



Universidade de Brasília
Instituto de Geociências
Programa de Pós-graduação em Geologia

FACIOLOGIA E GEOQUÍMICA DE ROCHAS DO GRUPO ALTO TAPAJÓS NO EXTREMO SUDESTE DO ESTADO DO AMAZONAS, BRASIL

**FACIOLOGY AND GEOCHEMISTRY OF
ALTO TAPAJÓS GROUP ROCKS IN THE
EXTREME SOUTHEAST OF AMAZONAS
STATE, BRAZIL**

João Gabriel Cavalcante Vieira

Dissertação de mestrado N° 523

Orientadora: Profa. Dra. Adriana Maria Coimbra Horbe

Brasília, 20/03/2024



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RESUMO

Este estudo apresenta dados petrográficos, de geoquímica elementar e isótopos de Nd em rocha total, ao longo de três seções de sondagens da porção noroeste da Bacia Alto Tapajós. A sucessão estudada hospeda uma ocorrência de fosfato com importância econômica regional. As seções compreendem uma porção lamosa-dolomítica basal, associada à Formação Terra Preta, e uma porção areno-lamosa, relacionada à Formação São Benedito. As associações de fácies e a paragênese mineral autigênica de siderita, glauconita, fluorapatita e pirita sugerem deposição em ambiente marinho raso dominado por tempestades, passando de plataforma externa para *shoreface* inferior. Dados geoquímicos suportam contexto tectônico de rifte intracratônico e algumas assinaturas colisionais podem ser herdadas das rochas fontes. As concentrações de Rb, Ba, Sr, Th, U, Zr, Hf, Y, Sc, V, Cr, Cu, Ni e Zn indicam fontes félsicas. Remobilizações eodiagênicas de ETR relacionadas à fluorapatita autigênica ocorreram ao longo das seções. As rochas afetadas não foram utilizadas para interpretações de proveniência baseadas em isótopos. As composições isotópicas de Nd, especialmente de lamitos e margas, sugerem proveniência da crosta continental superior e/ou do retrabalhamento de rochas sedimentares, com idades modelo variando de 2,32 a 2,49 Ga. As principais áreas fontes para a sucessão estão relacionadas às províncias Rondônia-Juruena, Tapajós-Parima e Amazônia Central. Uma marga apresentou idade modelo de 3,35 Ga, sugerindo possível contribuição de áreas fontes de maior distância, relacionadas às Províncias de Carajás e Transamazonas, ou de unidades proximais desconhecidas.

Palavras-chave: Bacia Alto Tapajós; Isótopos de Nd; Proveniência.

ABSTRACT

This study provides petrographic, whole-rock element and Nd isotope geochemical data for sedimentary rocks from three drill core sections in the extreme northwestern region of the Alto Tapajós Basin, Mid-South Amazonia, Brazil. The investigated succession hosts a phosphate occurrence with regional economic significance. The sections comprise a basal muddy-dolomitic portion, associated with the Terra Preta Formation, and an upper sandy-muddy portion, related to the São Benedito Formation. Facies associations suggest deposition in a shallow marine environment dominated by storm activity, from outer shelf to lower shoreface. Geochemical data support an intracratonic rift setting with some collisional signatures probably inherited from source rocks. Concentrations of Rb, Ba, Sr, Th, U, Zr, Hf, Y, Sc, V, Cr, Cu, Ni, and Zn indicate felsic sources. Early diagenetic REE redistributions related to authigenic fluorapatite occurred along the sections. Affected REE and isotopic compositions were not used for provenance considerations. Nd isotopic compositions, particularly of fine-grained rocks, suggest upper continental crust and/or recycled provenance, with model ages ranging from 2.32 to 2.49 Ga. The main source areas for the succession are related to Rondônia-Juruena, Tapajós-Parima, and Central Amazon Provinces. Notably, one marl sample exhibited a much older model age of 3.35 Ga, suggesting a possible contribution from more distal source areas, related to Carajás and Transamazon Provinces, or from unknown proximal units.

Keywords: Alto Tapajós Basin; Nd isotopes; Provenance.

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CAPÍTULO 1

INTRODUÇÃO

1 INTRODUÇÃO

A Bacia Alto Tapajós, localizada entre as províncias geocronológicas Tapajós-Parima e Rondônia-Juruena do Cráton Amazonas (Santos et al., 2000, 2008), é classificada como do tipo rifte intracratônico e compreende essencialmente rochas sedimentares siliciclásticas depositadas em zonas de falhas reativadas de direção NW-SE e NNE-SSW (Toczeck et al., 2019). Sua estratigrafia continua pouco compreendida, devido às dificuldades de realização de trabalhos de mapeamento geológico na Amazônia. Desde a década de 80 a partir do Projeto RADAM foram propostos alguns quadros estratigráficos que necessitam de maior atenção e detalhamento.

1.1 Justificativas e objetivos

O objeto de estudo deste trabalho compreende seções em subsuperfície do Grupo Alto Tapajós, acessadas por meio de sondagens no segmento extremo noroeste da Bacia Alto Tapajós, sudeste do Estado do Amazonas, Brasil. A sucessão compreende rochas das formações Terra Preta e São Benedito. Tanto a bacia quanto as unidades carecem de estudos e diante das ocorrências de agrominerais/remineralizadores, como o fosfato, glauconita e rochas dolomíticas, sua melhor compreensão é crucial. Trabalhos recentes sobre a Bacia Alto Tapajós deram início ao seu melhor entendimento (Motta et al., 2016; Simões et al., 2021; Toczeck et al., 2019; Albuquerque et al., 2023), entretanto, ainda não há estudos em seções que alcancem maiores profundidades.

Foram utilizadas petrografia, geoquímica elementar e isotópica para a melhor compreensão do sistema deposicional, proveniência, contexto geotectônico e de processos pós-deposicionais ao longo de sondagens de até 200 m de profundidade. Ao todo foram estudadas 19 sondagens, das quais 3 foram escolhidas para a realização das análises geoquímicas. A avaliação da ocorrência de fosfato para a exploração não é abordada, mas os resultados podem ser úteis na questão.

1.2 Localização da área de estudo

A área de estudo encontra-se no extremo sudeste do estado do Amazonas, à sudoeste da sede do município de Apuí (AM) e ao longo da margem norte do médio curso do rio Jatuarana (Figura 1.1). Neste local foram realizadas sondagens pela empresa FASA – Fertilizantes da

Amazônia S.A., que colaborou com o trabalho de campo e cedeu amostras das sondagens para a realização deste trabalho.

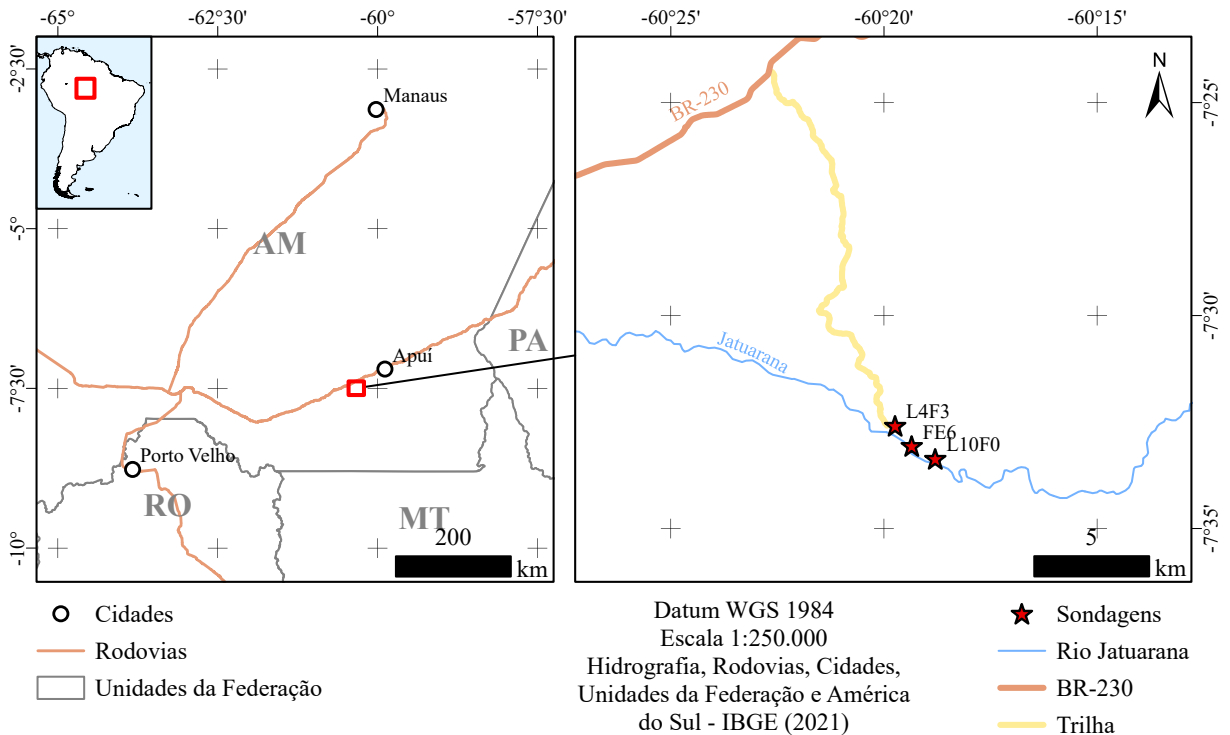


Figura 1.1: Localização da área de estudo.

1.3 Estrutura da dissertação

A dissertação é dividida em seis capítulos. Este primeiro apresenta os objetivos, justificativas e a área de estudo. O Capítulo 2 contém um breve referencial teórico para a melhor compreensão do texto. O Capítulo 3 resume brevemente a evolução do conhecimento sobre a Bacia Alto Tapajós e o contexto geológico da área de estudo. O Capítulo 4 apresenta os resultados e discussões, na forma de artigo. Por fim, o Capítulo 5 refere-se as considerações finais.

CAPÍTULO 2

REFERENCIAL TEÓRICO

2 REFERENCIAL TEÓRICO

2.1 Proveniência Sedimentar

Estudos de proveniência sedimentar investigam a origem dos sedimentos, a localização e a natureza das áreas fontes, os caminhos pelos quais foram transportados até o local de deposição e os processos pós-deposicionais que podem influenciá-los (Haughton et al., 1991). Estes estudos são úteis em reconstruções paleogeográficas e paleoclimáticas, investigações indiretas de rochas não expostas na superfície atualmente, testar modelos tectônicos, mapear sistemas deposicionais, estabelecer correlações estratigráficas, prever a qualidade de reservatórios e, em escala global, no estudo da evolução crustal (Haughton et al., 1991; McLennan et al., 1993; Rudnick and Gao, 2013).

Inicialmente, os estudos de proveniência sedimentar eram limitados ao uso de diagramas discriminatórios baseados na composição de arenitos, avaliando os fragmentos líticos em conglomerados, por análises de minerais pesados e de paleocorrentes (Dickinson and Suczek, 1979). Atualmente, o uso de ferramentas geoquímicas e isotópicas, aliadas as abordagens clássicas, permitem a resolução de problemas complexos em proveniência de forma acurada (McLennan et al., 1993).

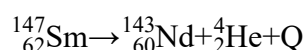
A escolha da abordagem em um estudo de proveniência depende da granulometria do material e dos dados disponíveis na literatura sobre as possíveis fontes para a comparação. Esses parâmetros influenciam a direção que o estudo de proveniência sedimentar tomará (Haughton et al., 1991). Além disso, é crucial levar em consideração que os processos pós-deposicionais podem afetar significativamente a composição das rochas sedimentares, por meio da influência de processos como intemperismo, erosão, abrasão, seleção e diagênese na modificação da composição dos sedimentos ao longo do tempo (McLennan et al., 1993).

2.2 Sistema Sm-Nd

A aplicação dos isótopos de Sm-Nd na proveniência de rochas sedimentares fundamenta-se na premissa de que os sedimentos siliciclásticos consistem em fragmentos de rochas ígneas, metamórficas e sedimentares mais antigas. Considera-se que grandes extensões dos continentes normalmente têm assinaturas isotópicas relativamente semelhantes e de certa forma definidas. A partir da erosão das áreas fontes, os sedimentos são carregados e depositados em novos locais. Caso não haja alteração isotópica pós-deposicional, os depósitos resultantes mantêm a

assinatura das áreas de origem. Assim, ao identificar prováveis fontes e conhecer suas razões isotópicas, é possível restringir a origem dos sedimentos (McCulloch and Wasserburg, 1978; DePaolo, 2012).

Neste contexto, o Sm e Nd são elementos terras raras leves, que ocorrem como traços em minerais formadores de rocha. Os dois elementos têm sete isótopos de ocorrência natural. O ^{147}Sm é radioativo e o único dos isótopos de Sm utilizado em estudos de geoquímica isotópica, por sua meia-vida relativamente curta. Ele decai por emissão de partículas α para o isótopo de ^{143}Nd :



Em que He é a partícula alpha e Q é a energia de decaimento.

O sistema Sm-Nd tem um longo tempo de meia-vida ($T_{1/2} = 1,06 \times 10^{11}$ anos, $\lambda = 6,54 \times 10^{-12} \text{ anos}^{-1}$) e é útil para datar rochas, meteoritos e como traçador de processos geológicos. A composição isotópica de Nd, em um sistema fechado, é comumente expressa pela razão $^{143}\text{Nd}/^{144}\text{Nd}$, que aumenta em função do tempo de decaimento de ^{147}Sm , de acordo com a equação:

$$\frac{^{143}\text{Nd}}{^{144}\text{Nd}} = \left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_i + \frac{^{147}\text{Sm}}{^{144}\text{Nd}} (e^{\lambda t} - 1)$$

O comportamento geoquímico desses elementos é efeito da contração dos lantanídeos, que leva ao particionamento preferencial do Nd para a fases líquidas, assim, as rochas da crosta continental são enriquecidas em Nd. O particionamento preferencial de Sm para fases sólidas residuais durante a fusão parcial no manto causa o seu enriquecimento em ^{143}Nd radiogênico (DePaolo, 2012; Faure and Mensing, 2005).

