos calcários laminados portadores de fósseis excepcionalmente bem preservados (*Konservat-Lagerstätte*) apresenta evidências contundentes que atestam para mineralização microbialmente induzida e/ou influenciada. As diversas morfologias de microbialitos descritas, tais como domos, mounds, *MISS*, estromatólitos e oncóides, são elementos característicos de sistema lacustre restritos (com *input* reduzido de terrígenos), de águas calmas e rasas, com alta salinidade, e possivelmente deficientes em oxigênio. A descoberta de cianobactérias cocóides, filamentosas e espiraladas, e de mucilagem secretada por metabolismo de bactérias (*EPS*), corroboram a interpretação de que os calcários laminados portadores de fósseis com tecidos moles preservados, tenham grande influência de atividade microbiana. O paleoambiente restrito e extremo foi essencial, portanto, para a proliferação de esteiras microbianas e para a preservação excepcional dos restos orgânicos, incluindo no nível celular.

A descoberta de microbialitos no intervalo do *Konservat-Lagerstätte* inaugura, dessa forma, importante linha de pesquisa no que tange ao papel direto, ou indireto, de comunidades microbianas na preservação fossilífera. O estudo detalhado do modo de preservação da assembleia fossilífera da Formação Crato revelou a importante ação das esteiras microbianas na proteção contra degradação física e biológica dos restos orgânicos por constituir o ambiente de permineralização adequado, promovendo a preservação de tecidos moles de maneira excepcional. Nesse contexto, o sepultamento microbial é descrito pela primeira vez para a Formação Crato. Ressalta-se que esse processo difere bastante do modelo de *death mask* proposto para organismos Ediacaranos e constitui um novo mecanismo de preservação de assembleias fossilíferas excepcionais.

Os resultados obtidos nesta tese suportam interpretação de deposição lacustre para o intervalo de preservação fossilífera, porém a história deposicional da sucessão como um todo é bastante complexa. Durante a deposição da Formação Crato, o nível do mar estava em ascensão

e a atividade tectônica da fase rifte ainda estava em etapa de arrefecimento. Estratos tipicamente marinhos foram reconhecidos logo acima do intervalo do *Konservat-Lagerstätte* e constituem uma camada de lamitos ricos em gastrópodes e bivalves marinhos / salobros (Bruno & Hessel, 2006; Silva et al., 2017). Este nível estratigráfico bem delimitado é registrado em intervalo definido que se estende por dezenas de quilômetros, marcando também o nível de máxima inundação marinha na Formação Crato. Essa é a evidência mais antiga de ingresso marinha no Cretáceo das bacias interiores do Nordeste do Brasil e representa importante implicação no que se refere aos aspectos paleogeográficos, paleoclimáticos e paleoecológicos.

Durante a fase regressiva da Formação Crato, sistemas de sabkha costeiros são descritos acima dos depósitos dominados por maré (incluindo os lamitos com moluscos). Nestes sabkhas, predominou a deposição de calcários laminados intercalados a folhelhos com feições eodiagenéticas típicas de ambientes de alta evaporação (nódulos carbonáticos, contração de camadas por cristalização salina e precipitação tardia de sais). Estruturas *loop bedding* ocorrem em abundância nos laminitos em associação direta com gretas de sinérese produzidas por diferentes estágios de cristalização de gipsita. Em ambientes com alta salinidade, a cristalização de sais e sulfatos no sedimento inconsolidado causa aumento no volume do sedimento, produzindo compressão e distensão nos planos do acamamento sedimentar, originando o *loop bedding*. Estas estruturas são usualmente observadas em sedimentos finamente laminados e não litificados lacustres a marinhos e são relacionadas a deformação sinsedimentar produzidas por atividade sísmica. No entanto, a relação morfológica entre *loop bedding* e feições tipicamente evaporíticas geradas, portanto, sem nenhuma ação direta de sismicidade concomitante à sedimentação, sugere origem não tectônica para estas estruturas.

No topo da Formação Crato, a formação de calcários laminados com sinal isotópico tipicamente lacustre evidencia retorno de sedimentação tipicamente continental que transiciona para os depósitos francamente evaporíticos da Formação Ipubi. Como anteriormente citado, a grande variação de espessura, e o padrão arquitetural diverso no qual se organizam as diferentes associações verticais de facies descritas (e respectivos sistemas deposicionais) na unidade dificulta seu pleno entendimento quando esta é analisada em exposições localizadas. Deste modo, técnicas de correlação estratigráfica são fundamentais, tal como a construção de curvas isotópicas de C e O aliadas a curvas de variação de palinomorfos (autóctones x alóctones). Este procedimento foi essencial na correlação dos diferentes intervalos carbonáticos da unidade em suas diversas áreas de ocorrência e na comparação dos valores obtidos com aqueles conhecidos para o oceano aptiano. Os dados isotópicos apontam para deposição carbonática não-marinha

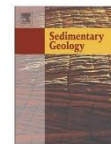
associada a alta quantidade de matéria orgânica amorfa, separada por intervalos siliciclásticos marinhos costeiros rasos onde prevalece a ocorrência de fitoclastos. Dessa forma, as curvas isotópicas e de palinomorfos permitiram delimitar precisamente e identificar a extensão dos eventos transgressivos-regressivos, possibilitando uma análise integrada entre a estratigrafia e a paleogeografia. Finalmente, Formação Crato constitui importante registro da extensão da sucessão evaporítica transicional das bacias marginais no interior do nordeste do Brasil e constitui um excelente análogo aos depósitos do Pré-Sal.

APÊNDICE



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Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Microbialite fields developed in a protected rocky coastline: The shallow carbonate ramp of the Aptian Romualdo Formation (Araripe Basin, NE Brazil)

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ARTICLE INFO

Article history:

Received 9 May 2019

Received in revised form 6 June 2019

Accepted 7 June 2019

Available online 14 June 2019

Editor: B. Jones

Keywords:

Stromatolites

Microbialites

Echinoids

Bivalves

Shark Bay analogue

Lower Cretaceous

ABSTRACT

The Aptian Romualdo Formation is a siliciclastic-dominated sedimentary unit recording the last marine incursion within the Cretaceous interior basins of northeastern Brazil. At the western margin of the Araripe Basin, rocks of the Romualdo Formation are mainly represented by carbonates resting abruptly over the Proterozoic crystalline basement. Detailed mapping and stratigraphic analysis revealed two stromatolite fields that were described and discussed for the first time. Several bioherms, biostromes and isolated stromatolites characterized by distinct microbialite morphologies associated with echinoid-rich strata have been identified, suggesting that hypersalinity, water depth and hydraulic conditions were the main factors controlling stromatolite morphogenesis. A cm-thick amalgamated bivalve rudstone, resting directly on the basement and representing a shell concentration formed above the fair-weather wave base was also recorded. Based on the regional distribution of the stromatolite types and associated sedimentary facies, we interpret the depositional environment as a local low-gradient carbonate ramp deepening to the east. Our data robustly indicated that the western rocky shorelines of the Araripe Basin during the Aptian were populated by microbial mats and stromatolites in a condition analogous to the modern world-famous Hamelin Pool, Shark Bay, Western Australia. Finally, the development of stromatolites and echinoid-bearing microbialites at the western margin of the basin may be correlated with the formation of bivalve-rich and cassidopid-rich shell beds in the upper part of the Romualdo Formation at the eastern margin.

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1. Introduction

Compared to the Precambrian geological record, microbialites were rare in the Phanerozoic with present-day occurrences found mainly in particular aquatic settings, such as the hypersaline embayment of Shark Bay, Australia (Riding, 2000) and the marine Exuma Cays, Bahamas (Reid et al., 2011). The rise of the metazoans is thought to have played a critical role in restricting the distribution of microbialites by imposing a competition pressure – although an inverse microbialite vs. metazoan presence/absence is not always observed (see discussion

in Riding, 2006). Indeed, metazoan skeletal remains are found associated with stromatolites in many modern locations worldwide, such as in the Lizard Island, Great Barrier Reef (Reitner, 1993), Shark Bay, Australia (Jahnert and Collins, 2011), and Lagoa Salgada, Brazil (Ricardi-Branco et al., 2018).

Microbialites grow in response to the close association between sedimentation and lithification (Reid et al., 2000) binding sediment and/or directly precipitating calcium carbonate (Reid et al., 2003; Dupraz et al., 2009). They are complex geo-biosphere systems that potentially record morphological changes that may unlock several physical environmental parameters (Andres and Reid, 2006; Dupraz et al., 2006). In this way, microbialites are fine tools to use in the reconstruction of depositional environments (Buongiorno et al., 2019).

Epeiric seas are generally the result of a rising relative sea level with consequent formation of thin transgressive deposits during overall landward migration of the shoreline/coastal onlap (Merletti et al., 2018). Carbonate ramps may develop in these settings, constituting

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¹ In memoriam.

excellent sites for the preservation of microbialites (Lokier et al., 2018). When sea level starts to fall, the formation of restricted embayments is favored, which are potential areas for stromatolite growth due to the increasing likelihood of elevated salinity conditions (Jahnert and Collins, 2013). However, recognizing such structures in ancient deposits is not common, as the thin microbial deposits generated over basement rocks were exposed and removed by erosion.

Here we record, for the first time, well-preserved isolated stromatolites, biostromes, bioherms and associated carbonate facies from the Lower Cretaceous Romualdo Formation at the western margin of the Araripe Basin, NE Brazil. The microbialites directly rest on Precambrian basement rocks, indicating that littoral areas were populated by microbialites at that time. Surprisingly, echinoid tests are also associated with the microbialites suggesting their close relationship. The carbonate facies, including microbialites and bioclastic deposits, resembled the conditions existing in the present-day Hamelin Pool, Shark Bay, Australia. There, microbial facies coexist with shallow coastal deposits constituting an excellent model for analogous deposits in the geological record.

In this context, the main goals of this contribution are: (a) categorize the microbialites based on their macro-, meso- and micro-structures; (b) record the lateral and vertical distribution of the stromatolites in order to understand their paleoenvironmental distribution; (c) discuss the factors controlling the formation of these microbially induced structures and their relationships with other paleoenvironmental parameters, and (d) correlate the stromatolite-bearing carbonate interval with other carbonate units of the Romualdo Formation at the eastern margin of the Araripe Basin.

2. Background: the stromatolites of the Santana Group

The occurrence of microbialites in rocks of the Early Cretaceous Santana Group were already recorded in the Barbalha, Crato, Ipubi and Romualdo formations of the Santana Group (Assine et al., 2014; Neumann and Assine, 2015), although detailed description, classification based on modern protocols, and their illustration are still lacking in many cases.

Cavalcanti and Viana (1990), and Martill and Wilby (1993) were the first to describe these structures in the Cretaceous succession of the Araripe Basin. Later, Srivastava (1996) recorded diverse forms of stromatolites in the Crato, Ipubi, and Romualdo formations. In the Crato Formation, Srivastava (1996) recorded the presence of stratiform and pseudo-domal stromatolites that were interpreted as generated at the bottom of shallow, quiet and protected water bodies. In the Ipubi Formation, Srivastava (1996) recorded stratiform, domal and columnar stromatolites in micritic limestones and marls, which occur interbedded with gypsum and anhydrite (cf. Cavalcanti and Viana, 1990). Stratiform, domal and columnar stromatolites were also mentioned from the Romualdo Formation cropping out at the western margin of the Araripe Basin, resting directly on the basement (Srivastava, 1996).

Microbialites from the Santana Group were studied by Sales (2005), that recorded well-laminated, echinoid-bearing carbonates from the Romualdo Formation in the vicinities of the Araripe Town, Pernambuco State. These carbonates were interpreted as microbial mats that grew in shallow and calm waters.

Based on a detailed microfacies analysis, Catto et al. (2016) suggested that the limestone morphogenesis of the Crato Formation involved strong and pervasive microbial activity. Calcified coccoid and filaments were identified as well as abundant calcified biofilms composed of Extracellular Polymeric Substances (EPS) within the laminites. Therefore, contrary to previous studies (e.g., Heimhofer et al., 2010), we concluded that microbes considerably influenced the formation of the laminated limestones.

In a subsequent study, Warren et al. (2017) described in detail the stromatolites and associated carbonate sedimentary facies of the Crato Formation from the succession analyzed by Catto et al. (2016).

According to these authors, at least three stromatolite-bearing levels occur at the lower part of the Crato Formation and are intercalated between the apparently monotonous succession of laminated carbonates. In the lower level (Level 1), stromatolites occurred discontinuously as 30-cm-tall domal stromatolites (Warren et al., 2017). Each structure produced a symmetric high convexity with internal undulating lamination with a lenticular shape. Centimeter-sized elliptical oncoids occur trapped in laminae between domes. The intermediate stromatolite-bearing level (Level 2) was emplaced approximately 1.5 m above Level 1, consisting of low discontinuous biostromes. The domes are slightly asymmetric and locally coalescing. The upper microbialite-bearing level (Level 3), occurred 2.2 m above Level 2 and is characterized by a discontinuous layer with isolated, domal stromatolites. According to Warren et al. (2017), during the Aptian, microbial mats thrived in shallow-water, hypersaline settings at the margins of the Araripe lacustrine system and were responsible for the formation of stromatolites in the Crato Formation. The record of these microbialites, together with recent findings of in situ coccoid, filamentous and spiral cyanobacteria cells and preserved EPS in the laminites of the Crato Formation (Catto et al., 2016), suggests well-laminated limestones genesis strongly influenced by microbial activity (Warren et al., 2017).

Fabin et al. (2018) mentioned wavy laminations in laminated limestones at the top of the Crato Formation that may represent microbial structures recognized near the Town of Nova, Ceará State. Similar microbial laminites with preserved coccoid cells were briefly described from the Batateira Bed of the Barbalha Formation (Dias-Brito et al., 2015).

The study of the microbialites and associated carbonate sedimentary facies of the Santana Group is still in its initial stage, and the Romualdo Formation provides an important site for advances in the stratigraphic and paleontological knowledge of the world-famous Lower Cretaceous unit.

3. Geological context

The Araripe Basin is an intracratonic Cretaceous rift basin that originated in response to the tectonic stresses of the Gondwana break-up and the opening of the South Atlantic Ocean (Matos, 1992; Valença et al., 2003; Assine, 2007). During its post-rift stage I, rocks of the Santana Group, encompassing in stratigraphic ascending order the Barbalha, Crato, Ipubi, and Romualdo formations, were deposited (Assine et al., 2014; Neumann and Assine, 2015). The Romualdo Formation can reach 100-m-thick of siliciclastic-dominated sediments (Custódio et al., 2017; Fürsich et al., 2019) that strongly decreases in thickness to the western margin of the basin (Figs. 1 and 2).

At the eastern margin, the Romualdo Formation is a marine-influenced unit corresponding to a depositional sequence encompassing two transgressive-regressive (TR) cycles (Fürsich et al., 2019). The first TR cycle includes the concretion-bearing black shales that are world-wide renowned for the exceptional preservation of the Santana fossils (vertebrates with soft tissue preservation, mostly fishes) (e.g., Maisey, 1991; Fara et al., 2005; Martill et al., 2007). This fauna differs drastically from that preserved at the second TR cycle, which comprises a few-meters-thick (<5 m) mixed carbonate-siliciclastic succession containing several bivalve- and gastropod-dominated shell concentrations mainly deposited under high-energy conditions (Fürsich et al., 2019). Parts of the carbonates correspond to one of the main phases of marine influence in the basin, a time with near-normal marine salinity conditions where echinoids and bivalve-like bivalves thrived (see also Beurlen, 1966 and Martill, 2007).

The reduced thickness of the Romualdo Formation in the western part of the basin is composed by a sedimentary package distinct from its eastern counterpart (Custódio et al., 2017, Fig. 2). The scattered and discontinuous occurrences in the western margin are mainly represented by incomplete successions of concretion-bearing shales and

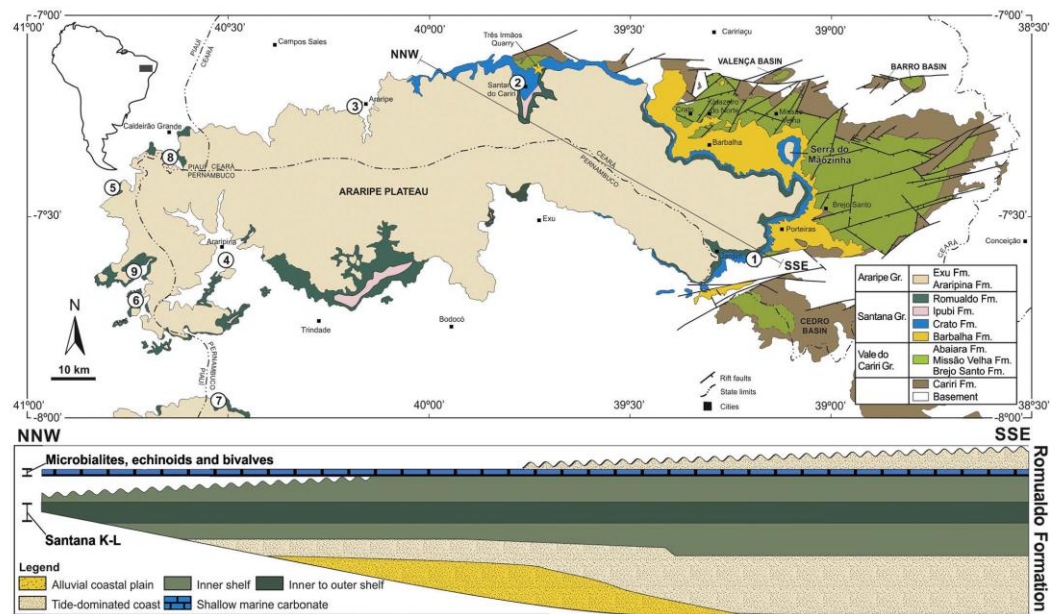


Fig. 1. Geologic map of the Araripe Basin and idealized diagram showing the depositional sequence of the Romualdo Formation (modified from Custódio et al., 2017). Columnar sections studied in detail: 1-Sobradinho; 2-Estiva; 3-Hospital; 4-Sítio Canastra; 5-Alagoinha; 6-Curralinho; 7-Inácio; 8-Caldeirão Grande; 9 – Sítio Alecrim. Santana K-L – Santana Konservat-Lagerstätte; Fm. – Formation; Gr. – Group.

shell-rich limestones. Within the shell beds, the molluscan fauna is predominantly composed of gastropods (cassiopids, cerithiids and naticids) and bivalves (bakevelliids, mytilids and corbulids) (Pereira et al., 2015, 2016, 2017). In addition, macroinvertebrate concentrations and articulated echinoids have also been recorded (Beurlen, 1966; Sales, 2005; Prado et al., 2015; Pereira et al., 2017). Some of these echinoids occur within lithified microbial mats associated with bivalves and gastropods near Araripina Town, Pernambuco State (Sales, 2005).

4. Material and methods

The field program in the Araripe Basin was conducted during the period of 2013 to 2019. These results were combined with previously (2001–2005) data acquired by others researchers. All the new data gathered come from the western margin of the Araripe Basin, where upper strata of the Romualdo Formation unconformably rest over Proterozoic basement rocks. In this area, a total of seven columnar sections (i.e., Serra do Inácio, Curralinho, Sítio Alecrim, Alagoinha, Sítio Canastra, Caldeirão Grande and Hospital, see Fig. 1 for location) were measured and their facies described in detail.

Several samples of stromatolites, echinoid-bearing microbialites and bivalve shell beds produced slabs for macroscopic examination and laboratory classification. Additionally, 17 petrographic thin-sections were examined under both normal and polarized light using a Zeiss Axio Imager A.2 binocular petrographic microscope and a Zeiss Stereo Discovery V.11 binocular magnifying glass, at the Center for Geosciences Applied to Petroleum Geology, São Paulo State University (UNESP-Petro-UNESP). The micro and ultrastructural images were acquired with the SEM X-ray energy-dispersive spectrometer JEOL JXA 8230 equipped with 5 WDS spectrometers and a solid-state EDS detector, at the Department of Petrology at São Paulo State University (UNESP), Brazil. The resulting images were generated in high-pressure mode, using

secondary electron images operated at EHT 15 kV, working distance of 10 mm and spot size of 40, without metal coating.

For the facies classification of microbialites Fairchild and Sanchez (2015) protocol was applied, based on data of Hofmann (1969), Preiss (1972), Walter (1972), and Grey (1989), which categorized microbialites on the basis of macro-, meso-, and micro-scale structures. Classification of the bivalve-bearing rock was based on biofabric and taphonomic arrange of shells, from which the degree of hydraulic reworking and transport of biogenic particles was inferred (Fürsich and Oschmann, 1993). The terms allochthonous and parautochthonous are used in the sense of Kidwell et al. (1986).

5. Sedimentary facies

At the western margin, the Romualdo Formation is almost exclusively calcareous with scattered basement pebbles, resting directly on Proterozoic basement rocks. The contemporaneity of these carbonates with rocks from the depositional succession in the eastern side is based in biostratigraphic correlations and basin architecture indicating that at least, part of the sediments is time-equivalent. (Figs. 1 and 2A). In the upper 40-m-thick the Serra do Inácio section (Fig. 1), from the Romualdo Formation reveals a well-developed sequence with transgressive-regressive cycles.

Detailed columnar sections were measured in the western part of the Araripe Basin. Stromatolites were documented in the Curralinho and Alagoinha sections (Sections 6 and 5), while echinoid-bearing microbial laminites and bivalve rudstones were registered in the Sítio Canastra and Hospital sections, respectively (Sections 4 and 3, Fig. 2B). Fig. 3 summarizes all the carbonate sedimentary facies that are directly associated with microbialites described and interpreted in the following section.