A evolução isotópica de Nd da Terra pode ser descrita em relação ao *chondritic uniform reservoir* (CHUR) (DePaolo and Wasserburg, 1976a, 1976b). O modelo de evolução isotópica para a Terra assume que a composição isotópica de Nd do manto evoluiu a partir de um reservatório uniforme no qual a razão Sm/Nd é igual a de condritos (Figura 2.1). A razão $^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}}$ em qualquer tempo t no passado pode ser calculada a partir da equação:

$$\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_{\text{CHUR}}^0 = \left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_{\text{CHUR}}^i + \left(\frac{^{147}\text{Sm}}{^{144}\text{Nd}} \right)_{\text{CHUR}}^0 (e^{\lambda t} - 1)$$

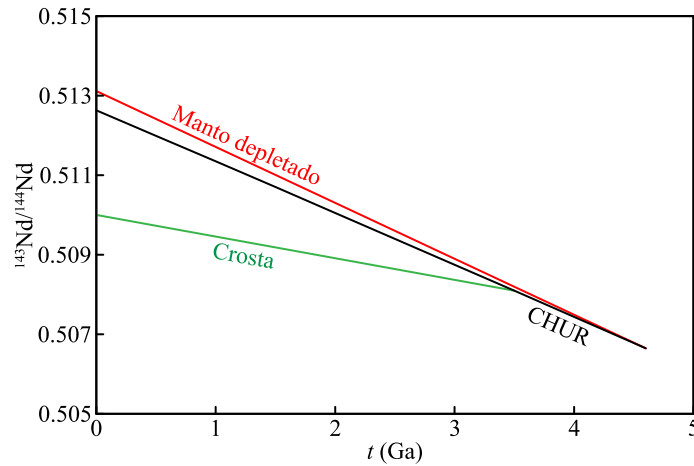


Figura 2.1. Diagrama da evolução da razão $^{143}\text{Nd}/^{144}\text{Nd}$ em função do tempo para o manto e uma crosta hipotética a partir do CHUR (DePaolo and Wasserburg, 1976a).

Devido as razões de $^{143}\text{Nd}/^{144}\text{Nd}$ terem variações pequenas, as razões das rochas são normalmente expressas de forma conveniente como desvios da razão do CHUR, pela notação ϵNd (DePaolo and Wasserburg, 1976a):

$$\epsilon\text{Nd}(t) = \left[\frac{(^{143}\text{Nd}/^{144}\text{Nd})_R^t - (^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}^t}{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}^t} \right] \times 10^4$$

Os valores de $\epsilon\text{Nd}(t)$ para rochas podem ser positivos, negativos ou zero. Valores positivos implicam que o material é derivado de uma fonte com razão Sm/Nd maior que a do CHUR, assim, de uma fonte mantélica (radiogênica). Valores negativos indicam derivação de fontes menos radiogênicas ou a partir da fusão de rochas crustais, com razões Sm/Nd menores do que o CHUR. Em resumo, rochas ígneas derivadas de fontes mantélicas têm valores positivos de $\epsilon\text{Nd}(t)$, enquanto rochas da crosta continental têm $\epsilon\text{Nd}(t)$ negativos.

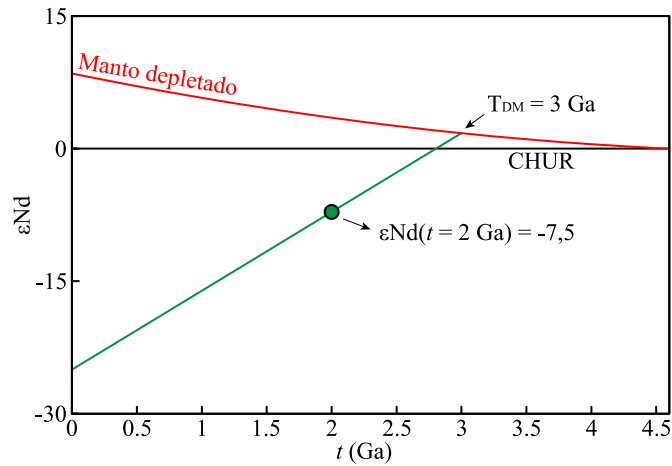


Figura 2.2. Diagrama de ϵNd em função do tempo, mostrando a curva de evolução do manto depletado e de uma rocha derivada da fusão de rochas crustais com T_{DM} de 3 Ga e $\epsilon\text{Nd}(t = 2 \text{ Ga})$ de -7,5 (DePaolo, 1981; DePaolo and Wasserburg, 1976b).

Outra forma útil de utilizar dados isotópicos é a idade modelo (T_{DM}) (Figura 2.2), que representa o tempo passado desde a extração a partir do manto depletado, ou seja, o tempo médio de residência crustal. Em estudos de proveniência sedimentar, considera-se que a idade modelo de um sedimento ou rocha sedimentar é a média ponderada do tempo de residência crustal de suas fontes contribuintes (McCulloch and Wasserburg, 1978). A idade modelo é dada pela equação:

$$T_{\text{DM}} = \frac{1}{\lambda} \ln \left[\frac{(\text{}^{143}\text{Nd}/\text{}^{144}\text{Nd})_{\text{R}}^0 - (\text{}^{143}\text{Nd}/\text{}^{144}\text{Nd})_{\text{DM}}^0}{(\text{}^{147}\text{Sm}/\text{}^{144}\text{Nd})_{\text{R}}^0 - (\text{}^{147}\text{Sm}/\text{}^{144}\text{Nd})_{\text{DM}}^0} + 1 \right]$$

CAPÍTULO 4

CONTEXTO GEOLÓGICO

3 CONTEXTO GEOLÓGICO

3.1 Cráton Amazônico

O Cráton Amazônico é um dos maiores e menos conhecidos terrenos pré-cambrianos do mundo, limitado a leste pelo Sistema Orogênico do Tocantins, a nordeste pela Província Margem Continental Equatorial, e a oeste por bacias fanerozoicas periandinas (Santos et al., 2000, 2008; Almeida et al., 2016). Atualmente, há duas principais compartimentalizações para o Cráton com base em dados geocronológicos, os modelos propostos por Tassinari e Macambira (1999) e Santos et al. (2000). O último modelo é o utilizado neste trabalho, por basear-se em um maior número de dados isotópicos de Sm-Nd e ter sido utilizado nos trabalhos mais recentes sobre a Bacia Alto Tapajós (Toczeck et al., 2019; Albuquerque et al., 2023). Este modelo foi posteriormente modificado por Santos et al. (2008) e divide o Cráton Amazônico nas seguintes províncias geocronológicas: Carajás (3.0-2.5 Ga); Amazônia Central (Arqueano?); Transamazônia (2.26-2.10 Ga); Tapajós-Parima (2.03-1.88 Ga); Rio Negro (1.82-1.52 Ga); Rondônia-Juruena (1.82-1.54 Ga); e Sunsás-K'Mudku (1.45-1.10 Ga) (Figura 4.1).

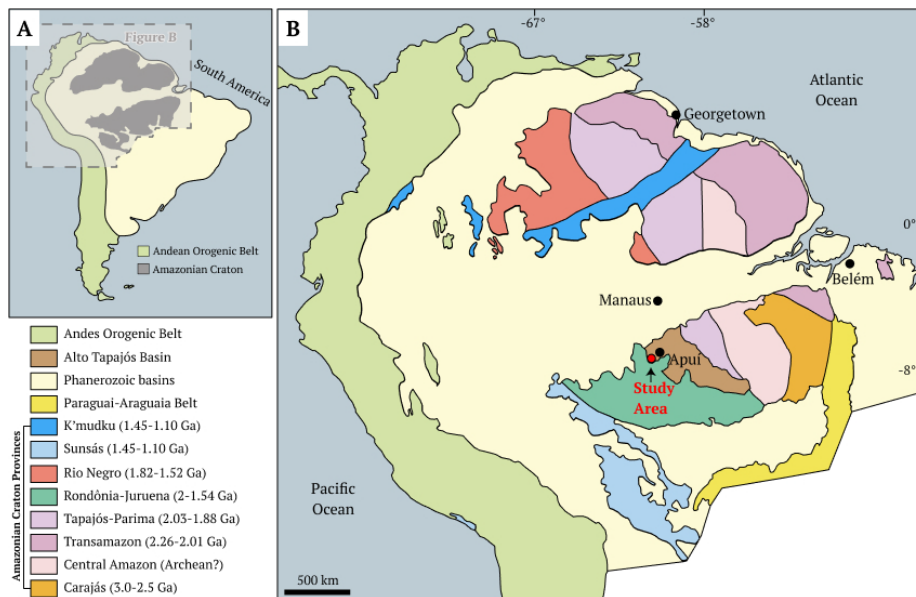


Figura 3.1. A) Mapa da América do Sul com a localização do Cráton Amazônico. B) Mapa da localização da área de estudo em relação ao Cráton Amazônico, suas províncias geocronológicas e a Bacia Alto Tapajós (adaptado de Santos et al., 2008).

Entre as províncias Tapajós-Parima e Rondônia-Juruena, encontra-se a Bacia Alto Tapajós (Figura 3.1), que ocupa uma área aproximada de 97,000 km². Segundo Toczeck et al. (2019), a Bacia é do tipo rifte intracratônico e composta essencialmente por rochas sedimentares siliciclásticas paleozoicas depositadas em zonas de reativação de falhas normais de orientação NW-SE e falhas oblíquas NNE-SSW.

Acredita-se que a instalação da bacia se iniciou no Eopaleozoico com a reativação de um rifte precursor, onde se depositou a sucessão vulcanossedimentar do Grupo Beneficente (~1.7 Ga). Entre o Devoniano e o Permiano ocorreria subsidência da bacia a partir de um rifteamento passivo. Durante o Jurássico, ocorre um evento tectono-termal, relacionado a fragmentação do Pangeia e expansão da *Central Atlantic Magmatic Province* (CAMP), quando houve a intrusão dos enxames de diques máficos (180 – 220 Ma). O relevo positivo e a ausência de depósitos cenozoicos, em contraste com a Bacia do Amazonas, indicam soerguimento da região (Toczeck et al., 2019).

3.2 Bacia Alto Tapajós

A estratigrafia da Bacia Alto Tapajós é pouco compreendida, devido à falta de trabalhos de mapeamento geológico e dados de subsuperfície, e desde a década de 80 foram propostos alguns quadros estratigráficos. Inicialmente, Santiago et al. (1980) separa dez unidades para a Bacia Alto Tapajós, a partir de trabalhos de campo na área da porção meridional da Amazônia Brasileira, entre os estados do Amazonas, Pará e Mato Grosso, abrangendo parte das bacias dos rios Tapajós, Juruena e Teles Pires. Assim, a sucessão da bacia foi estabelecida somente no flanco norte, a partir de estudos ao longo da BR-230 e do rio Juruena.

Santiago et al. (1980) estimou espessura de 1.700 m para a sucessão estudada, separando-a em duas sequências: a basal, Formação Palmares, de ambiente continental e rápida deposição, tectonicamente dobrada e admitida como cobertura de plataforma, correlata ao Grupo Beneficente. As demais formações seriam de ambiente predominantemente marinho, pouco perturbadas tectonicamente e depositadas em bacia intracratônica durante o Paleozoico. Da base para o topo, a sequência paleozoica é composta pelas seguintes formações e unidades informais: Formação Borrachudo; Formação Capoeiras; Formação São Benedito; Formação Ipixuna; Unidades F e G; Formação Navalha; e Unidades I e J.

Posteriormente, a denominação Grupo Jatuarana (Bizinella et al., 1980) foi proposta para reunir numa mesma unidade somente a sequência siluro-devoniana, que compreenderia as formações Borrachudo, Capoeiras e São Benedito. Bizinella et al. (1980) formaliza o grupo sobre o pretexto das unidades serem retratadas de modo indiviso na área do rio Jatuarana. O quadro estratigráfico proposto por Bizinella et al. (1980) não considera a existência das unidades informais I e J. Posteriormente, em levantamento na região do alto curso do rio Tapajós, Reis et al. (2006a) amplia o grupo para conter também as formações Ipixuna, Navalha e Providência.

Reis et al. (2006b) estabelece um quadro litoestratigráfico com base em duas regiões para a Bacia Alto Tapajós: (i) Alto curso do rio Tapajós e baixo curso dos rios Juruena e Teles Pires; e (ii) Médio curso dos rios Jatuarana, Juma, Acari e médio-alto curso dos rios Sucunduri e Camaiú. A região do rio Tapajós compreenderia as formações Capoeiras, São Benedito, Ipixuna, Navalha e Providência, previamente estabelecidas (Santiago et al., 1980; Bizinella et al., 1980; N. Reis et al., 2006); enquanto a região do rio Jatuarana compreenderia as formações Juma, Prainha e Terra Preta (Reis, 2006). Reis (2006) e Reis et al. (2006b) rebaixam o Grupo Beneficente à nível de formação e o consideram de idade paleozoica, assim, pertencente a Bacia Alto Tapajós. Posteriormente, idades U-Pb em zircão de vulcânicas félsicas comprovaram idade pré-cambriana para o Grupo Beneficente (Reis et al., 2013; Simões et al., 2020). Reis (2006) propõe o Grupo Alto Tapajós em substituição ao Grupo Jatuarana, reunindo as propostas litoestratigráficas das porções a oeste e leste do rio Tapajós.

Em estudo no extremo sudeste do estado do Amazonas, Simões et al. (2021) rebaixa as formações Borrachudo e São Benedito à membros da Formação Juma. Aqui não serão discutidas as mais recentes redefinições das unidades, prezando-se o resgate das primeiras nomenclaturas. Abaixo estão descritas as unidades que compõem a Bacia Alto Tapajós, a partir da proposta estratigráfica de Santiago et al. (1980), modificada por Bizinella et al. (1980) e adicionando a Formação Terra Preta de Reis (2006), que foi reposicionada a base da Bacia Alto Tapajós (Meloni et al., 2021).

3.2.1 Formação Terra Preta

A Formação Terra Preta foi proposta por Reis (2006) para reunir calcários, em parte estromatolíticos, de cores cinza escuras, compostos por cristais de pseudoesparita de cerca de 5 mm, cortados por vênulas e veios de calcita e magnesita, com sulfetos de ferro e cobre

disseminados e substituição parcial de sílica. Nas porções com maior abundância de opacos, laminações irregulares foram interpretadas como esteiras microbianas. Ocorrem ainda, em menor volume, rochas terrígenas intercaladas às carbonáticas.

A unidade teria se depositado em ambiente marinho raso de inframaré, propício ao desenvolvimento de recifes. Reis (2006) sugere associação com as fácies de intermaré da Formação Prainha (correlata a Formação Ipixuna). Inicialmente a unidade é proposta como correlata a Formação Navalha (Reis, 2006). Posteriormente é retratada como a unidade basal da Bacia Alto Tapajós no Mapa Geológico do Sudeste do Amazonas (Meloni et al., 2021).

3.2.2 Formação Borrachudo

A Formação Borrachudo tem como localidade-tipo a bacia do igarapé Borrachudo, afluente da margem esquerda do rio Tapajós (Santiago et al., 1980). A unidade é composta essencialmente por arenitos finos com níveis carbonosos e intercalações de siltitos. Os arenitos são cinza escuros, micáceos, caulíníticos, de matriz argilosa e intercalados com siltitos argilosos cinza claros a creme. As rochas da unidade têm icnofósseis e gretas de contração preenchidas por areia fina (Santiago et al., 1980).

Estimou-se uma espessura mínima de 200 m para a Formação Borrachudo. A deposição da unidade ocorreu em ambiente marinho costeiro com influência fluvial e o seu conteúdo de palinomorfos indicaria idade siluro-devoniana (Santiago et al., 1980).

3.2.3 Formação Capoeiras

A Formação Capoeiras tem seção-tipo nos travessões Capoeiras e Chacorão do rio Tapajós. O nome da unidade foi dado com base no trecho das corredeiras Capoeiras, que se iniciam a cerca de 95 km a montante de Jacareacanga, onde a unidade foi originalmente descrita. Ela compreende arenitos intercalados com siltitos e argilitos avermelhados, ambos com marcas onduladas e raras gretas de contração. Os arenitos são geralmente quartzo-arenitos brancos e avermelhados, finos e bem selecionados. Em alguns afloramentos ocorrem siltitos e argilitos vermelhos intercalados esparsamente com os arenitos (Bizinella et al., 1980; Santiago et al., 1980). Posteriormente Reis et al. (2006b) descreve quartzo-arenitos róseos, friáveis, de granulação média, com estratificações cruzadas acanaladas de pequeno a médio porte. Os

pacotes arenosos comumente têm marcas onduladas assimétricas de variável direção e comprimento de onda (2 a 6 cm) para o topo. Espessura estimada entre 100 e 120 m.

Santiago et al. (1980) interpreta que a unidade constituiria fácies de intermaré, sob condições de maior recuo da beira-mar que a Formação Borrachudo, mas não descarta possibilidade de deposição em sistema fluvial.

O icnofóssil *Palaeophicus sp.* é reconhecido na unidade, e seria indicativo de ambiente marinho (Reis et al. 2006b). Reis et al. (2006b) interpreta deposição em ambiente flúvio-deltaico com domínio de marés. Quartzo-arenitos com geometria de lobos sigmoides e marcas onduladas seriam relacionados a fácies proximal da unidade, enquanto aqueles com bioturbações e marcas onduladas de interferência comporiam a fácies distal.

3.2.4 Formação São Benedito

A Formação São Benedito tem localidade-tipo no Morro São Benedito, à margem esquerda do rio Tapajós. Ela foi reconhecida inicialmente na bacia do igarapé Mingau para compreender siltitos e folhelhos com matéria carbonosa e quartzo-arenitos intercalados (Santiago et al., 1980). Bizinella et al. (1980) estende a ocorrência da unidade para a bacia do rio Jatuarana e a inclui de forma indivisa das formações subjacentes no Grupo Jatuarana.

A unidade é composta predominantemente por folhelhos e siltitos, geralmente cinza escuros ou claros, por vezes levemente esverdeados, e quartzo-arenitos finos, compactos, cinza escuros, às vezes com pirita, que formam delgadas intercalações com os lamitos. São reportados arenitos glauconíticos, intercalados com siltitos microfossilíferos (Bizinella et al., 1980).

Reis et al. (2006b) descreve a unidade como um pacote de arenitos e siltitos intercalados, silicificados, finamente laminados e com arenitos de maior espessura para o topo da sequência. Lateralmente ao Morro São Benedito, os ritmitos gradam para pacotes de quartzo-arenitos maciços de aproximadamente 1 m de espessura, por vezes, intercalados com camadas métricas de arenitos e siltitos finamente laminados.

Sob a nomenclatura de Formação Juma, Reis (2006) reúne um espesso pacote sedimentar de siltitos e arenitos finos intercalados, que ocorrem na bacia do rio Juma. Os siltitos e arenitos finos são acinzentados, compactos, com marcas onduladas assimétricas e por vezes silicificados. A alternância de níveis centimétricos de colorações acinzentadas claras e escuras configuram laminações, com uma discreta ondulação no topo dos sets. As camadas têm por

vezes fosfato, glauconita e sulfetos disseminados, o que sugere ambiente marinho. Os níveis areníticos em lâmina delgada são formados principalmente por grãos de quartzo, feldspato e nódulos de material fosfático. Os componentes fosfáticos são amarronzados e correspondem a pelóides e raros oóides.

Estima-se 120 m de espessura para a Formação São Benedito (Santiago et al., 1980; Bizinella et al., 1980). Santiago et al. (1980) interpreta que a Formação São Benedito corresponderia a depósitos de ambiente sublitorâneo epinerítico. Reis et al. (2006b) afirma que os arenitos maciços seriam depósitos de frente deltaica (progradação deltaica da sobrejacente Formação Ipixuna sobre fácies prodelta/turbidítica São Benedito).

Reis (2006) interpreta a Formação Juma como depositada em uma extensa e espessa planície lamosa gerada a partir do gradativo afogamento (transgressão marinha). De forma marginal a planície, desenvolveram-se áreas de intermaré da sobrejacente Formação Prainha. A espessura ao longo do rio Juma é estimada em 50 metros. Contudo, na região do alto curso do rio Sucunduri, baseando-se em furos de sondagem, a unidade apresenta maior espessura, em torno de 150 a 250 metros.

Apesar do potencial fossilífero, a unidade teve apenas algumas amostras de siltitos e folhelhos investigadas para a identificação de palinomorfos por N. M. da Costa Cruz. De acordo com os dados palinológicos, a unidade provavelmente depositou-se no Siluriano ou Devoniano, ou entre o Carbonífero e Permiano. Amostras da margem direita do rio Jatuarana teriam indícios de graptozoários, mais precisamente, estruturas de *climacograptus* (Bizinella et al., 1980).

3.2.5 Formação Ipixuna

A Formação Ipixuna tem a Bacia do igarapé Ipixuna como localidade-tipo. Proposta para compreender quartzo-arenitos sobrejacentes a Formação São Benedito. Ela tem ampla distribuição geográfica, ocorrendo nos terrenos da bacia hidrográfica do igarapé Ipixuna e de seus afluentes nas altas vertentes do vale do rio Tapajós (Santiago et al., 1980; Bizinella et al., 1980). A unidade é constituída essencialmente por quartzo-arenitos finos e por vezes médios, brancos e vermelhos. Eles são bem selecionados e tem marcas onduladas, gretas de contração, estratificações cruzadas e plano-paralelas, nem sempre distintas (Santiago et al., 1980).

Reis et al. (2006b) reporta que os arenitos têm geometria tabular ou de lobos sigmoides, estratos cruzados acanalados de pequeno porte, marcas onduladas simétricas bifurcadas e

assimétricas. Também afloram ritmitos, de arenitos finos e siltitos intercalados, finamente laminados, por vezes silicificados, com marcas onduladas e bioturbações.

Embora a Formação Ipixuna possa truncá-las, não são observados contatos discordantes com as unidades subjacentes. Santiago et al. (1980) interpreta que haveria discordância com a Formação São Benedito, pelo fato de a Formação Ipixuna recobrir também as formações Capoeiras, Borrachudo e o Grupo Beneficente. Estima-se espessuras mínimas de 140 (Santiago et al., 1980) e 160 m (Bizarella et al., 1980) para a unidade.

Interpreta-se idade paleozoica pós-devoniana para a Formação Ipixuna. Santiago et al. (1980) aponta duas hipóteses para a deposição da Formação Ipixuna. A primeira seria em ambiente continental, sugerido pelas características litológicas e estruturas primárias: quartzoarenitos com óxidos de ferro, gretas de ressecamento, marcas onduladas e estratificação cruzada. A segunda hipótese compreende deposição em ambiente marinho raso, na zona de supamaré, com exposições subaéreas para a formação das gretas de ressecamento. A maturidade e boa seleção dos arenitos demonstram longo retrabalhamento dos sedimentos e assim, estabilidade na plataforma, o que é mais favorável ao ambiente marinho litorâneo.

Sob a nomenclatura de Formação Prainha, Reis (2006) descreve quartzoarenitos silicificados e friáveis, de cores rosadas, avermelhadas, esbranquiçadas e acinzentadas, de granulometria areia média a fina. As principais estruturas encontradas são estratificações cruzadas acanaladas de médio a grande porte (0,5 a 5 m) e marcas onduladas assimétricas de comprimento de onda centimétrico variável, bifurcadas ou não. Subordinadamente, há laminação interna plano-paralela e estratificação cruzada tipo espinha de peixe. Há o registro de algumas exposições de brechas silicosas, na forma de blocos e matacões. As brechas têm microlentes de material silteoso envolto pela matriz cristalina e cavidades centimétricas, semelhantes às drusas. Ao topo da unidade ocorrem arenitos finos e siltitos intercalados, ambos silicificados de colorações rosadas, arroxeadas ou esbranquiçadas. São comuns as marcas onduladas assimétricas. Reis (2006) estima espessura entre 100 e 150 m para a Formação Prainha e interpreta deposição em intermaré.

3.2.6 Unidade F

A Unidade F localiza-se entre os baixos cursos dos rios Cururu e Teles Pires, estendendo-se para oeste, até o rio Tapajós. A unidade compreende arenitos vermelhos na base, com

manchas esbranquiçadas e cimento carbonático, calcário vermelho e brecha sedimentar, composta por fragmentos de siltitos, argilitos e estromatólitos, brancos e envoltos por chert marrom (Santiago et al., 1980).

3.2.7 Unidade G

A Unidade G foi reconhecida entre os cursos dos rios Bararati e Juruena e em suas confluências com o rio Tapajós. A unidade compreende quartzo-arenitos que afloram como lajes e blocos métricos tabulares. Os arenitos são finos de cor creme a levemente rosados, bem selecionados, de grãos subarredondados, cimento silicoso, maciços, pouco friáveis e com manchas escuras, interpretadas como ferríferas (Santiago et al., 1980).

3.2.8 Formação Navalha

A Formação Navalha foi inicialmente descrita nos rios Juruena e Bararati, compreendendo arenitos rosa com cimento calcítico, siltito calcífero cinza claro e calcário nas cores cremes e cinza claro (Santiago et al., 1980). Reis et al. (2006b) reporta a unidade na serra Navalha como terrígena na base, com intercalação de arenitos e siltitos avermelhados, finamente laminados. Os ritmitos teriam até 3 m de espessura. A maior parte da Serra seria formada por calcilito acinzentado claro a escuro, intensamente silicificado e com pirita disseminada.

3.3 Geologia Local

A área de estudo insere-se na porção noroeste da Bacia do Alto Tapajós (Figura 3.2), onde as formações Borrachudo e São Benedito recobrem o substrato pré-cambriano do Domínio Juruena ou *Western Amazonia Igneous Belt* (Scandolara et al., 2017; Rizzotto et al., 2019), Província Rondônia-Juruena (Santos et al., 2000; Santos, 2003; Santos et al., 2006, 2008). O embasamento da área de estudo compreende: metassiltitos com intercalações arenosos e argilosas da Formação Abacaxis (>1,85 Ga), granitoides orosirianos (1,85 -1,83 Ga), rochas vulcânicas félsicas e máficas subordinadas do Grupo Colíder (1,82 – 1,78 Ga), granitoides estaterianos alcalinos a subalcalinos das suítes intrusivas Igarapé das Lontras e Teodósia (1,76 – 1,75), paragnaisses do Complexo Quatro Cachoeiras (~1,75 Ga), rochas vulcanossedimentares do Grupo Beneficente (~1,74 Ga) (Simões et al., 2021, 2020), granitoides

tipo-A da Suíte Serra da Providência (1,57-1,53 Ga), Suíte Mata-Matá (1,57 – 1,54 Ga), e Formação Prainha (Mesoproterozoico) (Scandolaro et al., 2017; Rizzotto et al., 2019; Simões et al., 2020, 2021; Albuquerque et al., 2023).

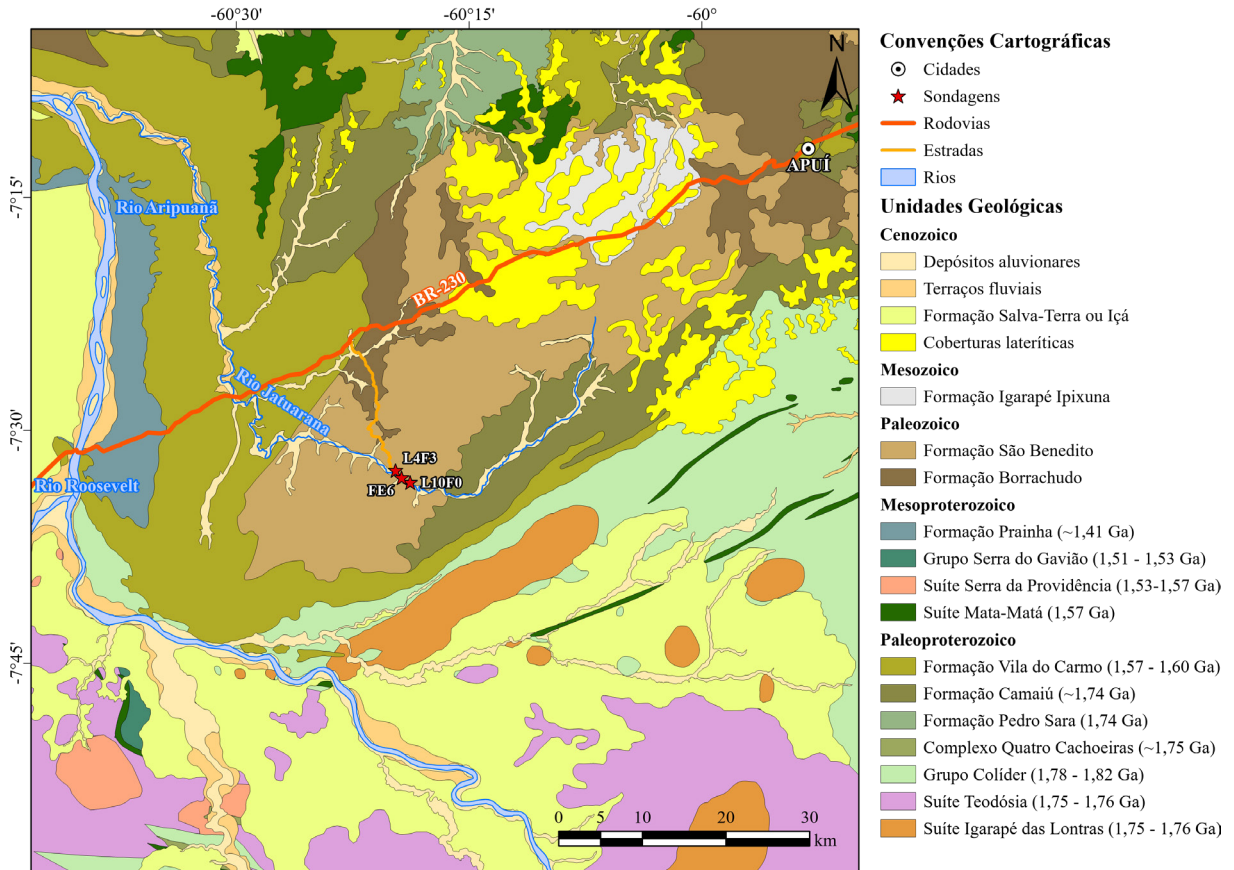


Figura 3.2. Mapa das unidades geológicas locais, adaptado de Meloni et al. (2021).