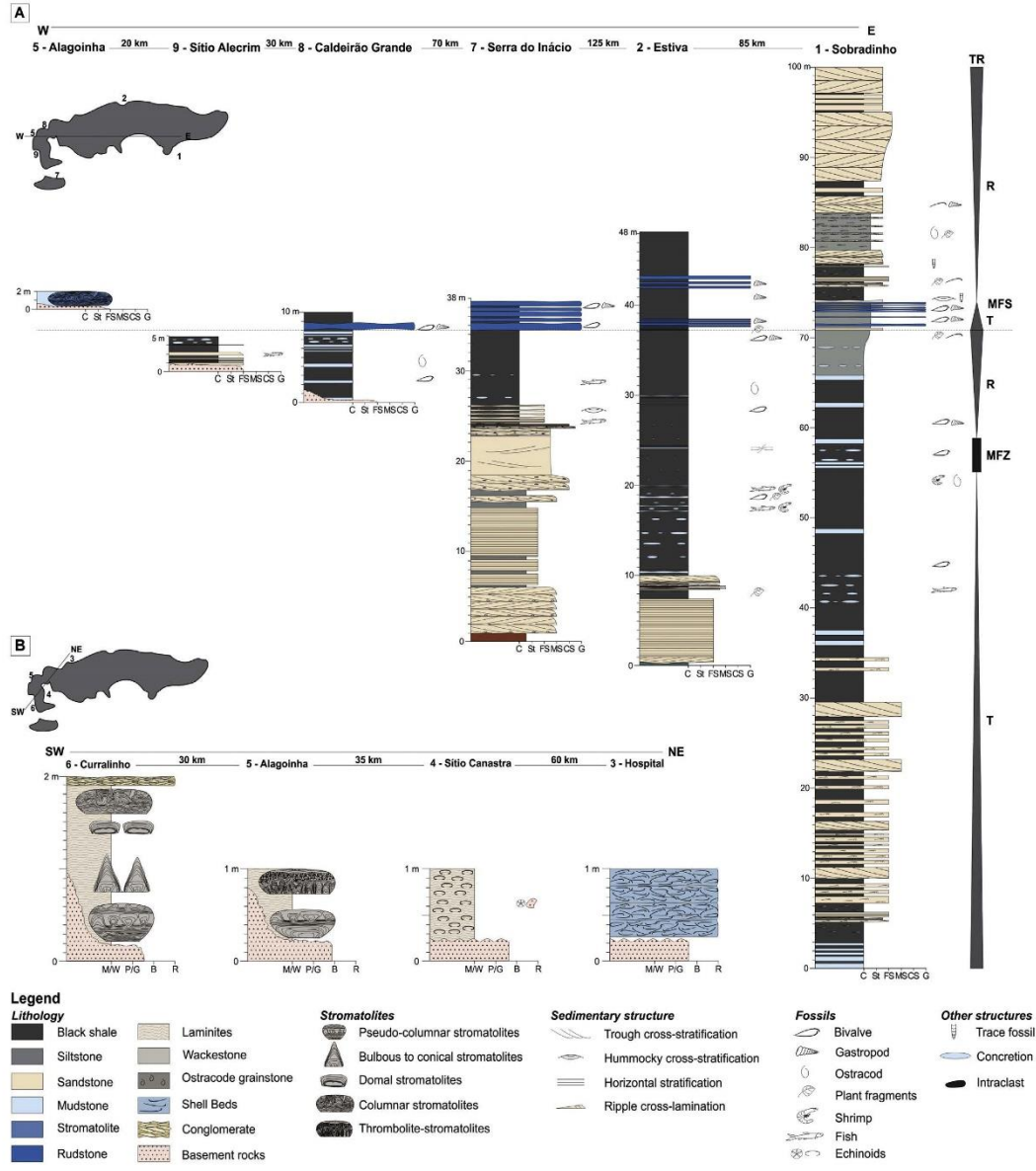


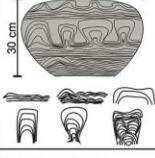
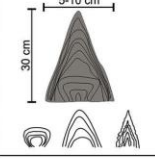
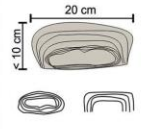
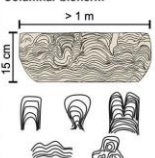
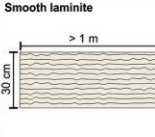
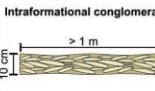
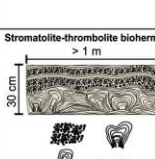
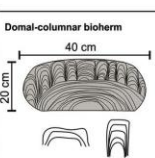
Fig. 2. Columnar sections of the Romualdo Formation. A: Transect (E-W) of measured columnar sections showing thicker preserved strata in the eastern part and a thin carbonate-dominated succession in the western part of the Araripe Basin. C – clay; St – silt, FS – fine sandstone; FM – medium sandstone; CS – coarse sandstone; G – granule; TR – Transgressive-Regressive cycles; T – Transgressive; R – Regressive; MFZ – Maximum Flooding Zone; MFS – Maximum Flooding Surface. B: Transect (NW-SE) of the studied sites, highlighting the occurrence of stromatolites, echinoid-bearing microbial laminites and bivalve rudstones. M/W – mudstone/wackestone; P/G – packstone/grainstone; B – boundstones; R – rudstone.

5.1. Cauliflower bioherms

5.1.1. Description

Isolated bioherms are found in a N-S oriented stromatolite field of about 3600 m² at the Curralinho site, directly overlying the basement

rocks. Bioherms are approximately 30 cm high and 40 cm wide exhibiting a typical silicified cauliflower shape (Fig. 4A) and forming isolated reefs. These bioherms consist of at least two cycles of smooth microbial laminites passing into pseudo-columnar and columnar stromatolites. The columnar stromatolites present three main

Morphology	Macrostructures	Mesostructures	Microstructures
Cauliflower bioherm 	- Body morphology: Columnar-laminated microbial complex - Transverse outline: Intergrown irregular bodies - Growth vector: Straight to sinuous - Proximity of structures: Adjoined - Frequency of branching: Abundant - Dichotomy: Parallel to divergent - Connection between structures: Bridges - Column width: Wrinkled	- Growth surface: Moderately convex / Parabolic / Rectangular - Laminar curvature: Curved to wrinkled - Regularity of laminar stacking: Little to moderately laminated - Micro- unconformities: Present - Laminar behaviour: Laminar inflection with partial to extensive recovering	- Lamination: Wrinkled - Continuity: Continuous do disrupted and brecciated - Relative thickness: Coarse (~0.5 mm) - Composition: Micrite with microclotted structure - Components: Peloids, nodules, coccooid cells, and possibly ooids - Other components: - - Preservation: Silicified
Conic stromatolite 	- Body morphology: Bulbous to conoid dome - Transverse outline: Round elliptical bodies - Growth vector: Straight to curved - Proximity of structures: Close to spaced - Frequency of branching: Absent - Dichotomy: Absent - Connection between structures: Bridges - Column width: Wrinkled	- Growth surface: Conform with axis / Conform without axis / Overarching - Laminar curvature: Wrinkled - Regularity of laminar stacking: Moderate to high axial zones - Micro- unconformities: Present - Laminar behaviour: Laminar inflection with extensive recovering	- Lamination: Smooth - Continuity: Continuous - Relative thickness: Medium (~0.2 mm) - Composition: Sparite with microclotted structure - Components: Peloids, coccooid cells, ostracodes - Other components: Pyrite - Preservation: Silicified
Domal stromatolite 	- Body morphology: Normal dome / Oncoid - Transverse outline: Round oblong bodies - Growth vector: Straight - Proximity of structures: Isolated - Frequency of branching: Absent - Dichotomy: Absent - Connection between structures: - - Column width: -	- Growth surface: Coated / Rectangular - Laminar curvature: Curved - Regularity of laminar stacking: Symmetric - Micro- unconformities: Present - Laminar behaviour: Laminar inflection with extensive recovering	- Lamination: Smooth - Continuity: Continuous - Relative thickness: Fine to medium (~0.1-0.2 mm) - Composition: Micrite with microclotted structure - Components: Peloids, coccooid cells - Other components: - - Preservation: Silicified
Columnar bioherm 	- Body morphology: Anastomosed microbial complex - Transverse outline: Intergrown oblong bodies - Growth vector: Straight to sinuous - Proximity of structures: Adjoined - Frequency of branching: Common - Dichotomy: Parallel - Connection between structures: Coalescent to bridged - Column width: Uniform	- Growth surface: Highly convex to rectangular - Laminar curvature: Curved - Regularity of laminar stacking: Symmetric to asymmetric - Micro- unconformities: Present - Laminar behaviour: Laminar inflection with partial to extensive recovering	- Lamination: Smooth - Continuity: Continuous - Relative thickness: Fine to medium (~0.1-0.2 mm) - Composition: Micrite with microclotted structure and organic laminae - Components: Ostracodes, organic matter - Other components: Pyrite and accessory minerals - Preservation: -
Smooth laminite 	- Body morphology: Laterally continuous (planar laminated) - Transverse outline: - - Growth vector: - - Proximity of structures: Lateral linked - Frequency of branching: - - Dichotomy: - - Connection between structures: Coalescent - Column width: -	- Growth surface: Plane - Laminar curvature: Without - Regularity of laminar stacking: - - Micro- unconformities: Present - Laminar behaviour: Without inflection	- Lamination: Smooth - Continuity: Continuous - Relative thickness: Medium to coarse (~0.2-0.5 mm) - Composition: Micrite with microclotted structure and sparite with clotted structure - Components: Peloids, fish fragments, ostracodes - Other components: Pyrite and accessory minerals - Preservation: -
Intraformational conglomerate 	- Body morphology: - - Transverse outline: - - Growth vector: - - Proximity of structures: - - Frequency of branching: - - Dichotomy: - - Connection between structures: - - Column width: -	- Growth surface: - - Laminar curvature: - - Regularity of laminar stacking: - - Micro- unconformities: - - Laminar behaviour: -	- Lamination: - - Continuity: - - Relative thickness: - - Composition: Micritic clasts and micritic matrix - Components: Coccooid cells - Other components: - - Preservation: -
Stromatolite-thrombolite bioherm 	- Body morphology: Columnar-laminated microbial complex - Transverse outline: Intergrown oblong bodies - Growth vector: Curved to sinuous - Proximity of structures: Adjoined - Frequency of branching: Common - Dichotomy: Parallel to divergent - Connection between structures: Coalescent to bridged - Column width: Uniform	- Growth surface: Moderately convex / Parabolic - Laminar curvature: Curved to wrinkled - Regularity of laminar stacking: Symmetric to asymmetric - Micro- unconformities: Present - Laminar behaviour: Laminar inflection with partial to extensive recovering	- Lamination: Smooth - Continuity: Continuous - Relative thickness: Fine to medium (~0.1-0.2 mm) - Composition: Micrite with microclotted structure and organic laminae - Components: Ostracodes, organic matter - Other components: Pyrite and accessory minerals - Preservation: -
Domal-columnar bioherm 	- Body morphology: Anastomosed microbial complex - Transverse outline: Intergrown round to oblong bodies - Growth vector: Straight - Proximity between structures: Adjoined - Frequency of branching: Absent to rare - Dichotomy: - - Connection between structures: Coalescent - Column width: Uniform	- Growth surface: Moderately convex / Rectangular - Laminar curvature: Curved - Regularity of laminar stacking: Symmetric - Micro- unconformities: Present - Laminar behaviour: Laminar inflection with partial to extensive recovering	- Lamination: Smooth - Continuity: Continuous - Relative thickness: Fine to medium (~0.1-0.2 mm) - Composition: Micrite with microclotted structure and organic laminae - Components: Ostracodes, organic matter - Other components: Pyrite and accessory minerals - Preservation: -

morphologies: cylindric, parabolic and rectangular. These morphologies occur in the same interval, grading laterally into each other and forming connected structures linked by bridges. Silicified smooth laminites and pseudo-columns are characterized by numerous millimetric fractures and by abundant porosity filled by silica cement (Fig. 4B–C). In the columns, laminae are inflected with partial to extensive recovering and locally exhibit micro-unconformities. Columns have a straight to slightly sinuous growth vector and abundant branches with parallel to divergent dichotomy. In plan-view, these structures are closely emplaced, round to oblong (Fig. 4D) and are locally interconnected. Smooth lamination presented commonly disrupted in thin-sections composed predominantly of micrite with rounded and ellipsoidal silicified bodies. These structures were also observed under SEM where spheres with ~10 µm in diameter are associated with elongated varieties, ~15 µm in length (Fig. 5A–B). SEM analysis also revealed the presence of small clusters (up to 10 µm in diameter) of cubic to rounded crystals resembling framboidal pyrite (Fig. 5C). The carbonate fabric is strongly silicified, although it kept its original morphology.

5.1.2. Interpretation

In general, the bioherms begins with smooth laminites that grade upwards into pseudo-columns and finally culminate indistinct columns at top. This arrangement does not necessarily represent a deepening-upward cycle but may just exemplify a setting, in which environmental parameters, such as accommodation space, hydrodynamics and sediment dispersion, vary (Andres and Reid, 2006). In this way, the commonly observed branching and dichotomy in the columns are probably directly related to oscillations in the hydrodynamic conditions. Columns connect each other by bridges/menisci in association with wrinkle lamination and absence of detrital components suggesting carbonate precipitation induced by microbial activity (sensu Dupraz et al., 2009) and not by trapping and binding of particles by filamentous cyanobacteria (see Reid et al., 2000). Spheres and elongated shapes as well as pyrite presence suggest sulphate reducing bacteria entombed in the inner portions of the mat.