3.4 Proveniência

Em estudo pioneiro utilizando geoquímica elementar e isótopos de Sr, Nd e Pb, com o objetivo de determinar a proveniência e deduzir a evolução geológica regional durante o Proterozoico e Paleozoico, Albuquerque et al. (2023) restringem as prováveis fontes contribuintes para as sucessões sedimentares no sudoeste do Cráton Amazonas. O trabalho identifica derivação a partir do retrabalhamento das rochas locais (principalmente Grupo Colíder e granitóides orosirianos-estaterianos) da Província Rondônia-Juruena e do Grupo Beneficente, para as formações Borrachudo e São Benedito.

CAPÍTULO 4

RESULTADOS

4 RESULTADOS – ARTIGO CIENTÍFICO

Os resultados do estudo serão apresentados a seguir na forma de artigo, que será submetido a revista “Chemical Geology” ou “Journal of South American Earth Sciences”.

PROVENANCE AND REE REDISTRIBUTION OF A PHOSPHATIC SUCCESSION, ALTO TAPAJÓS GROUP, MID-SOUTH AMAZONIA, BRAZIL

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ABSTRACT

This study provides petrographic, whole-rock element and Nd isotope geochemical data for sedimentary rocks from three drill core sections in the extreme northwestern region of the Alto Tapajós Basin, Mid-South Amazonia, Brazil. The investigated succession hosts a phosphate occurrence with regional economic significance. The sections comprise a basal muddy-dolomitic portion, associated with the Terra Preta Formation, and an upper sandy-muddy portion, related to the São Benedito Formation. The facies associations suggest deposition in a shallow marine environment dominated by storm activity, from outer shelf to lower shoreface. Geochemical data support an intracratonic rift setting with some collisional signatures probably inherited from source rocks. Concentrations of Rb, Ba, Sr, Th, U, Zr, Hf, Y, Sc, V, Cr, Cu, Ni, and Zn indicate felsic sources. Early diagenetic REE redistributions related to authigenic fluorapatite occurred along the sections. Affected REE and isotopic compositions were not used for provenance considerations. Nd isotopic compositions, particularly of fine-grained rocks, suggest upper continental crust and/or recycled provenance, with model ages ranging from 2.32 to 2.49 Ga. The main source areas for the succession are related to Rondônia-Juruena, Tapajós-Parima, and Central Amazon Provinces. Notably, one marl sample exhibited a much older model age of 3.35 Ga, suggesting a possible contribution from more distal source areas, related to Carajás and Transamazon Provinces, or from unknown proximal units.

Keywords: Alto Tapajós Basin; Neodymium isotopes; Whole-rock geochemistry.

1. Introduction

Geochemical and isotopic techniques are potent tools for exploring the tectonic settings, provenance, and post-depositional processes that influenced sedimentary rocks (Dickinson and Suczek, 1979; Dickinson et al., 1983; Bhatia and Crook, 1986; Nelson and DePaolo, 1988; McLennan et al., 1990, 1993). Mudstones, owing to their higher trace element contents, more uniformly mixed sources, and lower susceptibility to alterations during deposition and diagenesis, are typically favored for whole-rock geochemical and isotopic provenance studies (Blatt, 1985; Cullers, 1995; Meinhold et al., 2022). However, focusing solely on mudstones may lead to overestimation of certain contributions, and source differences dependent on grain size necessitate evaluating all particle sizes available in a succession (McLennan et al., 1990, 1993; Nesbitt and Young, 1996).

Rare earth elements (REE) are very useful in provenance studies, as they are minimally affected or fractionated by post-depositional processes (McLennan, 1989; McLennan et al., 1990, 1993). While this assumption holds true for most cases, diagenetic redistributions have been observed in sedimentary successions containing specific authigenic phases like phosphate minerals (Awwiller and Mack, 1991; Milodowski and Zalasiewicz, 1991; Bock et al., 1994; McDaniel et al., 1994; Ohr et al., 1994; Bouch et al., 1995; Cullers et al., 1997; Lev et al., 1999; Ehrenberg and Nadeau, 2002; Bock et al., 2004; Evans et al., 2009). The mechanism of REE fractionation remain poorly constrained, and sedimentary rocks affected by it yield Nd model ages that may not accurately represent the mean age of mantle extraction for provenance components (Bock et al., 1994; McDaniel et al., 1994; Ehrenberg and Nadeau, 2002).

From an economic perspective, phosphatic sedimentary rocks play a crucial role as the primary source of phosphorus for fertilizer production, with Brazil being an exception where igneous deposits contribute the most (Glenn et al., 1994; Abram et al., 2011). Sedimentary phosphate deposits occurs since the early Paleoproterozoic, coinciding with the Great Oxidation Event, which facilitated chemical weathering of the continental crust and significant phosphate delivery to the oceans (Pufahl and Hiatt, 2012). Until the late Ediacaran, phosphogenesis was believed to be confined to shallow environments, resulting in thin stratiform deposits of phosphate-rich stromatolites (Pufahl and Groat, 2017; Reinhard et al., 2017). Following the Neoproterozoic Oxygenation Event and increased weathering of a progressively phosphatic crust, biogeochemical cycling of phosphorus led to the formation of giant phosphorite deposits,

composed of granular reworked authigenic and biogenic phosphate particles, on continental margins throughout the Phanerozoic (Föllmi, 1996; Pufahl and Groat, 2017).

In mid-south Amazonia, the Alto Tapajós Group encompasses predominantly siliciclastic rocks with dolomitic and phosphatic intervals. This succession is probably related to Terra Preta (non-outcropping on the region) and São Benedito formations. Previous studies on the region were limited to road and river outcrops, but the access to drill cores open an opportunity to complement existing studies with subsurface data up to 200 m depth. From this starting point, the research aimed to delve into the depositional system, provenance, the effects sedimentary and diagenetic processes on REE composition. It was employed petrography and whole-rock geochemistry including Nd isotopes. The results contribute to a better understanding of the geological context and stratigraphy of these rocks in a poorly constrained region, with economic implications related to phosphate concentrations. The study initially evaluates the influence of the authigenic minerals and diagenesis on the continental signal of the sedimentary rocks to further constrain the siliciclastic sediment provenance on a succession affected by REE redistributions caused by phosphate-rich sandstone beds.

2. Geological Setting

The Amazon Craton (Figure 1 A), one of the largest yet least explored Precambrian terrains in the world, is flanked to the east by the Tocantins Orogenic System, to the northeast by the Equatorial Continental Margin Province, and to the west by Phanerozoic peri-Andean basins (Santos et al., 2000, 2008). There are two main models of geochronologic provinces for the Amazon Craton: the Tassinari and Macambira (1999) and the Santos et al. (2000) model, later modified by Santos et al. (2008). This study adopts the latter model due to its reliance on a broader array of Nd isotopic data and has been employed in the most recent studies on the Alto Tapajós Basin (Toczeck et al., 2019; Albuquerque et al., 2023). According to Santos et al. (2000, 2008), the Amazon Craton is divided on the following geochronological provinces (Figure 1 B): Carajás (3.0-2.5 Ga); Central Amazon (Archean?); Trans-Amazonian (2.26-2.10 Ga); Tapajós-Parima (2.03-1.88 Ga); Rio Negro (1.82-1.52 Ga); Rondônia-Juruena (1.82-1.54 Ga); and Sunsá-K'Mudku (1.45-1.10 Ga).

The Alto Tapajós Basin (Figure 1 B), in the southern portion of the Amazon Craton, with an area of 97,000 km², covers the boundaries between the Tapajós-Parima and Rondônia-

Juruena provinces (Toczeck et al., 2019). The predominantly siliciclastic sedimentary succession within the basin is called by Alto Tapajós Group (Reis, 2006). The basin is believed to have evolved from a rifting event triggered by the reactivation of a precursor rift, where Paleoproterozoic successions of the Beneficente Group (~1.7 Ga) was deposited. Subsequent subsidence occurred between the Devonian and Permian. Associated with the fragmentation of Pangea and the expansion of the Central Atlantic Magmatic Province, during the Jurassic occurred a tectonic-thermal event, that led to the intrusion of mafic dike swarms (180 – 220 Ma). Unlike the Amazon Basin, the Alto Tapajós Basin exhibits positive relief, suggesting regional uplift, coupled with the absence of Cenozoic deposits (Toczeck et al., 2019).

2.1. Study area

The northwestern segment of the Alto Tapajós Basin (Figure 1 C), overlies the Precambrian basement rocks of the Juruena Domain (Scandolara et al., 2017) or the Western Amazonia Igneous Belt (Rizzotto et al., 2019). Within this area, The local basement rocks encompass several Paleoproterozoic units, including metasedimentary rocks of the Abacaxis Formation (>1.85 Ga), Orosirian granitoids (1.85-1.83 Ga), felsic and subordinate mafic volcanic rocks of the Colíder Group (1.82-1.78 Ga), Statherian alkaline to subalkaline granitoids of the Igarapé das Lontras and Teodósia intrusive suites (1.76-1.75), paragneisses of the Quatro Cachoeiras Complex (~1.75 Ga), volcanic-sedimentary rocks of the Beneficente Group (~1.74 Ga, comprising the Pedro Sara Formation felsic volcanic rocks, the Camaiú Formation alluvial sedimentary rocks and effusive basalts, and the Vila do Carmo Formation delta front and pro-delta successions), and type-A granitoids of the Serra da Providência Suite (1.57-1.53 Ga). The local mesoproterozoic rocks comprise mafic igneous rocks from the Mata-Matá Suite (1.57-1.54 Ga) and the sedimentary rocks from the Prainha Formation (Santos et al., 2000; Reis et al., 2006a; Almeida et al., 2016; Meloni and Filho, 2017; Reis et al., 2017; Scandolara et al., 2017; Rizzotto et al., 2019; Simões et al., 2020, 2021; Albuquerque et al., 2023).

In the study area (Figure 1 C), geological surveys have identified Alto Tapajós Group rocks from Borrachudo and São Benedito formations. The Borrachudo Formation consists mainly of fine-grained gray micaceous and kaolinitic sandstones, with clayey matrix, interlayered with light-gray argillaceous siltstones (Santiago et al., 1980). The São Benedito

Formation comprise interlayered gray to greenish shales/siltstones and quartz-arenites, some containing phosphate, glauconite, and pyrite (Santiago et al., 1980; Bizinella et al., 1980; Reis, 2006). Based on these lithofacies descriptions, only the São Benedito Formation is recognized on the studied succession. Although Reis (2006) proposed renaming the Borrachudo and São Benedito formations as Juma Formation, this study adopts the Santiago et al. (1980) nomenclature due to its stratigraphic priority.

The muddy-dolomitic part of the succession, not exposed in the region may be correlated with the Terra Preta Formation (Reis, 2006). The unit comprises gray clastic carbonatic rocks, locally stromatolitic and magnesian, interbedded with laminated carbonaceous siltstones and claystones, and in lesser quantities, fine sandstones. These lithofacies are reported to bear diagenetic sulfides (pyrite and chalcopyrite) disseminated and as venules. Barite, calcite and magnesite can occur as venules too (Meloni et al., 2021).

Palynological investigations suggested Silurian-Devonian age for Borrachudo and São Benedito Formations (Bizinella et al., 1980), but ongoing studies are getting evidences of a probable Mesoproterozoic age (work in progress). The depositional system for these units is debatable, but there is general agreement on shallow marine to transitional environments (Santiago et al., 1980; Bizinella et al., 1980; Reis, 2006; Reis et al., 2006a, b; Motta et al., 2016; Reis et al., 2017; Simões et al., 2021).

According to Albuquerque et al. (2023), Borrachudo and São Benedito formations received major sediment contributions from the local basement, Rondônia-Juruena Province (T_{DM}: 3.50-1.60 Ga), specifically from the Colíder Group, Orosirian/Statherian granitoids/gneisses, Pedro Sara Formation, and the recycling of Beneficente Group and Prainha Formation sedimentary rocks.

3. Materials and Methods

For this research 20 medium to fine-grained sandstones, 13 mudstones, and 6 marls from three drill core sections in the extreme northwestern portion of Alto Tapajós Basin were collected (Figure 2). Sampling was designed to achieve whole-depth coverage avoiding weathered samples. 20 thin sections were made to determine composition, texture, classify the rocks, and provide initial provenance insights.

Mineral chemistry analyses were conducted at the Electron Microprobe Laboratory at the University of Brasília, Brazil, with a JEOL-JXA-8230 instrument. Analytical conditions included a bombarding voltage between 15 and 20 kV, a current of 2×10^{-8} A, and a beam diameter of 1 μm . For each analyzed element, calibrations were performed on standards with known concentrations. The analysis focused in determine the glauconitic minerals, phosphate, and carbonate compositions. The REE contents were determined qualitatively.

The samples were ground and homogenized in a tungsten carbide disc mill. The powder of each sample was used for X-ray diffraction analysis, elemental and Nd isotopic geochemistry. The bulk samples mineralogy was carried by X-ray diffraction. It was used a Rigaku Ultima IV instrument (X-ray Diffractometry Laboratory, University of Brasília) with copper $K\alpha$ radiation filtered by Ni, a 35 kV voltage, and a 15 mA current. The samples were scanned from $2-60^\circ$, with 0.05° of step size and $5^\circ/\text{min}$ scan speed. Interpretation of the diffractograms was carried out using MDI/Jade® 9 software.

Whole-rock geochemical analyses for 39 samples were conducted by the ALS Global Laboratory in Lima, Peru. For major oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , K_2O , MgO , Na_2O , K_2O , TiO_2 , P_2O_5 , and trace elements (Ba, Cr, Cs, Ga, Hf, Ho, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Y, Zr and REE), powdered samples were fused with lithium meta- and tetraborate, and the resulting melt was acid dissolved. Major oxides were determined by ICP-AES and trace elements were determined by ICP-MS. Base metals (Ag, As, Cd, Co, Cu, Li, Mo, Ni, Pb, Sc, Tl, and Zn) were determined by four-acid digestion and analyzed by ICP-AES. It was employed BCS-348, BXSP-1, EMOG-17, GBM321-8, GRE-3, MRGeo08, NCSDC71301, OREAS 146, OREAS 24b and SY-4 as standards for the analyses and the uncertainties are lower than 5% for major elements and lower than 10% for minor and trace elements. Loss of ignition (LOI) was determined by gravimetry at 900°C .

REE and other trace elements were normalized to UCC (Upper Continental Crust), values after McLennan (2001). Here it is considered light rare earth elements (LREE) as La, Ce, Pr, and Nd; the middle rare earth elements (MREE) as Sm, Eu, Gd, Tb, and Dy; and the heavy rare earth elements (HREE) as Ho, Er, Tm, Yb, and Lu.

Nd Isotope analysis was performed using a Thermo Scientific Neptune Series High Resolution Multicollector ICP-MS at the Laboratory of Geodynamic, Geochronological, and Environmental Studies (LEGGA), Institute of Geosciences (IG), University of Brasília (UnB).

Sample preparation, digestion, and Nd isotope extraction followed the procedures described in Gioia and Pimentel (2000). The data were corrected for fractionation using $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Validation of the results was performed using the BHVO-2 reference material, which yielded $^{143}\text{Nd}/^{144}\text{Nd} = 0.513008 \pm 0.000007$ (2SE) and 0.513002 ± 0.000019 . For $\epsilon\text{Nd}(t)$ and $f_{\text{Sm}/\text{Nd}}$ calculations, it was used $^{147}\text{Sm}/^{144}\text{Nd}_{(0)} = 0.1960$ and $^{143}\text{Nd}/^{144}\text{Nd}_{(0)} = 0.512630$ as CHUR ratios (Bouvier et al., 2008). For depleted mantle model ages (T_{DM}) it was used $\epsilon\text{Nd}(t) = 0.25T^2 - 3T + 8.5$ as the depleted mantle (DM) evolution curve (DePaolo, 1981).

4. Results

4.1. Lithofacies

The drill cores examined in this study are divided into a sandy-muddy upper portion correlated to the São Benedito Formation and a muddy-dolomitic lower portion correlated to the Terra Preta Formation (Figure 2). The upper section consists of fine to medium and rarely coarse-grained sandstones interbedded with mudstones and rare brecciated horizons (Figure 3). The basal muddy-dolomitic succession is composed of mudstones, dolomitic mudstones, marls, dolostones, and carbonate breccias (Figure 3). These lithofacies are detailed below (Table 1).

4.1.1. Sandstones

The sandstone beds range from centimetric to decametric in thickness, light to dark gray, composed of medium to very fine-grained sand, moderate to well sorted, predominantly with subrounded grains, compositionally classified as quartz-arenites, except for some of the topmost beds where subarkoses occur (Figure 3 A). Microcline is the most common feldspar and plagioclase is rare. White micas and zircon are common accessory minerals. Quartz grains overgrowths and siderite cement occurs frequently. The sandstones are apparently massive (F1) or normal-graded (F2). The normal-graded beds are generally massive on the base, passing to planar, quasi-planar, and low-angle cross-laminations with occasionally symmetric ripples at the top (Figure 4 A). Some coarser-grained beds commonly have sandstone and mudstone fragments at their base.

210 4.1.2. Sandstones with mudstone interbeds

211 Intervals comprising centimetric fine to medium-grained sandstone beds with millimeter
212 to 2-3 cm thick mudstone interbeds (F3) are also observed (Figure 3 G and D). These beds
213 primarily exhibit planar to quasi-planar laminations, and low-angle cross-laminations and
214 truncations. Some cross-laminations resemble hummocky cross-laminations (Figure 4 C and
215 D), although their identification is somewhat limited in drill cores. Often normal-graded
216 sandstone beds transition to mudstones interbeds ending on sharp planar or erosive contacts
217 (Figure 4 B). Soft-sediment deformation structures (SSDS), such as dewatering syneresis
218 cracks, disturbances of the laminations, and convolute beddings, are observed on these
219 interbedded intervals (Figure 4 E, F, G, H, and I).

221 4.1.3. Mudstones

222 The mudstones (F4) include dark-colored siltstones and shales (Figure 3 E). They
223 typically exhibit planar laminations or appear massive and are composed of quartz, feldspars
224 (predominantly microcline), illite (clay fraction mica), white micas (probably muscovite),
225 kaolinite, fluorapatite (Figure 5 F), and pyrite (Figure 5 I).

227 4.1.4. Marls and dolostones

228 Light gray to white marls (F5) and impure dolostones (F6) within the basal succession
229 (Figure 3 H and I) are either massive or have planar laminations and SSDS (Figure 4 E, H and
230 I). They are interbedded in sharp or gradual contacts with mudstones, generally lighter-colored
231 dolomitic mudstones. The marls and dolostones are composed essentially of fine crystals of
232 dolomite, probably recrystallized, and the same minerals of the mudstones.

234 4.1.5. Breccias

235 The succession also includes some brecciated horizons (F7), reaching thicknesses of up
236 to 20 cm. They are composed of sandstone fragments in the upper terrigenous portion, and
237 carbonate intraclasts in the basal portion (Figure 3 F J). On the upper portion, the breccias show
238 brittle-style deformations (Figure 3 F), composed of little or non-rotated angular sandstone
239 fragments of millimeters to approximately 5 centimeters cemented by siderite (considering its
240 light orange color and no reaction with dilute HCl). The lower breccias have plastic-brittle style

deformations (Figure 3 J), their clasts maintain original structures with a chaotic/liquefied matrix surrounding them. Associated with these horizons there are faults (Figure 4 H), fault-breccias, and disturbed/liquefied horizons (Figure 4 E and I).

4.2. Authigenic minerals

The authigenic components, namely siderite, glauconite, fluorapatite, and pyrite, are present throughout the whole succession. Except for pyrite, these minerals are concentrated on sandstone beds and there is an apparently stratified distribution, where siderite grains are more commonly encountered in the uppermost sandstone beds, glauconite and fluorapatite occurs mainly in the sandstone-mudstone interbedded intervals and fluorapatite without glauconite is present on muddy-marly intervals. All these minerals contain some pyrite inclusions. Electron microprobe analysis was conducted on them to confirm their existence and evaluate contributions to whole-rock geochemistry.

Siderites occur mainly as ooids and blocky cements (Figure 5 E, G, H). Under the transmitted light microscopy, they are translucent with a slightly yellowish-brown color. The ooids have both detritic and authigenic nuclei with tangential siderite coatings. The siderites are compositionally Mg-rich (Table 2) and the mineral formula calculated based on 6 O is $\text{Fe}_{1.23}\text{Mg}_{0.66}\text{Mn}_{0.08}\text{Ca}_{0.03}(\text{CO}_3)_2$.

Glauconites are dark blueish green components. They are also green with masked interference colors on the transmitted light microscope, occurring as peloids, coatings, and commonly intergrown with fluorapatite (Figure 5). Among these composite grains, there are fluorapatite included or coated by glauconite (Figure 5 B, C, D), grains of glauconite with gradual transitions to fluorapatite at the borders (Figure 4 A), and intraclasts composed of both minerals (Figure 5 D, F, G, J). Based on electron microprobe results, the glauconitic components (Table 3) are dioctahedral interlayer deficient micas/illites, Fe and K-rich, and have higher Al contents compared to Phanerozoic glauconites. The K_2O contents between 6 and 8 % indicate an evolved stage glauconitic mineral (Odin and Matter, 1981; Amorosi et al., 2007). The glauconitic mineral formula based on 11 O, OH, F, Cl, and FeO as the total iron content is $\text{K}_{0.70}\text{Na}_{0.02}\text{Ca}_{0.02}(\text{Al}_{1.03}\text{Ti}_{0.01}\text{Fe}_{0.55}\text{Mg}_{0.56})(\text{Si}_{3.86}\text{Al}_{0.14})\text{O}_{10}(\text{OH}_{1.77}\text{F}_{0.23})$.

Fluorapatite are pale to dark brown and pseudo-isotropic (cryptocrystalline), occurring as peloids, ooids, intraclasts, coatings both on detrital and authigenic grains, and as fragments of

hardgrounds (Figure 5). Analysis of the phosphate components (Table 4) confirms fluorapatite as the only phosphate, probably the francolite variety, for presenting more than 2 atoms per formula unit of F. The fluorapatite mineral formula based on 25 O, Cl, and F is $\text{Ca}_{9.57}\text{Na}_{0.13}\text{Mg}_{0.03}\text{Al}_{0.02}\text{Fe}_{0.12}\text{Mn}_{0.02}\text{K}_{0.02}(\text{PO}_4, \text{CO}_3, \text{SO}_4)_6\text{F}_{2-3}$.

4.3. Whole-rock geochemistry

4.3.1. Major elements

The whole-rock geochemical data, given in Table 5, reveals four distinct lithogeochemistry groups: sandstones, Fe-sandstones, mudstones, and marls. Sandstones exhibit the highest SiO_2 contents (78.60-94.10 wt.%), while the Fe-sandstones show elevated Fe_2O_3 (9.76-11.57 wt.%), MnO (0.44-0.74 wt.%), and MgO (1.76-4.28 wt.%) contents. Some samples (L4F3 36.70, 40.58, 45.16, 56.46; L10F0 62.34, 67.20; FE6 10.85, 24.46) from both groups could be classified as phosphatic sandstones, due to P_2O_5 content between 2.52 and 5.09 wt.%. Mudstones show elevated Al_2O_3 (7.75-20.00 wt.%) and K_2O (6.10-9.10 wt.%) contents, while marls are distinguished by high CaO (9.11-11.09 wt.%) and MgO (5.27-6.94 wt.%) contents, along with lower SiO_2 contents (31.50-57.90 wt.%). These chemical compositions are reflected on the UCC-normalized patterns (Figure 6). Sandstones are depleted in Al_2O_3 , Fe_2O_3 , and MgO , while CaO and K_2O vary greatly but are depleted on average. Fe-sandstones are enriched in Fe_2O_3 , MgO , and depleted in Al_2O_3 and K_2O . Mudstones are the less uniform group, but on average Al_2O_3 , Fe_2O_3 , MgO , and K_2O values are closer to the UCC composition. Marls are enriched in MgO and CaO . A feature common to all sample groups are P_2O_5 enrichments and Na_2O strong depletions.

4.3.2. Trace elements

Although some variations exist among the lithogeochemistry groups, concentrations of immobile trace elements are largely similar, with mudstones exhibiting slightly higher concentrations (Table 6). UCC-normalized diagrams depict comparable patterns across the sample groups, with some exceptions of higher enrichments of Pb and Ta on sandstones and Fe-sandstones (Figure 6). Rb, Ba, Sr (large ion lithophile elements) are overall depleted and some mudstones showing Rb enrichments. Th, U, Zr, Hf (high field strength elements) vary from enriched to depleted, but most of the sandstones are depleted on Zr and Hf. Y

concentrations are close to the UCC values in all samples. Sc, V, and Cr, Cu, Ni, Zn (transition metals) are overall depleted and some of the mudstones and marls have Zn enrichments related to zinc sulfides.

4.3.3. Rare-earth elements (REE)

Total REE concentrations vary across the sample groups (Table 7). Sandstones and Fe-sandstones show similar REE contents, ranging between 67.79 and 171.02 ppm (mean of 104.77 ppm). Mudstones have the highest contents, ranging between 106.67 and 280.98 ppm (mean of 164.70 ppm), while marls have the lowest contents, ranging between 53.46 and 152.32 ppm (mean of 96.38 ppm).

The proportions between LREE, MREE, HREE are expressed by UCC-normalized diagrams and element ratios of $\text{La}_\text{N}/\text{Sm}_\text{N}$, $\text{La}_\text{N}/\text{Yb}_\text{N}$, and $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ (Table 7). Sandstones and Fe-sandstones exhibit lower $\text{La}_\text{N}/\text{Sm}_\text{N}$ (mean of 0.55 and 0.37, respectively) and $\text{La}_\text{N}/\text{Yb}_\text{N}$ (mean of 0.60 and 0.63, respectively), while higher $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ (mean of 1.38 and 1.91, respectively). This suggests LREE depletions and MREE enrichments in relation to HREE. Mudstones and marls have mean values of the three ratios closer to 1.

Four main REE patterns on UCC-normalized diagrams were identified (Figure 8). The sandstones show slight LREE depletions relative to HREE, and MREE enrichments (Figure 8 A). The Fe-sandstones exhibit LREE depletions and pronounced MREE enrichments, forming bell-shaped patterns (Figure 8 B). Most of the mudstones and marls display overall flat patterns (Figure 8 C and D). The mudstone samples L4F3 51.25, L10F0 9.87, L10F0 28.26, and L10F0 52.17 have slight concave up patterns, with MREE depletions (Figure 8 E). Only the L4F3 46.27 marl sample showed a MREE-enriched pattern (Figure 8 F), similar to the sandstones.

4.3.4. Nd Isotopes

Nd isotope results are shown in Table 9. Based on unpublished results of glauconite dating, it was used 1.5 Ga as the deposition age for $\epsilon\text{Nd}(\text{t})$ calculations. In general, the sandstones (17 samples) and Fe-sandstones (3 samples) yield a wide range of $f_{\text{Sm}/\text{Nd}}$ between -0.43 to 0.01, $\epsilon\text{Nd}(\text{t})$ ranging from -10.65 to -3.90, and T_{DM} model ages of 2.38 to 5.25 Ga. Most mudstones (8 samples) and marls (4 samples) have a lower narrow range of $f_{\text{Sm}/\text{Nd}}$ between -0.54 to -0.32, $\epsilon\text{Nd}(\text{t})$ ranging from -9.46 to -6.29, and model ages of 2.32 to 2.76 Ga (Table 9).

The slightly MREE-depleted mudstones (4 samples) presented consistently the lowest values of $f_{\text{Sm/Nd}}$ between -0.59 to -0.50, $\epsilon\text{Nd}(t)$ ranging from -6.98 to -5.92 (except for sample L10F0 28.26), and model ages of 0.92 to 2.29 Ga.

The marl sample FE6 55.15 exhibits $f_{\text{Sm/Nd}}$ of -0.41 and anomalously negative $\epsilon\text{Nd}(t)$ value of -17.97, and a much older T_{DM} of 3.35 Ga. The marl sample, FE6 46.27, which has MREE enrichment like the sandstones, have values of $-f_{\text{Sm/Nd}} = -0.22$, $\epsilon\text{Nd}(t) = -6.07$, and T_{DM} of 2.92 Ga.