5.2. Isolated cone-shaped stromatolites

5.2.1. Description

Isolated to loosely grouped silicified conical columns occur directly above basement rocks in area of approximately 1600 m² at the Curralinho site. Cone-shaped stromatolites may reach a height of 30 cm and a diameter of 5 to 10 cm and usually grow as spaced, straight to slightly curved constructions with elliptical contours. Cones occur as three different morphologies: bulbous overarching cone, cone without axis, and cone with axis. Usually, bulbous cones grade into cones without axis (Fig. 6A) and are uniformly laminated. Cones with axis (similar to *Conophyton*) show typically a wrinkled lamination and possess an irregular axial zone, uneven column margins and do not branch (Fig. 6B). In all three morphologies the lamination is highly inflected and micro-unconformities are present. Millimeter-scale light laminae alternate with wrinkled, dark, organic-rich laminae. Small spheres (75 µm in diameter) and ellipsoids (200 µm) are very common in both dark and light laminae. Particularly in dark laminae they are commonly associated with articulated and disarticulated ostracodes (Fig. 7A–B). SEM analysis revealed intense recrystallization with growth of hexagonal quartz crystals (Fig. 5D). Despite intense recrystallization of the original carbonate fabric, some phyllosilicates are still preserved (Fig. 5E).

5.2.2. Interpretation

Conophyton-like stromatolites area typical biologically influenced morphology that is usually assigned to relatively deep-water settings (Coffey et al., 2012). In modern environments, the separation between

cones is interpreted as the result of competition for nutrients between neighboring microbialite colonies in weakly turbulent environments without terrigenous input (Petroff et al., 2010). The here reported conical stromatolites have a bulbous morphology with uniform laminae that progressively overgrow each other to form typical cones with wrinkled lamination. This suggests that growth was strongly influenced by the dynamics of the microbial colony, probably in a quiet environment affected by progressive increase in water depth. Despite the relatively greater water depth in which the stromatolites grew, basement pebbles are still present, revealing a close source area and probably a still relatively shallow setting.

5.3. Isolated domal stromatolites

5.3.1. Description

Up to 10-cm-high and 20-cm-wide silicified domal microbialites occur dispersed in the stromatolite field of the Curralinho site above basement rocks. The domes are rectangular in cross-section and consist of symmetrically stacked curved and highly inflected laminae. Domes locally are developed on top of 10-cm-large oncoids. The oncoids are composed of thin, wrinkled laminae, occasionally disrupted by micro-unconformities, that coat a single carbonate core (Fig. 4C). The domes usually do not branch and have a straight growth vector. In transverse section this type of microbialite consists of isolated round oblong bodies. Smooth, planar lamination is observed in thin-sections. Laminae are characterized by silicified micrite commonly associated with peloids. SEM analysis revealed the presence of several up to 1-µm-sized spheres (Fig. 5F) and also filaments within the matrix (Fig. 5G).

5.3.2. Interpretation

Oncoids are concentrically laminated carbonate grains formed in shallow water bodies by alternating periods of agitation and absence of flux (Gerdes et al., 1993). The presence of micro-unconformities between wrinkle lamination suggest periods of reworking followed by microbial accretion during quiet periods (e.g., Lanés and Palma, 1998). After the initial phase of oncoid formation, marked by fluctuations in water energy, succeeded a period of stabilization, during which the oncoids were completely covered by microbial colonies, forming rectangular-laminated domes. This domal morphology suggests accretion under high-energy and shallow-water conditions, probably connected with frequent phases of subaerial exposure.

5.4. Columnar stromatolite bioherms

5.4.1. Description

Up to 15-cm-high and >1-m-wide bioherms with rectangular shape overlie silicified domes and occurred below the intraformational conglomerate facies in the Curralinho section (Fig. 2B). This bioherm type differs from most microbialite once facies are non-silicified composed by calcite. Bioherms are composed by smooth laminites that grew into cylindrical columnar stromatolites with inclined growth vector (Fig. 8A). Cylindrical columns occur as connected and coalescent structures with moderate to high laminar inflection (Fig. 8B–D). The stacking pattern of columns is symmetric with highly convex smooth laminae. Parabolic and pseudo-columnar morphologies co-occur with the cylindrical columns. Columnar stromatolites commonly branch dichotomously (Fig. 8E). The branches run parallel and touch each other. In plan-view, the columns are rounded to elongated and often connected (Fig. 8F). In thin-sections, laminae are up to 0.5-mm-thick, whereby light sparitic laminae are intercalated between dark micritic ones (Fig. 7C). Scattered opaque minerals are observed between laminae. Some dispersed minerals show high birefringence (Fig. 7D), and a few articulated ostracodes are filled with chalcedony (Fig. 7A). Isolated

Fig. 3. General characteristics (macro-, meso-, and microstructures) of the microbialites described in the western outcrops of the Romualdo Formation.

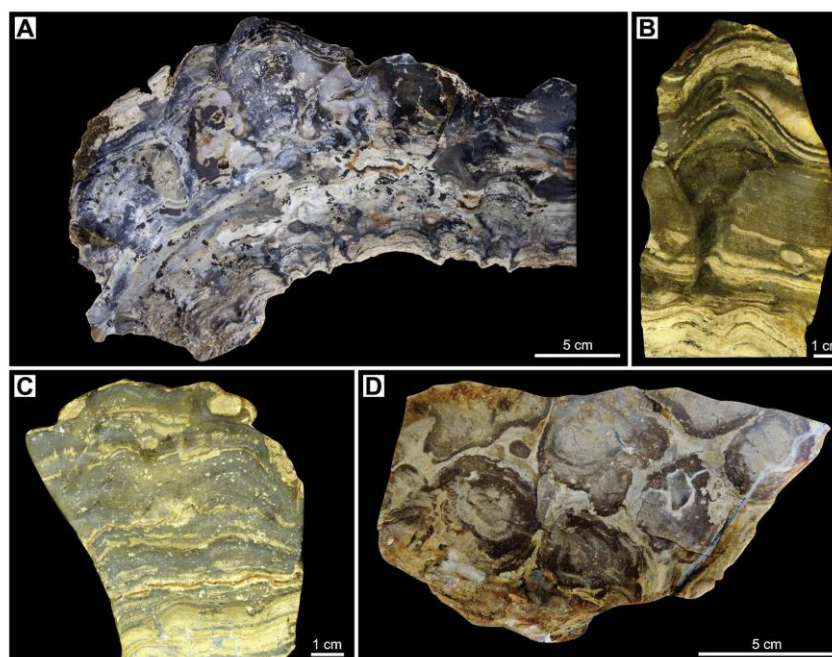


Fig. 4. Cauliflower bioherms. A: General morphology and internal arrangement of pseudo-columnar and columnar stromatolites. B: Pseudo-columnar stromatolite growing above a cracked microbial laminites. C: Silicified smooth laminites and pseudo-columns with cracks characteristic of subaerial exposure. D: Plan-view of columnar stromatolites showing closely spaced to intergrown irregular outlines.

and grouped filaments are abundantly preserved within the stromatolites (Fig. 5H–I).

5.4.2. Interpretation

Similar to the cauliflower bioherms, this stromatolite type shows a typical transition pattern between smooth laminites, pseudo-columnar and, finally, columnar morphologies. Contrary to the cauliflower bioherms, the lamination in this facies is smooth, and the columns coalesce with no gaps between them. In addition, there is a predominance of single cylindrical columns without gap between laminae. Straight and highly convex cylindrical columns predominate and suggest that they formed during a progressive increase in water depth. Variations in the hydrodynamic conditions probably are the cause of the branching with parallel dichotomy developed towards the top of the bioherms. Scattered ostracodes and basement minerals suggest that besides authigenic precipitation of carbonate by microbial activity, trapping and binding also contributed to microbialite growth. Preservation of abundant bacteria filaments is favored by conservation of original carbonate minerals.

5.5. Smooth laminites

5.5.1. Description

Smooth laminites occurred between stromatolite facies in both the Curralinho and Alagoinha sections, commonly forming laterally continuous biostromes (Fig. 9A–C). Laminites form up to 2-cm-thick beds commonly showing V-shaped cracks at their top. Occasionally, these cracks disrupt the lamination which results in rectangular clasts constituting intraformational conglomerates (Fig. 9B). In addition, locally cracked structures occur in these intervals (Fig. 9A). In thin-sections,

the lamination is characterized by well-defined alternations of dark, micro-peloidal laminae and light sparitic laminae with peloids (Fig. 10A). Peloids in the sparitic part are larger than in the dark laminae and are characterized by round and ellipsoid shapes (Fig. 10B). Spherulites are abundant in the dark laminae (Figs. 5J–L, 10C). Also common are fish bones and scales (Fig. 10D).

5.5.2. Interpretation

Smooth laminites are interpreted as lithified microbial mats formed in very shallow waters. Cracked bed planes are strong evidence of intermittent subaerial exposure and synsedimentary lithification. Spherulites are commonly associated with microbial deposits formed in saline and alkaline waters in the presence of organic acids typically found in EPS (Mercedes-Martín et al., 2016; Chafetz et al., 2018). These are usually formed by precipitation of radial aragonitic crystals around peloids formed by coalescence of carbonate nanoglobes around degraded organic matter (Spadafora et al., 2010). In this way, the smooth laminites are interpreted as lithified microbial mats that generated in shallow restricted settings, probably intertidal to supratidal settings, indicated by the presence of spherulites, peloids, and sedimentary cracks.

5.6. Intraformational conglomerates

5.6.1. Description

Thin conglomerate layers are common in the upper part of the Curralinho stromatolite sequence in close association with smooth laminites (Fig. 9D–E). They consist of up to 1-cm-high, 4-cm-wide, and 10-cm-long rectangular-shaped, imbricated clasts with rounded edges. Clasts are composed of light-colored microsparite with absent

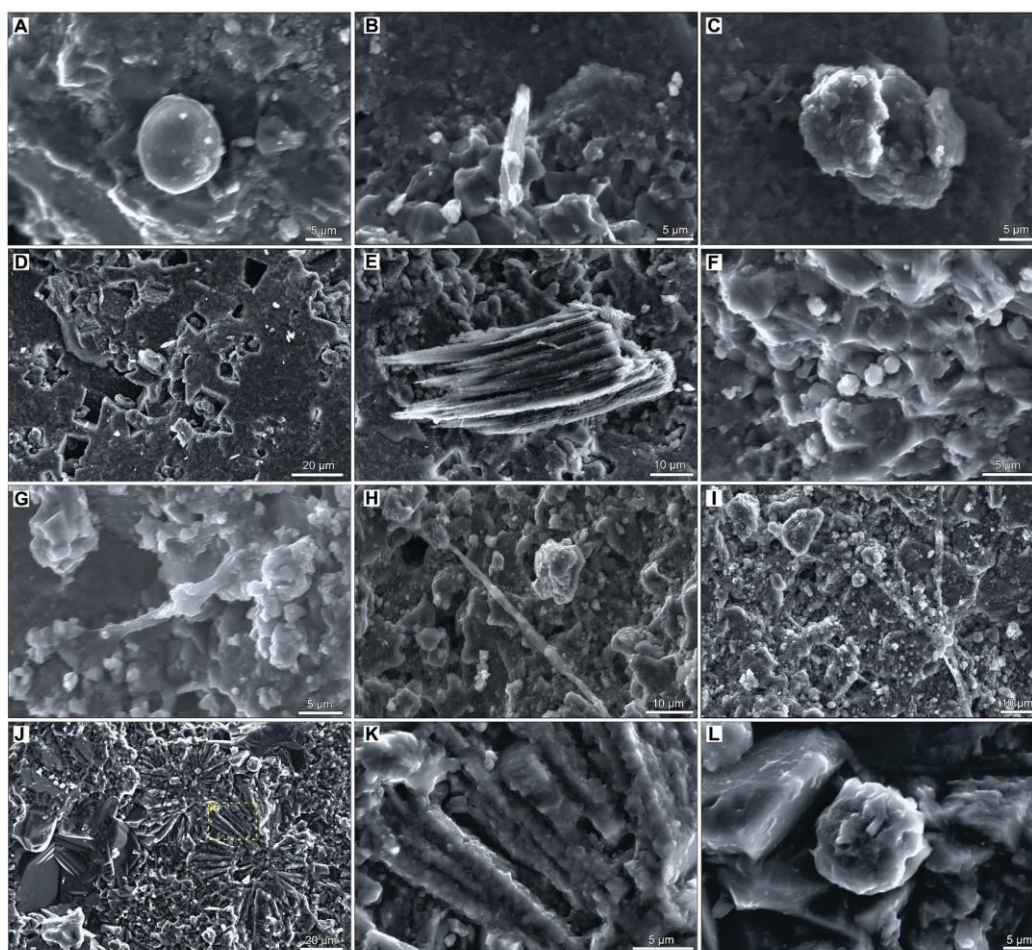


Fig. 5. SEM images of the microbialite facies. A: Coccoid microbe. B: Preserved elongated cell. C: Pyrite framboid. D: Highly silicified stromatolite. E: Phyllosilicate grain preserved in a silicified microbialite. F: Coccoid cells. G–I: Microbial filaments. J: Spherulites with typical radial arrangement. K: Detail of the radial structure of a spherulite represented in J. L: Probable framboidal pyrite associated with spherulites.

internal lamination and contain small vugs filled with silica. The matrix is typically dark micrite containing small calcispheres with radial extinction.

5.6.2. Interpretation

Formation of the pebbles was facilitated by the V-shaped cracks in the smooth laminites and their in-situ brecciation. Reworking events probably were only brief. The rounded edges of the clasts may indicate that the reworked layers were not fully lithified. Imbrication suggests the presence of bottom currents as transport agents of the clasts in intertidal to supratidal settings.

5.7. Stromatolite-thrombolite bioherms

5.7.1. Description

Up to 30-cm-high and approximately 1-m-wide bioherms of columnar stromatolites and thrombolites occur above basement rocks in the

Alagoinha section (Fig. 11A–D). Columnar stromatolites are characterized by parabolic to convex laminae and thrombolytic (clotted) fabrics (Fig. 11B–C). They occur as columns occasionally linked by bridges. In plan-view, these structures are closely spaced and partly connected resulting in elongated outlines (Fig. 11A). Columns grew sinuously and commonly branch with both, parallel and divergent dichotomies (Fig. 11D). Internal lamination is smooth to slightly wrinkled and the stacking pattern is symmetric to asymmetric with partial to extensive recovering of laminae. Towards the upper part of the bioherms, smooth laminites interbedded with thrombolites are common (Fig. 11B). The thrombolites are characterized by clotted fabric with up to 2-cm-sized rounded and irregular clots of different shapes.

5.7.2. Interpretation

Thrombolites are very common in carbonate buildups and are characterized by macroscopically rounded to irregular clotted fabrics with a blocky, unlayered mesoscale fabric (Riding, 2000; Shapiro, 2000;

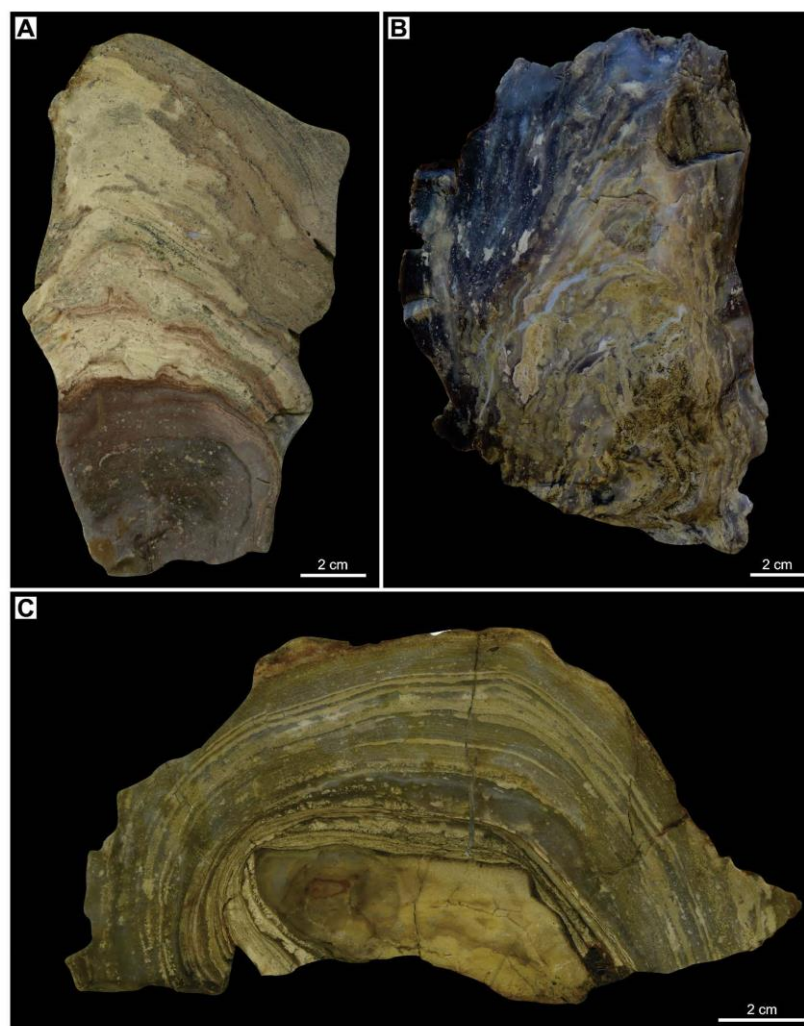


Fig. 6. Loosely grouped stromatolites. A: Bulbous stromatolite growing into conical morphology with wrinkled lamination. B: Cone-shaped stromatolite showing wrinkled lamination similar to *Conophyton*. C: Oncoid with a thin cortex overgrown by domal stromatolite.

Theisen and Sumner, 2016). The stromatolite-thrombolite bioherms are characterized by thick, massive, sub-parallel layers of thrombolite in association with columnar stromatolites. The alternation between stromatolites and thrombolites in the same bioherm is unusual - although the association of thrombolitic and stromatolitic structures within the same microbialite morphology is common in the Hamelin Pool, Shark Bay (see Burne and Johnson, 2012) - and may reflect a response to changes in environmental parameters, such as hydrodynamic conditions in the subtidal zone and/or variations in water depth (Feldmann and McKenzie, 1998). Although thrombolites occur in subtidal settings according to some scenarios, vertical growth of pustular laminae in shallow intertidal settings also produces mesoclotted fabrics (Jahnert and Collins, 2011). Regardless of the water depth, thrombolites are commonly associated with high energy settings. This can be confirmed

in the present case by abundant divergent dichotomy in the stromatolite-thrombolite columns. A third explanation for the co-existence of stromatolites and thrombolites might have been layer-by-layer formation of the thrombolite facies, with subsequent loss of the lamination during diagenesis (Theisen and Sumner, 2016).

5.8. Dome-shaped bioherms

5.8.1. Description

Up to 20-cm-high dome-shaped bioherms with a circular cross-section (40×40 cm) rest directly on basement rocks in the Alagoinha section. The bioherms are composed of a complex microbial frame work with domal stromatolites at the base and columnar stromatolites at the top (Fig. 11E–F). The 10-cm-high and 30-cm-wide domal

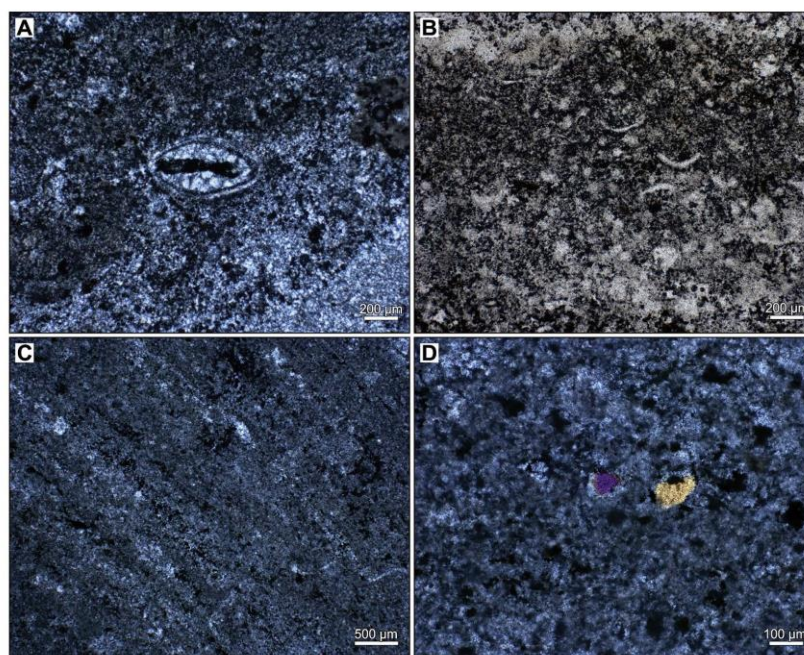


Fig. 7. Thin-sections of the microbial facies. A: Detail of a trapped articulated ostracod specimen filled with chalcidony (crossed nicols; 20 $\times$). B: Alternation of thick dark and light laminae with trapped single ostracod valve (20 $\times$). C: Detail of the fine lamination of columnar stromatolites (crossed nicols; 10 $\times$). D: High birefringence basement mineral grains (crossed nicols; 10 $\times$).

stromatolites have a single morphology with a circular core and a concentric, smooth to slightly curved lamination (Fig. 11F). In the upper part of the bioherms, columnar stromatolites changed morphologies from domes into cylindrical columnar stromatolites with an overall mushroom-shape morphology (Fig. 11E) characterized by straight, convex to rectangular growth surfaces, lacking branching. Columns coalesce, occasionally are linked by bridges, and are circular to elongated in plan-view. Lamination is smooth and symmetrically stacked, and laminae inflect downward with partial to extensive recovering of previous lamination.

5.8.2. Interpretation

Changes in the stromatolite morphology are mainly related to modification in physical parameters, even though it may be associated secondarily with modification within the surficial microbial communities (Dupraz et al., 2006). The transition between a single domal morphology into multiple columns records a physical change in the growth pattern of the described microbialite buildup, directly related to an increase in the sedimentation rate (Dupraz et al., 2006).

5.9. Echinoid-bearing microbial laminites

5.9.1. Description

Decimeter-thick layers of wrinkled laminites with abundant echinoids rest directly on the basement in the Sítio Canastra section (Fig. 12A). Abundant tests of *Bothriopneustes araripensis* are commonly found associated with the microbialites. They occur at the base and top of the microbialites but also between laminae (Fig. 12B). Most echinoid tests are arranged parallel to the microbial lamination with the aboral side facing upward (Fig. 12C–D),

but some are oblique and yet others exhibit an inverse orientation. The tests usually suffered compactional deformation and breakage, but in a few cases, their original shape is fully preserved. Oblique, horizontal and near-vertical burrows, some of them displaying meniscate structures, occur within the microbial lamination (Fig. 12E). In cross-sectional view, the height of these burrows varies between 6 and 11 mm. Occasionally, granite pebbles sourced from basement and reworked flat clasts eroded from nearby microbialites can be present embedded by wrinkle lamination (Fig. 12F).

5.9.2. Interpretation

The echinoid-bearing microbialites were generated under quiet water conditions, directly on the hard substrate represented by igneous and metamorphic Proterozoic basement rocks. Although the microbialites probably grew in a protected setting, the presence of pebbles and internal discontinuities point to growth interruptions and occasional reworking events. A characteristic feature of the echinoid tests is that on the oral side, the thickness of the plates is only half to one-third that of plates on the aboral side. During compaction, the tests cracked at the margins where oral and aboral sides meet. As a result, the oral part of the test was pushed inward often to the extent that hardly any space was left between oral and aboral side of the test, the curvature of both test parts being identical. However, not all echinoids are strongly compacted. In a few cases, they maintain fully or partly their original shape. In this case the test interior is filled with micrite, fine terrigenous material or both. All evidence cited above supports the hypothesis that the echinoids lived in direct association with the stromatolites in a similar way as recorded in Quaternary reefs in Tahiti (Camoin et al., 1999).