5. Discussions

From the collected petrographic, element geochemical and Nd isotope data, three main points are discussed: (i) the nature of the depositional system, (ii) potential effects of sorting and diagenesis on the REE and Nd isotope whole-rock compositions, (iii) tectonic implications and sedimentary provenance. Each of these points is addressed below.

5.1. Depositional system

The described characteristics of each lithofacies and their associations offer valuable insights into the depositional processes and environment. The massive sandstone beds could be deposited by gravity flows (Shanmugam, 2021) or high intensity combined flows with high depositional rates (Jelby et al., 2020). Normal-graded sandstones are interpreted as products of waning gravity flows or high intensity combined flows. While the planar, quasi-planar, low angle, and hummocky cross-laminated fine sandstones interbedded with mudstones (Figure 4 A to D) indicate deposition mainly by waning oscillatory-dominant combined flows (Dumas and Arnott, 2006). Symmetric ripples at the bed tops can be interpreted as a product of wave oscillation after storm deposition (Dott and Bourgeois, 1982). Fine-grained lithofacies likely were deposited by fair-weather suspended load settling (Jelby et al., 2020). The fine-grained muddy-carbonate intervals indicate low-energy deposition with some periods of minor terrigenous apport.

Brecciated horizons showing both brittle and brittle-plastic deformations may be seismic-breccias and/or fault-breccias, resulted from fracturing of semi-consolidated and liquefaction of unconsolidated sediment (Shukla and Sharma, 2018). Others soft-sediment deformation structures (Figure 4 E to G) are also attributed to liquefaction and fluidization due to

combinations of groundwater movements, storm rapid deposition, the seismic activity and density gradients (Owen G., 1987; Molina et al., 1998).

Based on these observations, the coarsening upward succession (Figure 2) likely represent a regressive storm-dominated shelf, that transitioned from the outer shelf to the lower shoreface (Figure 8). Occasional tidal influence is not dismissed but storm-waves dominance is interpreted by the abundance of planar to quasi-planar, low-angle truncations and hummocky cross-laminations. This interpretation aligns with previous studies on the Alto Tapajós Group successions, which have characterized similar or laterally associated depositional settings (Santiago et al., 1980; Bizinella et al., 1980; Reis, 2006; Reis et al., 2006a, 2006b; Motta et al., 2016; Reis et al., 2017; Simões et al., 2021).

The siderite, glauconite, fluorapatite and pyrite, marine authigenic phases, seems also indicative of inner to outer shelf deposition (Glenn and Arthur, 1988). Although the authigenic components show reworking features on sandstones (Figure 5 C), their presence on fine-grained lithofacies suggest that they formed at slow rates of sedimentation, probably during fair-weather conditions in between storm events and were later reworked and concentrated (Glenn and Arthur, 1988; Föllmi, 1996; Pufahl and Grimm, 2003; Mücke, 2006; Pufahl and Groat, 2017; Vuillemin et al., 2019; López-Quirós et al., 2020; Chang et al., 2022).

The phosphatic particles (dark to pale brown and cryptocrystalline/pseudo-isotropic grains - Figure 5) and the other marine phases confirms that most of the phosphate content is authigenic. The possible sources of phosphorus for the rocks are the degradation of organic matter and the release of adsorbed phosphorus from clays and oxyhydroxides. Phosphorus is delivered via continental weathering to the ocean as dissolved or particulate forms. Dissolved species are readily available for biological uptake, however, most particulate forms consists of insoluble igneous and metamorphic phosphatic minerals that never participate in the element cycling (Föllmi, 1996; Pufahl and Groat, 2017).

5.2. *Effects of sedimentary and diagenetic processes on REE and Nd isotopic compositions*

Here it is discussed firstly the impacts of sorting and REE redistribution to filter the Nd isotopic data for the later provenance considerations. As will be discussed in more detail on the next section, petrography and trace element compositions seem to reflect the same siliciclastic sediment sources for all analyzed samples. Consequently, sorting or post-depositional processes

could explain some of the Nd isotopic variations between sandstones and fine-grained rocks (Bock et al., 1994; Cullers et al., 1997).

In order to evaluate the potential effects of sorting and REE redistribution, the $\text{La}_\text{N}/\text{Sm}_\text{N}$ versus $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ diagram proposed by Bock et al. (1994) was used (Figure 9). The diagram uses CI chondrite values for normalization after Pourmand et al. (2012). Samples positioned around UCC and PAAS compositions are considered not influenced by sorting or REE redistribution ($\text{La}_\text{N}/\text{Sm}_\text{N}$ ranging from 3 to 5, and $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ from 1 to 2) (Bock et al., 1994; Meinhold et al., 2022). Based on these parameters, the diagram allows the identification of three sample groups: (i) the first group comprises most of the sandstones (except L4F3 54.35), all Fe-sandstones, and three marls (L4F3 65.44; FE6 46.27; FE6 195.60), with $\text{La}_\text{N}/\text{Sm}_\text{N}$ values lower than 3 and $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ ratios ranging from 1.36 to 3.54; (ii) the second group includes one sandstone (L4F3 54.35), most of the mudstones (except the MREE-depleted), and three marls (FE6 55.15; FE6 119.10; FE6 179.68) plotting closer to UCC and PAAS; (iii) the last group comprehends the MREE-depleted mudstones (L4F3 51.25; L10F0 9.87; L10F0 28.26; L10F0 52.17) exhibiting the highest $\text{La}_\text{N}/\text{Sm}_\text{N}$ and the lowest $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ ratios. The marl sample FE6 119.10 m, which has $\text{La}_\text{N}/\text{Sm}_\text{N}$ higher than 5, has a slight Sm negative anomaly and no MREE depletion, thus it is out of the third group. In summary, groups 1 and 3 deviates from UCC and PAAS compositions, so they could have been affected by sorting or REE redistributions. The group 2, close to UCC and PAAS, is probably suitable for REE and Nd isotopic composition provenance interpretations.

The group 1 samples, composed mainly by sandstones, are impacted by sorting, which led to enrichments in the authigenic fluorapatite. The fluorapatite is responsible for the bell-shaped REE patterns (Figure 7 A and B), indicative of anoxic marine porewaters where occurred the release of REE during dissolution of Fe-oxyhydroxides, later transferred to phosphatic particles during precipitation or diagenesis (Haley et al., 2004; Chen et al., 2015; Tostevin et al., 2016; Lumiste et al., 2023). The most prominent MREE enrichments on Fe-sandstones reinforces the possibility of a prior Fe-oxyhydroxides content responsible for this pattern. Probably after or during the Fe reduction, there would be siderite formation. Although useful to deduce the porewater conditions, group 1 patterns are indicative of continental signal contamination and can't be used for provenance.

The group 3 samples have slight MREE-depleted patterns contrasting with the bell-shaped/MREE-enriched patterns of sandstones and Fe-sandstones. This inverse relation hints at the possibility of fluorapatite REE uptake also from mudstones on interbedded intervals. The ability of fluorapatite to scavenge REE during early diagenetic porewater migration from desorption of clay minerals are reported in other contexts too (Milodowski and Zalasiewicz, 1991; Ohr et al., 1994; Lev et al., 1999; Chen et al., 2015; Yang et al., 2021; Huang et al., 2023; Lumiste et al., 2023).

Milodowski and Zalasiewicz (1991) observed a similar REE enrichment of phosphate bearing strata and REE depletion of interbeds on the Upper Llandovery mud-dominated turbidite sequence from central Wales. The authors proposed that the redistribution occurred from REE release from Fe-Mn oxyhydroxides reduction, followed by REE desorption from clay and unstable volcanic minerals. Burial and compaction would lead to continued upward porewater migration, driving REE uptake onto phosphate and organic matter on hemipelagites.

The T_{DM} versus Sm/Nd diagram (Figure 10) was also used to further evaluate provenance suitability of REE and Nd isotopic compositions. Usually, correlations between model age and Sm/Nd ratio are interpreted as Sm/Nd isotope system disturbance (Bock et al., 2004). Group 1 samples display a logarithmic curve with increasingly T_{DM} model ages, reaching absurd values (5.25 Ga). The unsuitability for provenance of group 3 samples is not so clear in comparison to the group 1, however they show lower than 0.16 Sm/Nd ratios with increasingly lower T_{DM} model ages (2.12 to 2.29 Ga). For comparison, average upper crust and mudstones expected to be derived from it normally have narrow ranges between 0.16 to 0.20 of Sm/Nd ratios (equivalent of $f_{Sm/Nd}$ between -0.5 to -0.4) (McDaniel et al., 1994). This Sm/Nd ratio interval is where group 2 samples are clustered, probably representing uniformly mixed UCC sources (Blatt, 1985; Chakrabarti et al., 2007).

Among the MREE-depleted mudstones, the sample L10F0 28.26 m yields a significant juvenile T_{DM} model age of 0.92 Ga (Figure 10). It also has a different isotopic composition from all potential source rocks in the compiled data (Figure 11). This result could be a consequence of Nd isotope fractionation caused by the REE redistribution.

5.3. *Tectonic implications and sedimentary provenance*

Discriminant function analysis diagrams (Figure 12 A, B and C), along with high textural maturity and Nd isotope results, indicates that deposition most probably occurred on a passive margin. These results are coherent with Toczeck et al. (2019) and earlier studies interpretations, that classified the basin as an intracratonic rift, considering structural-geophysical data, its elongated form, and location.

The collisional signature observed on Figure 13B for Fe-sandstones, marls, few mudstones (L4F3 62.45; L4F3 69.49; L10F0 9.87; FE6 99.31; FE6 160.07) and sandstones (L4F3 45.15; L4F3 54.35; L4F3 60.83) is probably the influence of authigenic marine phases, since the discriminant functions are sensitive to SiO₂ dilution.

The continental island arc signature (Figure 12 D), for a great part of the samples, is probably inherited from source rocks. Albuquerque et al. (2023) argued that the continental island arc signature on Beneficente Group is due to the arc-related basements of Tapajós-Parima and Rondônia-Juruena provinces. Thus, considering the same basement rocks as possibly sediment contributors for the studied rocks, the collisional signature can also be inherited on the Alto Tapajós Group.

Trace element (Rb, Ba, Sr, Th, U, Zr, Hf, Y, Sc, V, Cr, Cu, Ni, and Zn) compositions of all sample groups positively correlate with Al/Si, thus probably reflect siliciclastic provenance. UCC-normalized patterns indicates mainly felsic characteristics (Figure 6), presenting Ti, Na, Sc, V, and transition metals depletions (McLennan et al., 1993). Higher Zr/Hf ratios in comparison to Th/Sc suggest a zircon addition caused by sorting or sediment recycling (Figure 13 A) (McLennan et al., 1990), further supported by recycled plot on the Roser and Korsch (1988) diagram for source nature (Figure 13 B).

Nearly all Nd isotope values, deemed suitable for provenance ($f_{\text{Sm/Nd}} = -0.47$ to -0.41 ; $\epsilon_{\text{Nd(t)}} = -8.98$ to -6.33 ; $T_{\text{DM}} = 2.32$ to 2.49 Ga - Figure 15), fall within the fields of Rondônia-Juruena, Tapajós-Parima and Central Amazon provinces (Figure 11). Nd isotopic compositions are also very similar to some of Beneficente Group rocks (Albuquerque et al., 2023). Considering a recycled provenance component, the reworking of the underlying sedimentary rocks most likely contributed to the studied succession sediment budget. The marl sample FE6 55.15 m presented a more negative $\epsilon_{\text{Nd(t)}}$ value of -17.45 and a T_{DM} model age of 3.35 Ga (Figure 14). This isotopic composition aligns with Transamazon and Carajás Provinces,

suggesting a potential contribution shift from distant source areas (eastern part of Amazon Craton).

Based on similar Nd isotope results and Sr-Pb isotopes, Albuquerque et al. (2023) favored the hypothesis of a more proximal sediment source related to the local basement rocks (Colíder Group, Orosirian/Statherian granitoids/gneisses and Beneficente Group) on the northwestern portion of the Alto Tapajós Basin. Considering the presented Nd isotopic compositions, it is interpreted for the studied drill sections overall proximal sources from Rondônia-Juruena, Tapajós-Parima and Central Amazon Provinces (2.32 to 2.49 Ga), with only a brief period of main contribution of distal source areas, from the Carajás and Transamazon Provinces, or proximal unknown rocks ($T_{DM} = 3.35$ Ga) (Figure 15).

6. Conclusions

Based on lithologic and geochemical data from core sections of Alto Tapajós Group on the southeastern Amazonas State, the following conclusions are:

- The studied succession was deposited in a shallow marine environment, most probably on a regressive storm-dominated shelf. The basal muddy-carbonate portion is attributed to the Terra Preta Formation, while the sandy-muddy portion to the São Benedito Formation. The depth-related authigenic mineral paragenesis (siderite, glauconite, fluorapatite, pyrite, and dolomite) suggest overall anoxic conditions. Lithofacies associations indicate deposition from the outer shelf to the lower shoreface.

- Nd isotopic compositions mainly of coarser-grained rocks are influenced by authigenic fluorapatite and cannot be used for provenance. Slight MREE-depleted mudstones suggest early diagenetic REE redistribution due desorption from clay minerals and followed by fluorapatite uptake during porewater migration on interlayered sandstone/mudstones intervals. One MREE-depleted mudstone sample has a much juvenile T_{DM} model age of 0.92 Ga, which differs from any known possible source rocks. This value could be a product of Nd isotope fractionation caused by the REE redistribution.

- Major and trace element compositions indicate felsic and/or recycled sources contributing to the terrigenous sediment budget. The Nd isotope compositions, mainly from fine-grained rocks, show that Rondônia-Juruena, Tapajós-Parima and Central Amazon Provinces are possibly the main source areas for Alto Tapajós Group successions, at least on

the northwestern portion of the Alto Tapajós Basin. One marl sample yielded a much older model age of 3.35 Ga, which can suggest a provenance shift related to Carajás and Transamazon Province or unknown rocks.

Acknowledgments

The authors thank the University of Brasília (UnB) for their support in conducting this research. This work was carried out with financial support from the following funding agencies: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil (CAPES) - funding code 001; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) – Process 144663/2020-1 (scholarship) and 311702/2020-1; Fundação de Apoio à Pesquisa do Distrito Federal (FAP-DF) – Process 00193-00000228/2023-48.