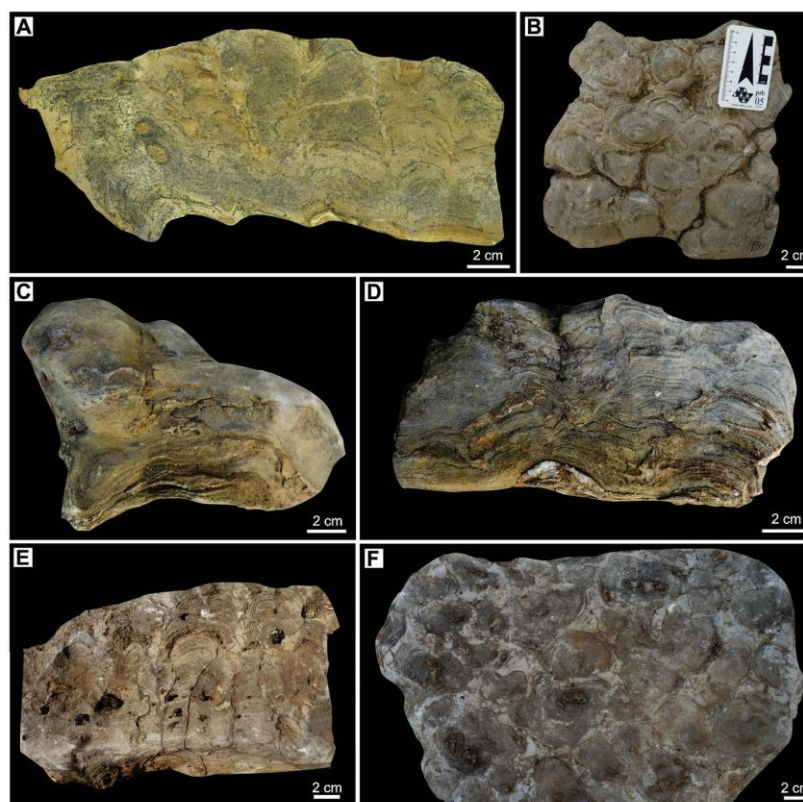


Fig. 8. Columnar bioherms. A: Coalescent cylindrical columns with curved growth vector. B: Upper view of the bioherm highlighting the round to elongated intergrown stromatolite columns. C: Single columns growing above domal stromatolite. D: Curved to sinuous columns which branch near the top. E: Straight cylindric columns with parallel dichotomies at the top. F: Plan-view of a bioherm showing small round intergrown columns and larger, closely spaced elongated bodies.

5.10. Bivalve rudstones

5.10.1. Description

Well-cemented bivalve-rich rudstones are represented by up to 1-m-thick, clast-supported, amalgamated shell beds (Fig. 13A), resting directly on the basement. This facies is well exposed in the Araripina Hospital parking lot (Figs. 1 and 2B). The concentration is dominated by disarticulated bivalve shells and shell fragments (Fig. 13B–D). Closed articulated shells are also recorded. Shell fragments are usually rounded (abraded) and without signs of encrustation, bioerosion and corrosion (sensu Brett and Baird, 1986). The shells are more or less of the same size (≤ 1 cm), usually recrystallized, and many show compactional distortion. In plan-view, the shells are randomly dispersed in a sparite cement. In cross-sectional view, the shells ($n = 197$) are also randomly oriented: 34.5% are convex-up, 36.5% convex-down, and 29% oblique/vertical (see Fig. 13B). Shells are commonly nested or stacked. Two small, shallow burrowing species of the heterodont bivalve *Calva* account for the bulk of the shells, whereas gastropod shells are rare. The overall species diversity is very low.

5.10.2. Interpretation

This thick shell-rich deposit is mainly formed by disarticulated bivalve shells, some fragmented and rounded (abraded). The poor

preservation quality of the shells and evidence of size sorting clearly indicate that the shells were winnowed from the sediment by hydraulic processes and underwent extensive transport. The biofabric of this deposit records several high-energy events leading to repeated amalgamation (Fig. 13A). This is clearly a fair-weather shell concentration (sensu Fürsich and Oschmann, 1993), generated under high hydraulic energy conditions, accumulating directly on the hard basement rocks. However, some shells are still closed articulated, suggesting that these underwent only limited transport and sorting. As the dominant bivalves, two species of *Calva*, are shallow burrowers that clearly did not live on basement rocks. These bivalves are an important part of the benthic fauna in fine-grained siliciclastic sediments of the first TR cycle (Fürsich et al., 2019). Such deposits were removed by erosive transgression during the beginning of the second TR cycle, which led to the concentration of the shells as lags on the basement rocks. Alternatively, the bivalves were introduced from some distance. This would explain the high degree of sorting, because elsewhere in the Romualdo Formation *Calva* is generally associated with a number of gastropods, which are rare in the present concentration. Thus, the shell bed is a parautochthonous to allochthonous shell concentration (sensu Kidwell et al., 1986). This condition is similar to what exist in the *Fragum*-dominated coquina barrier from Shark Bay (Jahnert et al., 2012).

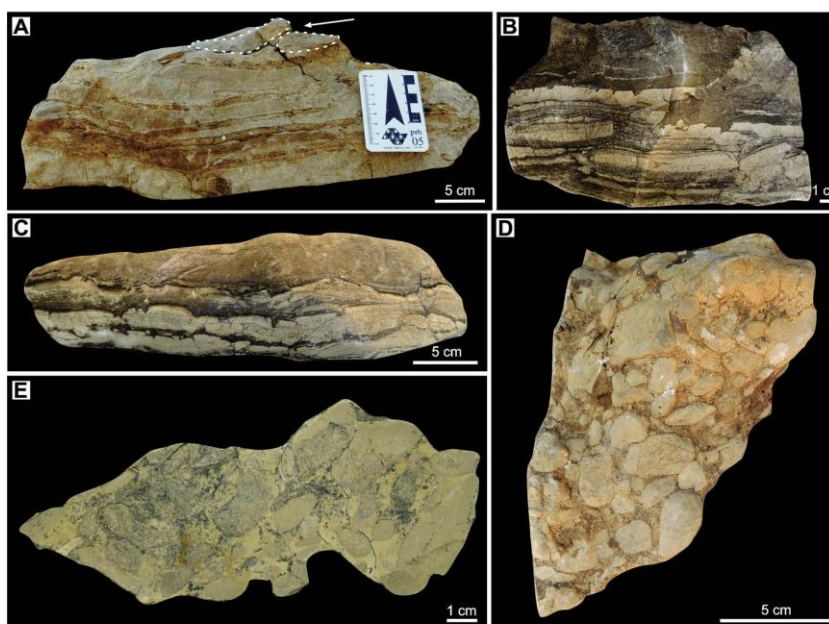


Fig. 9. Smooth laminites and rudstones. A: Cracked feature in the upper plane bed of a laminated limestone. B: V-shaped cracks leading to isolated clasts. C: Intensely cracked laminite. D: Plan-view of subangular to subrounded clasts of the rudstone facies. E: Polished cross-section of the rudstone facies showing dark-colored clasts and light-colored matrix. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Stromatolite morphology and small-scale local environmental changes

Microbialites are defined as organosedimentary structures formed by the activity of benthic microbial communities, including stromatolites, thrombolites, microbial mats, and oncoids (Burne and Moore, 1987). Trapping and binding of sediment and microbially-induced/influenced calcification are the main processes involved in the formation of microbialites (Burne and Moore, 1987; see also Dupraz et al., 2009). Microbial precipitation of carbonate is essential and is achieved by photosynthetic removal of CO_2 under oxygenated conditions, which increases the pH of water, and also by bacterial sulphate reduction of heterotrophic communities within mats (Visscher et al., 2000; Dupraz et al., 2009). The dynamic balance between sedimentation and lithification of mats is required in the growth of different microbialite morphologies (Reid et al., 2000). Indeed, increase/decrease in accommodation space, sediment availability and variation in hydrodynamics are regarded as the main mechanisms in this process (Andres and Reid, 2006). In areas characterized by high sedimentation rates, filamentous cyanobacteria predominate, and microbial laminae tend to grow fast (Reid et al., 2000). With a decrease in the sedimentation rate, coccoid cyanobacteria modify the organization of the microbial colony and form thick laminae (Reid et al., 2000). Similarly, to the stromatolites, thrombolites reflect changing environmental and biological parameters and contribute to paleoenvironmental interpretations (Burne and Moore, 1987; Buongiorno et al., 2019).

Stromatolites of the Romualdo Formation are strikingly distinct in their macro-morphology (Figs. 4, 6, 8–11), suggesting that an interplay of physical and biological factors drove their formation at the depositional site. Indeed, the transition between distinct stromatolite morphologies reveals changes in environmental parameters (i.e., turbidity, energy and flux velocity) without necessarily involving a relative sea-

level variation (Andres and Reid, 2006). For example, in a depositional setting characterized by stable accommodation space creation with increase in calcium and carbonate accretion, microbialites begin to grow faster generating columns and protruding appendages (Andres and Reid, 2006). Bridged to coalescent columns suggest a low contribution of trapping and binding of sediment by strong currents and points to a high sedimentation rate with rapid laminar accretion (Andres and Reid, 2006). Also, the presence of branching forms, as well as the interaction of thrombolites and stromatolites, support the hypothesis of an increase in the accretion rate and water energy of the environment. In this way, the stromatolite-thrombolite association can be a product of in situ cementation of microbial communities under high-energy conditions (Feldmann and McKenzie, 1998; Jahnert and Collins, 2011) and indicate the transition of subtidal to intertidal settings with likely high influence of tidal currents and/or waves.

Oncoids occur coated by small stromatolite domes and suggest their formation in shallow water with alternating periods of agitation and absence of flux (e.g., Gerdes et al., 1993). These oncoids are the result of initial accretion of microbial biofilms in response to constant particle mobilization by waves, bottom currents or tide action and subsequent stabilization of the microbial mat due to the decrease in water energy. Towards the top of the succession, microbial mats with features indicative of subaerial exposure (e.g., polygonal cracks) dominated. These thin beds are characterized by cracked laminites with fitted polygonal and rounded clasts. Reworking of the cracked mat fragments by currents/waves in the inter to supratidal zone rounded the sharp edges of the platy clasts and produced thin beds of clast-supported conglomerates at the top of the preserved succession. During periods of high-energy events under the influence of tides and waves, the formation of intraformational clasts and internal discontinuities in some stromatolites point to interruptions

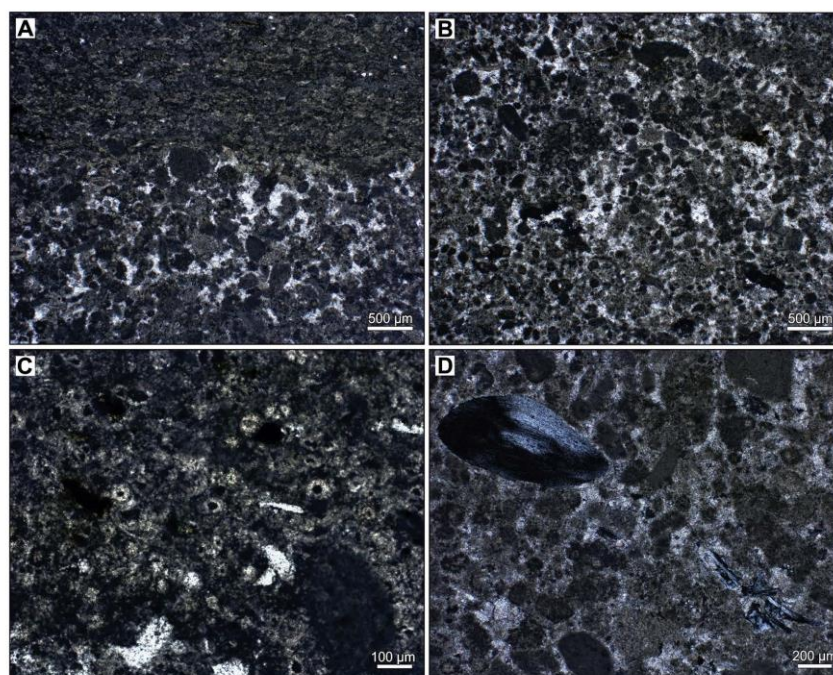


Fig. 10. Petrographic analysis of the smooth laminites. A: Fine interlamination of dark, spherulite-rich mudstone and peloidal grainstone (10 $\times$). B: Peloids cemented by sparite (10 $\times$). C: Spherulites in the dark, organic-rich mudstone (50 $\times$). D: Phosphatized fish scales (crossed nicols; 20 $\times$).

in the growth/accretion of the microbialites and subsequent occasional subaerial exposure and reworking events.

Despite the scattered geographic distribution of the microbialites in the Romualdo Formation, the diversity of morphologies recorded at least in two described sections (Fig. 2B), suggests that several environmental and/or biological processes were responsible for their morphogenesis. In this context, the interaction of some microbialites and echinoids is quite intriguing (Sales, 2005, p. 98). The echinoids discussed here occur not only at the base and the top but also between the laminae of microbialites. The vast majority of the echinoids in the studied laminites belong to *B. araripensis*. The specimens are usually oriented parallel to the microbial lamina with the aboral side facing upward. In some cases, oblique, horizontal and near-vertical burrows connect with the tests. This highly suggests that the echinoids moved (at least facultatively) within the soft substrate of the microbial mats, searching for shelter and/or food. In fact, based on the morphology of the tests, Beurlen (1966) had already suggested that this species was an epifaunal or a semi-infaunal form, which moved slowly through the soft substrate (see also Manso and Hessel, 2007, p. 276). The high number of complete echinoid tests in some layers and their association with oblique, horizontal and near-vertical burrows suggests a specific time interval of profuse proliferation of these invertebrates during the sedimentation. These occurrences suggest that the irregular echinoids of the Romualdo Formation lived in close association with mat-dominated bottoms in a period of pronounced marine incursion in the basin. This apparently contradicts the notion that mat-dominated bottoms formed in aquatic settings free of metazoans (see also Riding, 2006 for a detailed discussion of this issue).

7. Stratigraphic relationships at the western margin of the Araripe Basin

Shell-rich beds are a conspicuous feature of the transgressive deposits of the upper T-R cycle of the Romualdo Formation (Fürsich et al., 2019). Depending on their occurrence within the basin they are dominated by bivalves (*Bakevellia*, *Calva* and *Sinonia*) and/or gastropods (cerithiids and cassiopids) (Fürsich et al., 2019). Due to their wide lateral distribution across the basin, these deposits are key stratigraphic markers. In the eastern part of the Araripe Basin, the matrix of the shell beds is mainly mixed carbonate-siliciclastic, and the concentrations are interpreted as having been deposited above the storm wave-base, but below the fair-weather wave-base (Fürsich et al., 2019). In contrast, at the western margin of the basin, the bivalve-rich shell concentrations are less common, occurring in the Serra do Inácio and Caldeirão Grande sections (Fig. 2A), located at the southwestern and northwestern margins, respectively.

The western margin of the Araripe Basin is characterized by thin carbonate-dominated successions directly overlying basement rocks. Although they are apparently positioned at the same stratigraphic level, the facies association indicates that they should be part of different T-R cycle. At the Sítio Alecrim section, nearly 10 km far from the main stromatolite field (Fig. 2), siliciclastic-dominated deposits of the Romualdo Formation are also discordantly overlying the basement. These are mainly represented by a 5-m-thick succession of interbedded sandstones and shales including numerous fish-bearing concretions, constituted by both marine and non-marine assemblages (Fara et al., 2005; Fig. 2A). At the eastern margin of the Araripe Basin, coeval fossil-rich, laminated shales of the Romualdo Formation are associated to transgressive deposits of the lower cycle of this unit, representing

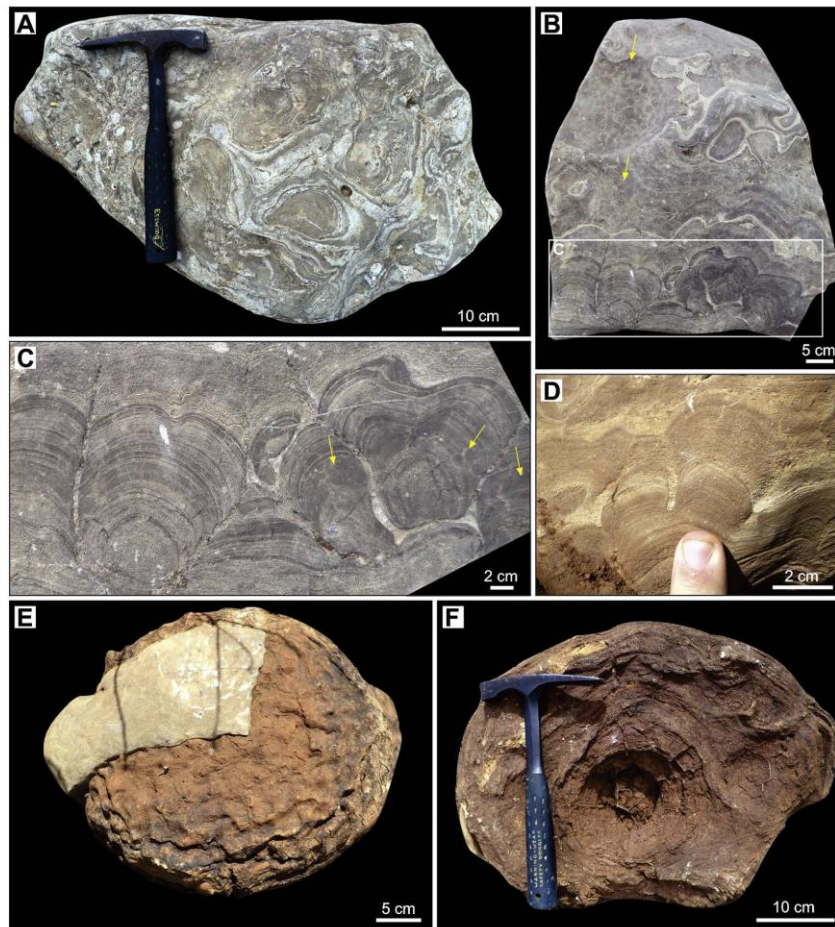


Fig. 11. Bioherms from the Alagoinha stromatolite field. A: Plan-view of bioherm showing irregular intergrown bodies. B: Thrombolite-stromatolite bioherm. C: Detail of B showing branching columnar stromatolites. D: Parallel dichotomy growing into a coalescent structure. E: Mushroom-shaped bioherm showing wrinkled top marked by coalescent columns. F: Lower view of the mushroom-shaped bioherm showing its early domal growth stage. Photo credits to Celso Lira Ximenes.

low energy, dysoxic to anoxic bottoms, generated below storm wave-base (Custódio et al., 2017; Fürsich et al., 2019). The occurrence of such concretion-bearing shales also at the western margin of the basin is a noteworthy evidence that this first transgressive event was widespread and occurred before the deposition of the shell beds and stromatolite fields (see diagram in the Fig. 1).

At the Serra do Inácio locality (Fig. 2), the sedimentary succession correlates to that described for the Sítio do Alecrim section, but the 40-m-thick sedimentary succession includes sandstones deposited in alluvial to coastal settings at the base. These are succeeded by concretion-bearing black shales with abundant, well-preserved fishes, deposited in inner to outer shelf settings, indicating a rapid transgression. Overlying this shale interval, shell-rich carbonates with abundant bivalves are also recorded. As for the Sobradinho section, the Serra do Inácio deposits occupies a more distal position along an onshore-offshore profile. In the Caldeirão Grande section (Fig. 2A), the shell beds were recorded a few meters above the crystalline basement. This means that those shell beds belong to another transgressive event

onlapping the basement (i.e., the upper T-R/C) and represent shallower deposits in relation to those from the Serra do Inácio and Sobradinho sections, although probably time equivalent.

The microbialite fields at the westernmost outcrops of the Romualdo Formation, microbialites rest directly on the basement (Fig. 2B). The shallowing-upward stacking pattern observed in the stromatolite fields, is represented by conical isolated forms at the base and microbial mats with subaerial exposure at the top evidence of a regional small-scale relative sea-level fall. Conical stromatolites indicate a relatively deep subtidal, low-energy environment, formed in the absence of sedimentation (see Petroff et al., 2010), while subaerially exposed microbial mats and their reworked clasts point to high-energy, shallow-water conditions, probably in the inter-supratidal settings, possibly within a drying up embayment area. In this scenario, variations in water energy occurred, during the transition from pseudo-columnar to columnar stromatolites in single bioherms, and respond for other stromatolite morphological changes. This

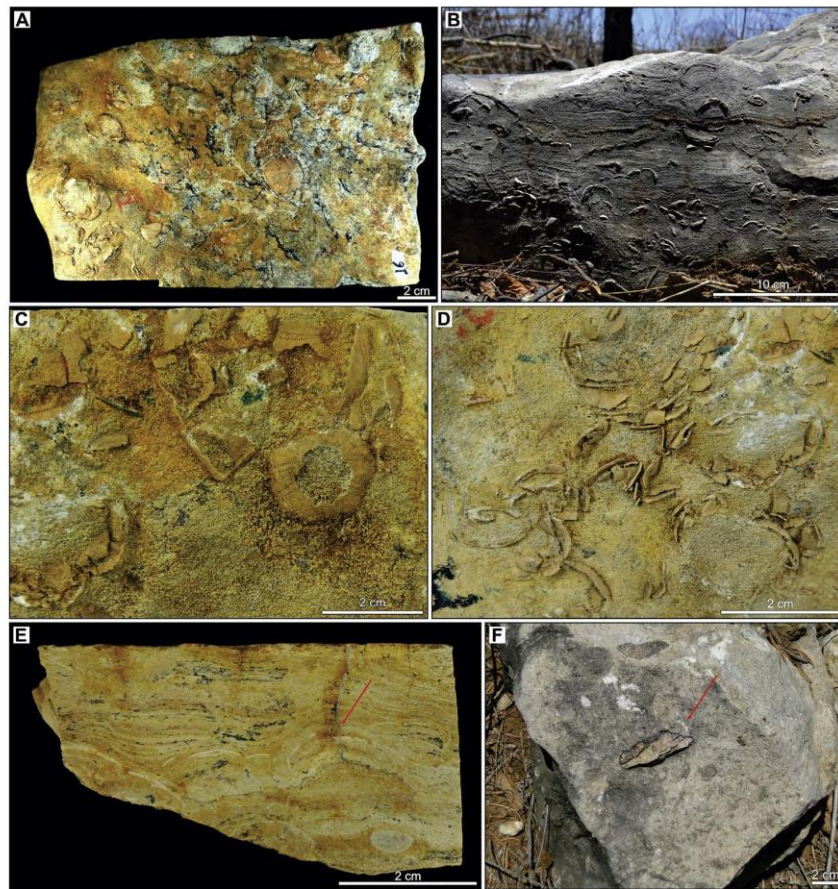


Fig. 12. Echinoid associated to microbial laminites. A: Plan-view of microbial laminites with abundant tests of echinoids. B: Preferential convex-up orientation of echinoids concordant to microbial lamination. C–D: In situ fragmented echinoid tests. E: Bioturbation associated with echinoids in life position (arrowed). F: Subangular basement clast (arrowed) incorporated in the echinoid-rich laminites.

indicates that the embayment area had restricted connection with open marine waters, which increased the potential and strength of tidal currents.