Figures

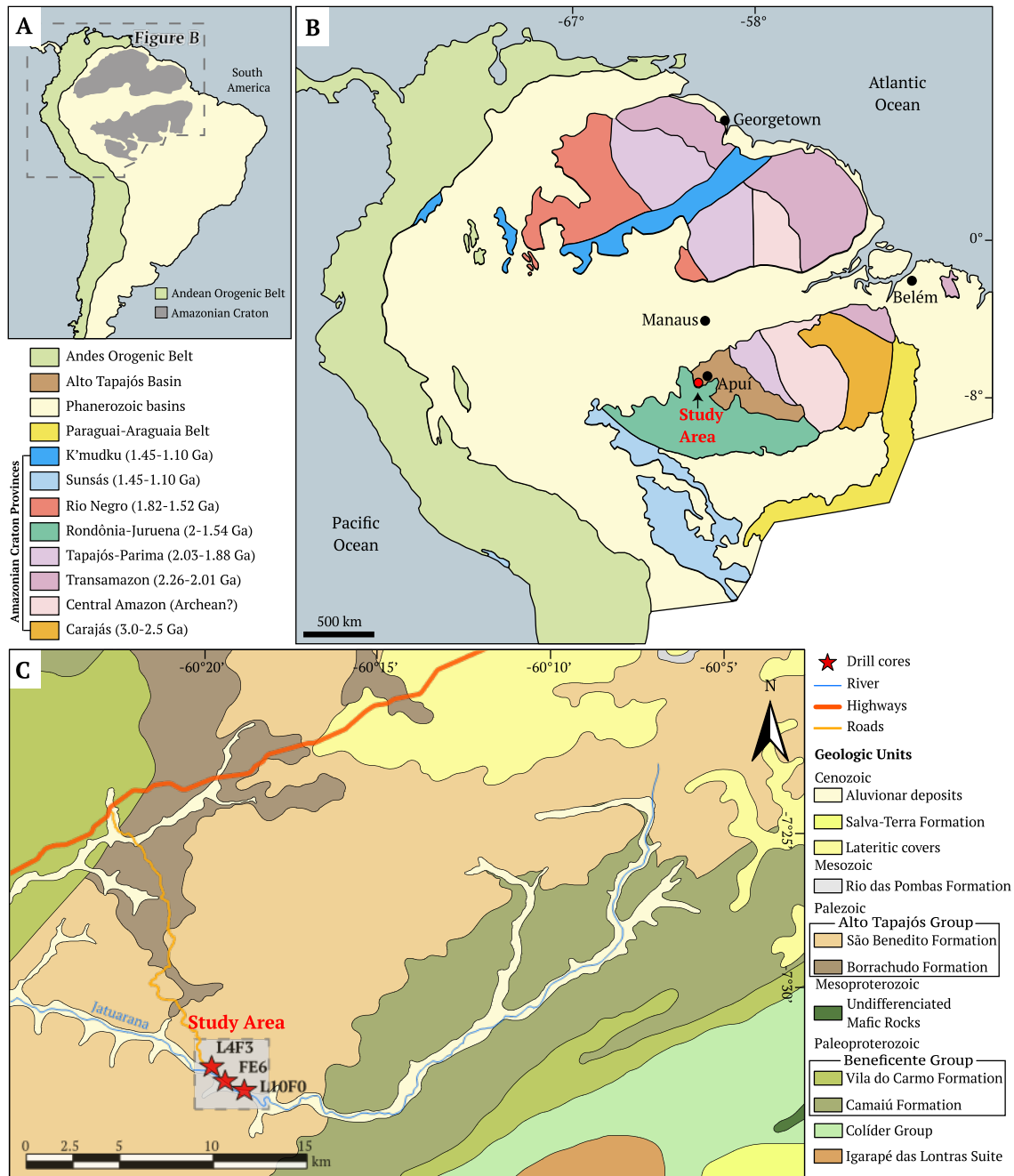


Figure 1. A) Map showing South America, the Andean Orogenic Belt, and the Amazon Craton contours; B) Map showing the studied area location relative to the geochronological provinces of the Amazon Craton (Santos et al., 2008) and Alto Tapajós Basin; C) Geological map showing the studied drill cores locations, adapted from Meloni et al. (2021).

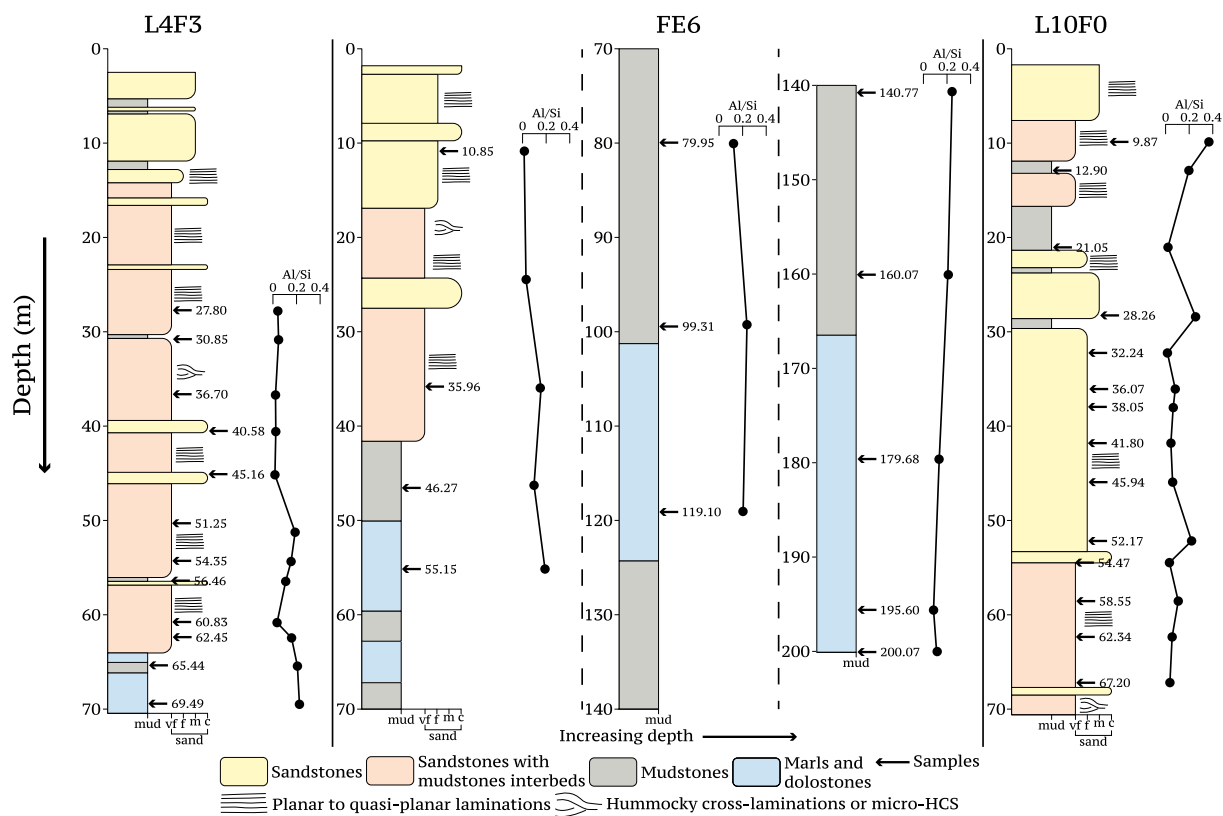


Figure 2. Simplified sedimentary logs of the studied drill cores. Black arrows mark the positions of analyzed samples for whole-rock geochemistry and Nd isotopes.

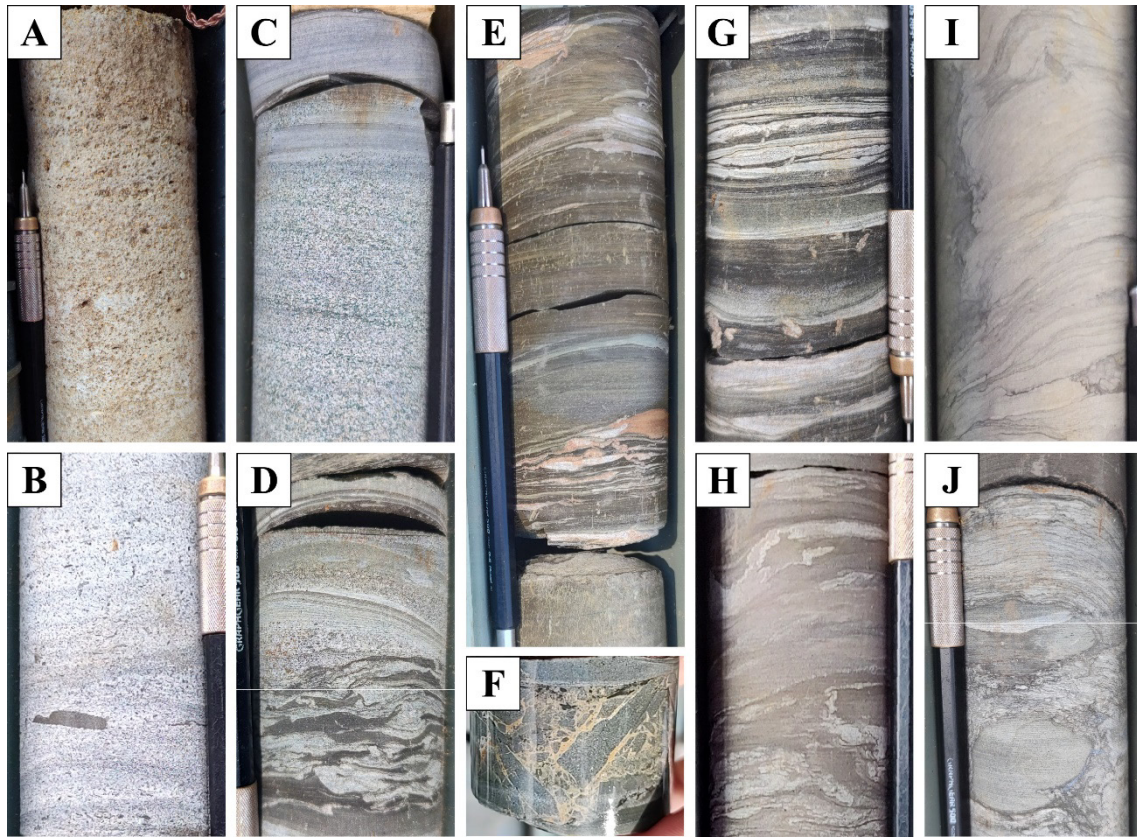


Figure 3. A) Subarkose, L4F2 drill core, 5.50 m depth; B) sandstones bed with shale fragment L8F-1 drill core, 29.90 m depth; C) glauconitic sandstone, L10F0 drill core, 68.40 m depth; D) interbedded and disturbed sandstone and siltstone, L4F3 drill core, 33.30 m depth; E) mudstone with sandy lenses/laminations, L10F0 drill core, 17.50 m depth; F) breccia composed of sandstone fragments and siderite cement, L10F-1 drill core, 32.50 m depth; G) interbedded fine sandstones and mudstones with syneresis cracks, L5F2 drill core, depth of 46.30 m; H) dolomitic mudstone, L8F-1 drill core, 69.77 m depth; I) dolostone, L4F1 drill core, 22.50 m depth; and J) carbonate breccia, L4F0 drill core, 20.85 m depth.

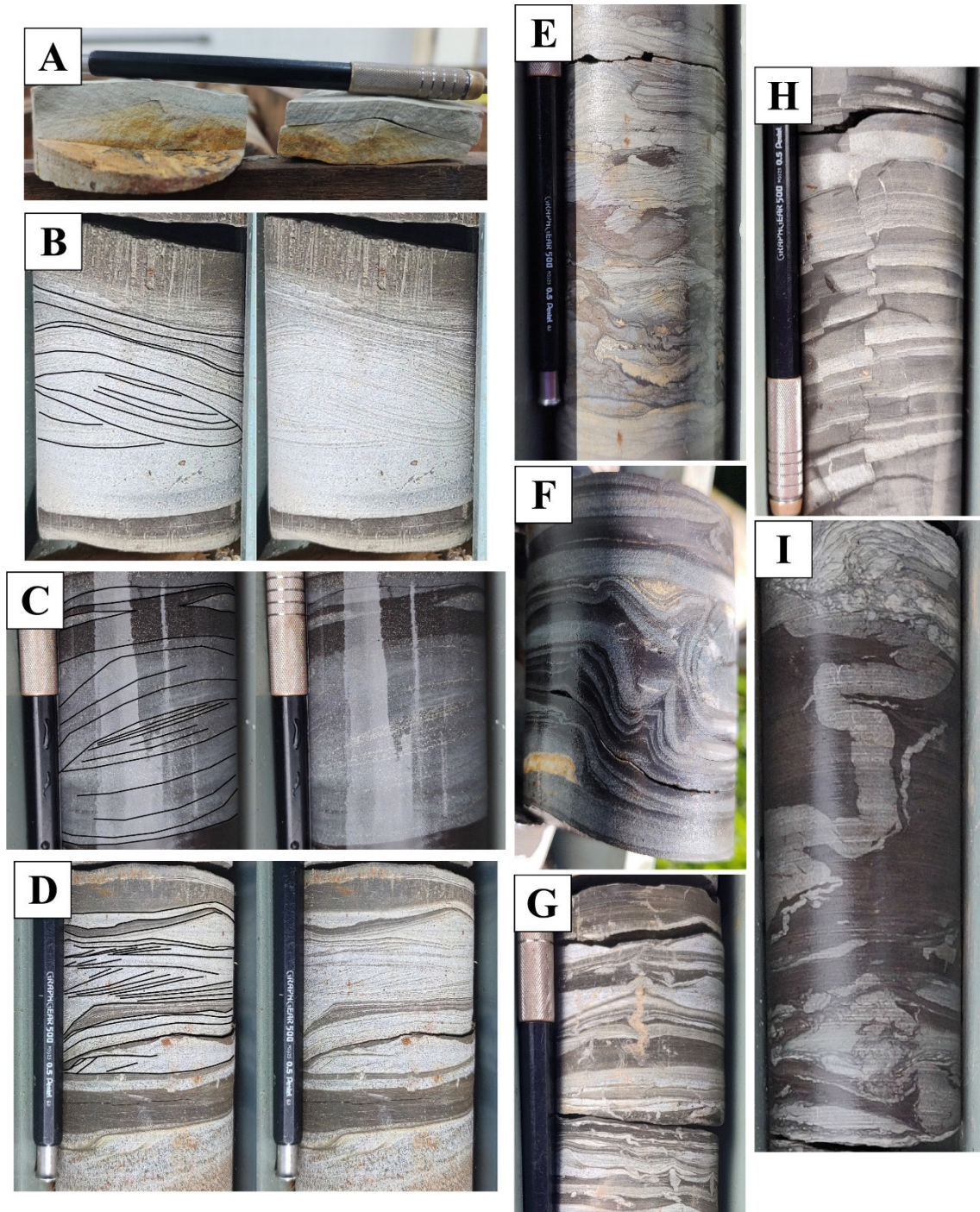


Figure 4. A) symmetric ripple, FE6 drill core, 7.80 m depth; B) hummocky cross-lamination, L4F3 drill core, 34.70 m depth; C) hummocky cross-lamination, L8F3 drill core, 61.65 m depth; D) complex low-angle cross-laminations, L4F3 drill core, 32.20 m depth; E) lamination disturbances – SSDS, L4F2 drill core, 41.05 m depth; F) convolute lamination, L8F2 drill core, 70.55 m depth; G) syneresis cracks, L8F-1 drill core, 21.15 m depth; H) syn-sedimentary

fault, L4F1 drill core, 14.50 m depth; and I) sedimentary dike? SSDS?, L8F3 drill core, 68.20 m depth.