The accretion of stromatolites above the basement required an important transgressive event. This transgression was probably very quick and erosive, due to the lack of typical shales. In this context, the beginning of deposition of stromatolites may have occurred during transgression, which means that the maximum flood surface (MFS) is positioned in the lower part of the stromatolite fields. Overall, the deposition of most part of these microbialites represents the beginning of the upper regressive cycle (i.e., above the MFS of the second TR cycle), right after the formation of the shell beds in distal depositional settings and the deposition of the first stromatolites. This situation represents the stacking of laterally distinct sedimentary facies. At the time when shell beds were emplaced in inner shelf settings (offshore transition, between the storm and the fair-weather wave-base), stromatolites were thriving in shallow water embayments near the coastline at the western margin of the basin. With the beginning of the regressive stage, the sites where earlier on storm-wave concentrations formed were transformed into several

embayments surrounded by basement highs favoring the growth of microbialites.

As mentioned before, shell beds are not restricted to the storm-wave concentrations described above. In the town of Araripe, Ceará State, lag deposits of the Romualdo Formation were recorded directly above the basement rocks in the Hospital section (Fig. 2B). These represent amalgamated paucispecific shell beds composed of shallow-burrowing, suspension-feeding bivalves and mobile gastropods that probably inhabited shoreface bottoms. The shells are highly abraded, rounded, and sorted, suggesting deposition in a shallow, high-energy setting above the fair-weather wave-base. The composition of these shell beds distinctly differs from the bivalve-gastropod-rich beds, representing fair-weather concentrations in the shallower area of the embayment area.

In summary, during transgression, the coastal areas of the Araripe Basin were flooded generating embayments flanked by crystalline rock promontories. In this context, the MFS of the second TR cycle, represent a phase where embayment bottoms along the western margin of the basin were colonized by benthic invertebrates (mainly mollusks)

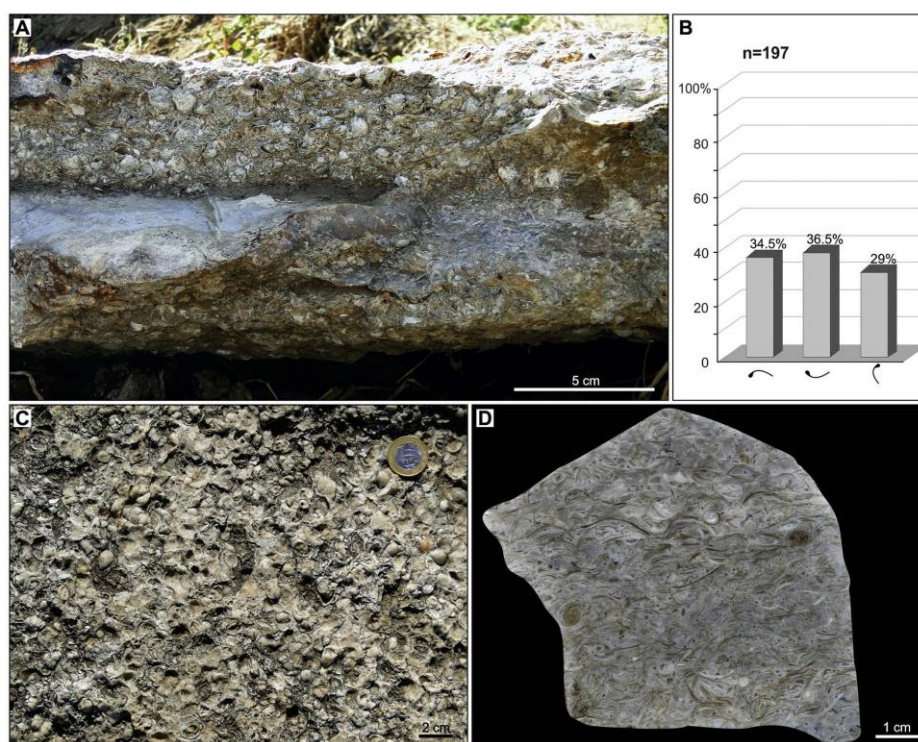


Fig. 13. Bivalve rudstone. A: Amalgamated shell beds. B: Predominantly disarticulated shells with few articulated individuals. C: Random orientation of bivalve shells.

and by the first stromatolites in the shallow zones. During the beginning of the subsequent regression ideal conditions existed for profuse stromatolite development. In this scenario echinoids colonized parts of mat-dominated bottoms in the embayments at the western margin of the Araripe Basin.

8. The shallow carbonate ramp of the Romualdo Formation – a Cretaceous analogue of the Shark Bay, Australia

The Hamelin Pool in Shark Bay World Heritage area, Western Australia, is a hypersaline-restricted embayment sectioned by several tidal channels (Jahnert and Collins, 2011, 2012). This particular area is famous for the great diversity of modern microbialites that were formed in response to sea-level fall after the Holocene transgression (Jahnert and Collins, 2011, 2013; Burne and Johnson, 2012). During this event, a near open marine system became a restricted embayment characterized by anomalous salinity (hypersaline), high alkalinity and evaporation rates. Such unusual environmental conditions restrict profuse benthic metazoan colonization of bay bottoms, enhancing the proliferation of microbial communities (Jahnert and Collins, 2011). Smooth stromatolites and thrombolites are common in the intertidal zone, and microbialites with cerebroid external morphology and non-laminated microbial internal fabric tend to occur in deeper waters associated with serpulids and other metazoans (Jahnert and Collins, 2011, 2012). Despite their marked variation in shape, the microbialites in Hamelin Pool exhibit internal morphologies indicating shallowing-upward carbonate cycles (Jahnert and Collins, 2011, 2013). The various microbial facies are commonly associated with bioclastic deposits and storm-

generated shell beds composed of bivalves in subtidal embayment areas or as beach ridges (Jahnert and Collins, 2011, 2012). The abundance of bivalve shells that proliferated within the embayment during the early stages of hypersalinity is striking (Jahnert and Collins, 2011).

As mentioned before, the Romualdo Formation encompasses a very thin carbonate succession that onlaps abruptly the igneous and metamorphic basement rocks at the western margin of the Araripe Basin (Fig. 14). These carbonate deposits consist mostly of bivalve, gastropod and echinoid rudstones, bioclastic grainstones and mudstones in association with microbialites. The great variety of microbialite morphologies just above the basement is a record of a shallowing-upward pattern with a regressive architecture after the widespread transgression that deposited bivalve/gastropod shell beds and at least part of the basal portion of the stromatolites, an analogous condition to the present-day Shark Bay. As discussed above, low-lying basement areas of the coastline were drowned during the marine transgression. Progressive sea level rise in these proximal and restricted areas resulted in embayments where low-diversity communities dominated by bivalves or gastropods thrived. When the sea-level started to rise at a slower rate, a regressive pattern took over and several restricted embayments formed favoring microbialite formation. Due to the high salinity, echinoids apparently were the only macrobenthic organisms that were able to thrive in this setting, most likely feeding on the stromatolites. Some burrowed inside the microbial mats where they finally became entombed. Others that grazed on the mat surface remained in their life position after death due to the sticky nature of the surface and were subsequently overgrown by microbial laminae. Thus, the preservation potential of the echinoids was very high despite their common subsequent

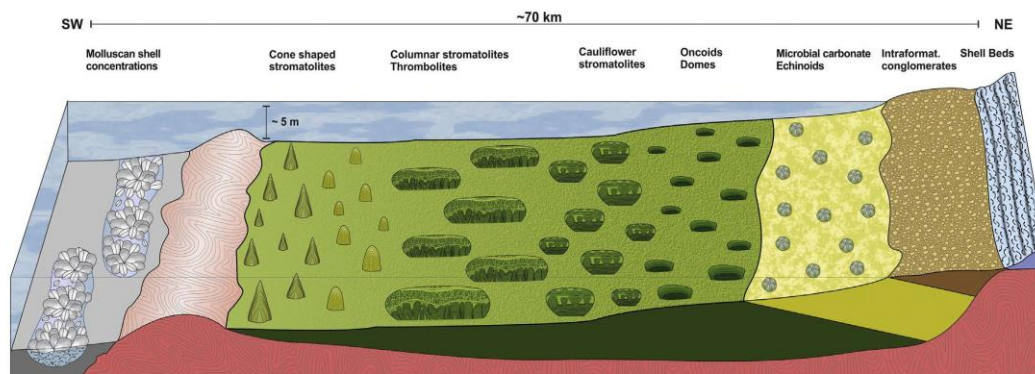


Fig. 14. Idealized block diagram of the stromatolite field at the westernmost occurrences of the Romualdo Formation onlapping on basement rocks.

compactional fragmentation (for further discussion on the microbial entombment processes see Iniesto et al., 2013). In these shallow areas, dead mollusks were repeatedly reworked by storm-induced waves and currents resulting in the formation of cm-thick shell beds that may have accumulated by fair-weather waves. Similarly, to the Hamelin Pool (Jahnert and Collins, 2011), abrasion, dissolution and microbial bioerosion of shells are thought to have been the most probable source of calcium ions for the stromatolite accretion, in an overall hypersaline condition.

In conclusion, part of the microbialites document the MFS in the western border of the Araripe Basin. The base of these deposits is here considered a transgressive surface. A probable erosive transgression likely removed shale deposits, which is revealed by a very thin MFS in the area. The overall regressive stacking of the great part of the stromatolites reveal that they are also part of the regressive cycle and can be considered a plausible analogue of the modern Hamelin Pool, Shark Bay, Australia. The here proposed model is coherent, if we assume a coastal setting where the stromatolites, echinoid-bearing microbialites, and shell beds generated by fair-weather conditions coexisted (Fig. 14).

9. Final remarks

The microbial facies herein described consist of diverse types of microbial mats, stromatolites, oncoids and thrombolites, arranged in shallowing-upward carbonate cycles. These suggest changes in water depth and hydraulic conditions during the deposition of the carbonate-dominated sedimentary succession. The co-occurrence of microbialites with autochthonous benthic invertebrates, especially echinoids indicated that these lived and thrived in the same environment where the microbial mats flourished, similar to what is observed in Hamelin Pool, Shark Bay, Australia. High salinity and elevated pH conditions both created stressful conditions that precluded the development of abundant and diverse metazoans that could proliferate on microbial mats environments. Such particular conditions allowed them to grow and form dm- to m-high bioconstructions. Various taphonomic and sedimentologic features indicate that only the echinoids lived in close association with the microbialites, probably using them as a source of food.

Finally, the record of several types of microbialites in the western part of the Araripe Basin represents the final stages of the last marine incursion during the Aptian. The stratigraphic position of these deposits in the upper part of the Romualdo Formation is coherent with the gradual migration of the coastal onlap to the west, reaching the most inland parts of the Cretaceous interior basins of the northeastern Brazil.

Acknowledgements

We would like to acknowledge the financial support by the São Paulo Research Foundation (FAPESP; grants 2016/13214-7, 2017/20803-1; 18/01750-7); Petrobras (2014/00519-9), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq; grants 444070/2013-1, 401039/2013-5, 1082 30017/2015-3, 152385/2016-9, 301294/2018-6). We thank Robert Burne and Ricardo Jahnert for their careful revision of the manuscript and very useful comments and corrections, which substantially improved the final version of this contribution. We also thank the Agência Nacional de Mineração (former Departamento Nacional de Produção Mineral, DNPM) for providing us with all fossil collecting permits and Celso Lira Ximenes for giving us information and pictures of the Alagoinha microbialite field. We are grateful to UNESPetro-UNESP for making its laboratories available for part of this research. F.G. Varejão, S.A. Matos and M.G. Rodrigues are FAPESP fellows; M.G. Simões, M.L. Assine, and L.V. Warren are CNPq fellows; and F.T. Fürsich was a CNPq-PVE fellow from 2015 to 2017.

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