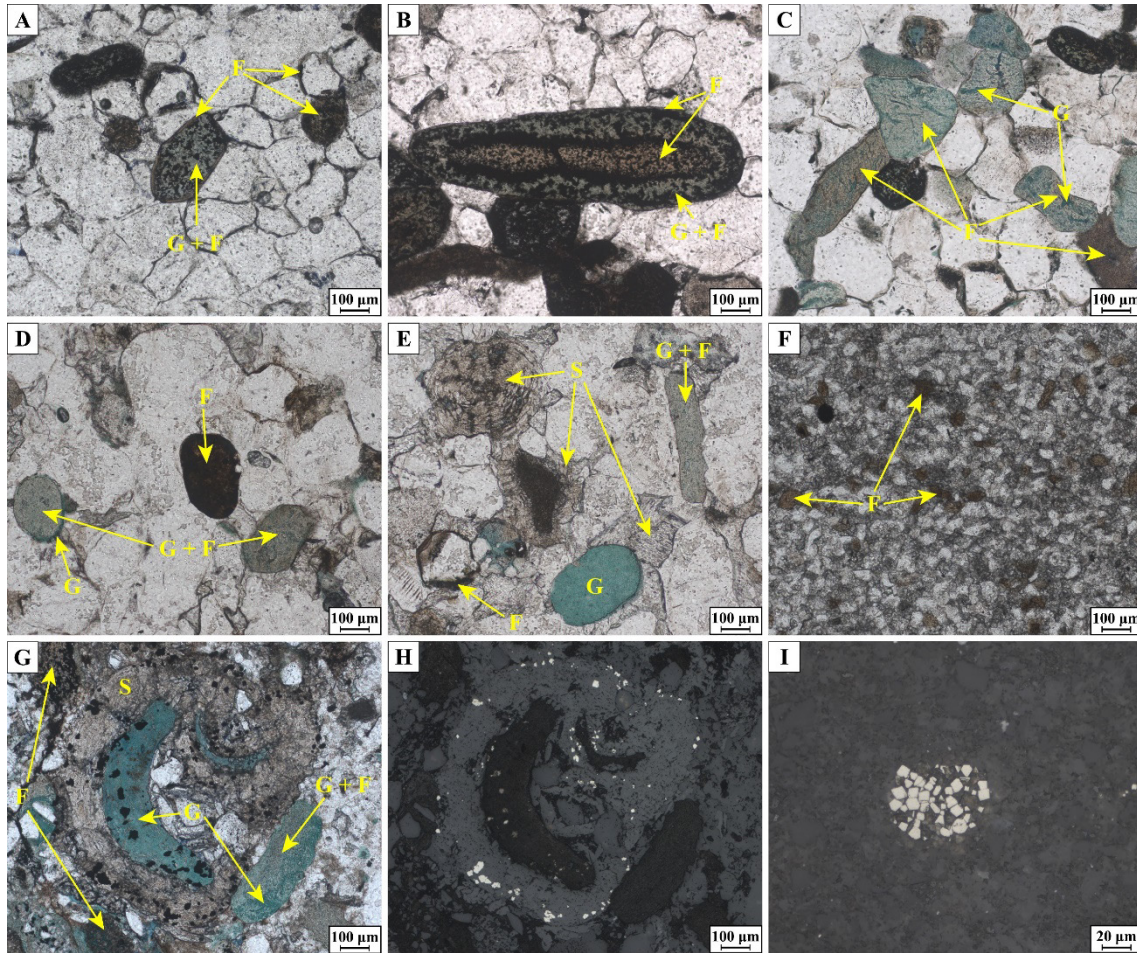


Figure 5. A) phosphate-glaucinite grain with phosphate coating, at the center, L4F3 drill core, 36.70 m depth; B) intraclast of phosphate nucleus with phosphate-glaucinite border, L4F3 drill core, 36.70 m depth; C) mainly phosphate peloids with cracks filled by glauconite, L4F3 drill core, 45.16 m depth; D) phosphate peloid at the center, and phosphate-glaucinite peloids, L10F0 drill core, 67.20 m depth; E) siderite ooids and cement, glauconite, and phosphate-glaucinite peloids, L10F0 drill core, 67.20 m depth; F) *in situ* phosphate particles, FE6 drill core, 195.60 m depth; G-H) siderite ooid with glauconite nucleus, both with sub- to euhedral pyrite inclusions, L4F3 drill core, 56.46 m depth; and I) framboidal pyrite, L4F3 drill core, 65.44 m depth. Obs.: Photomicrographs A to G were taken under transmitted light and parallel nichols. Photomicrographs H and I were taken under reflected light and parallel nichols.

Yellow labels indicate, respectively: F – phosphate components; G+F – phosphate-gluconite components; G – glauconite components; and S – siderite components.

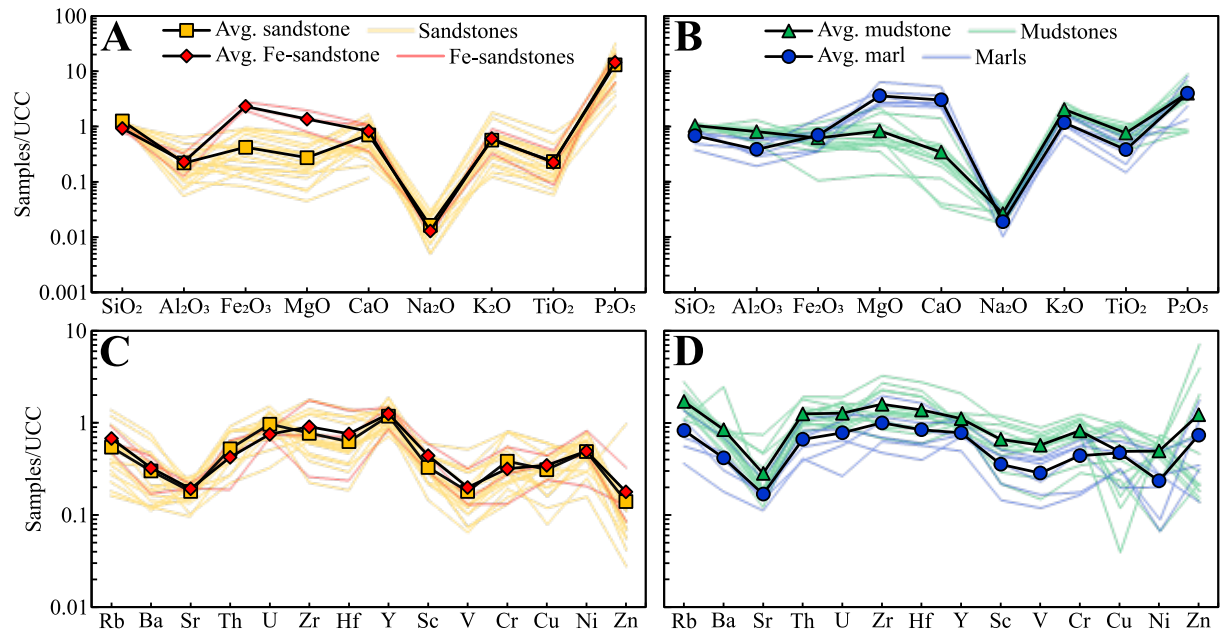


Figure 6. Upper Continental Crust – UCC (McLennan, 2001) normalized diagrams for A-B) major, C-D) selected trace elements.

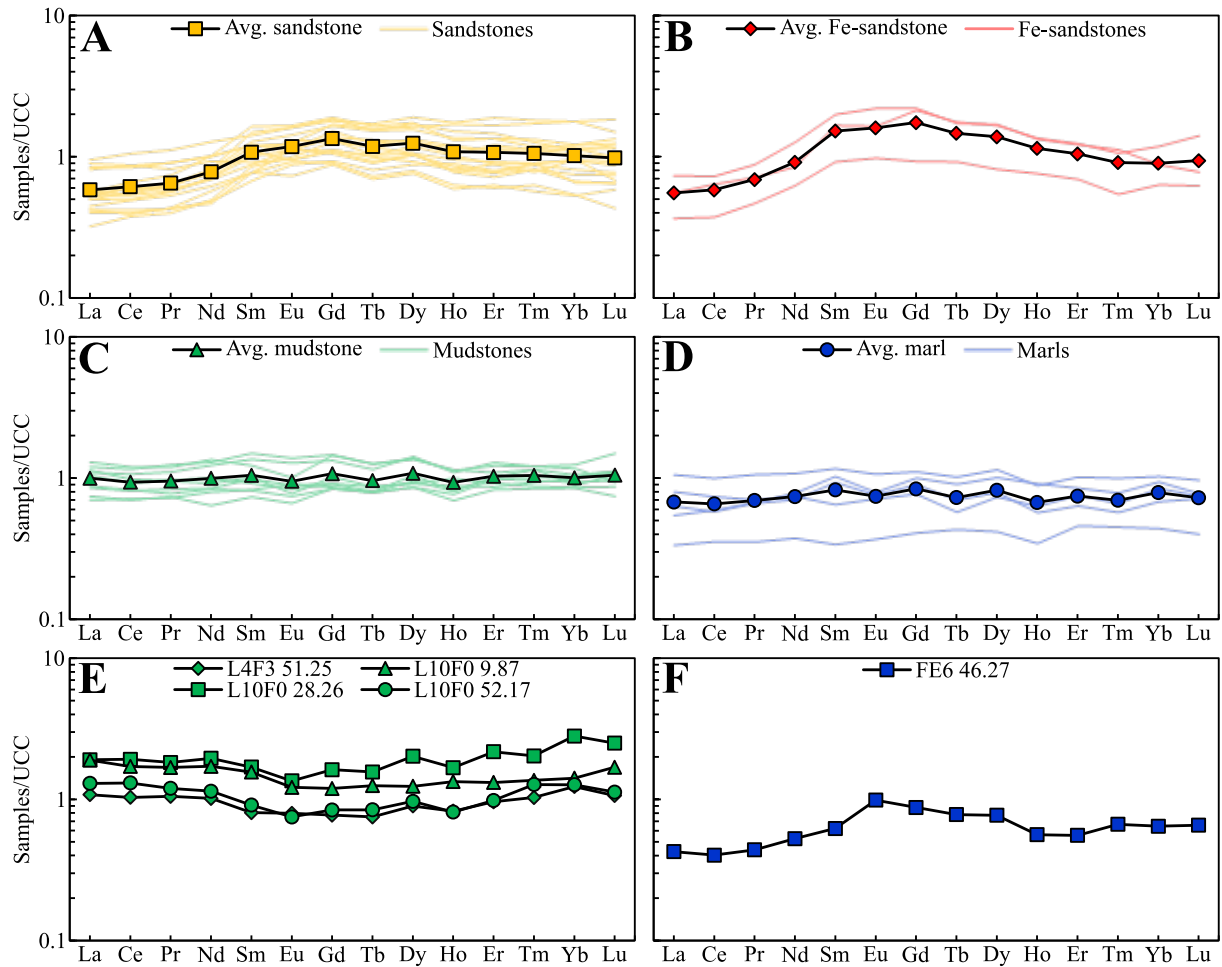


Figure 7. UCC-normalized REE diagrams for A) sandstones; B) Fe-sandstones; C) mudstones; D) marls; E) selected mudstones with slight MREE depletions; F) selected marl with MREE enrichment.

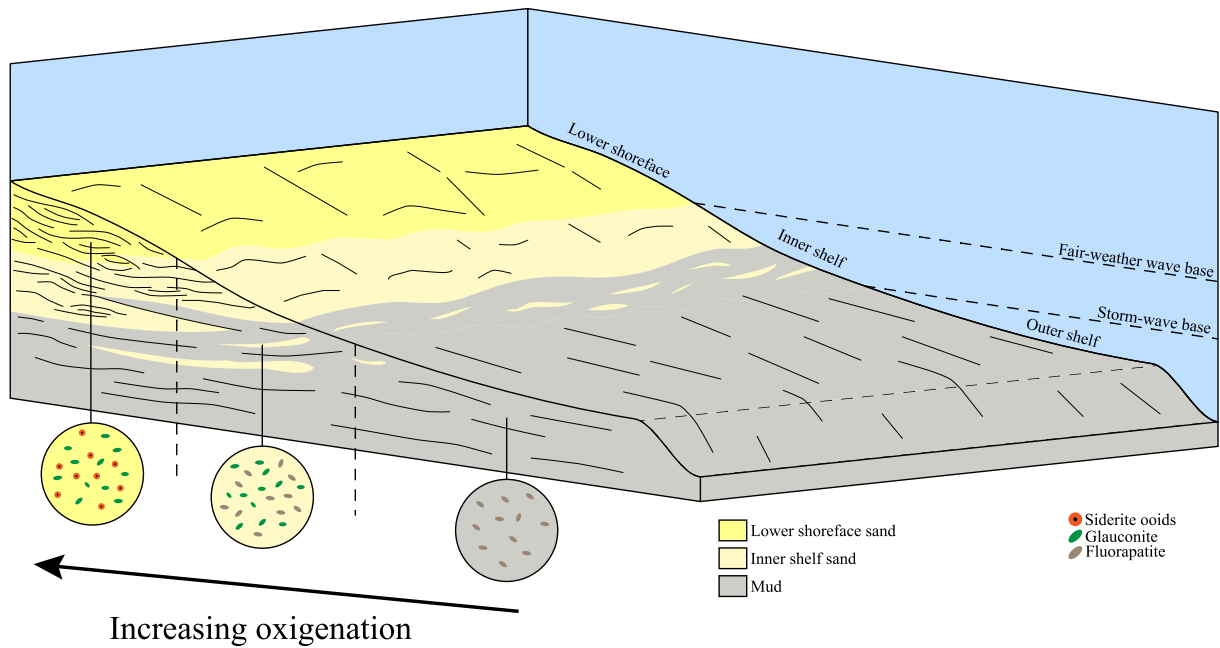


Figure 8. Schematic depositional model of the studied succession.

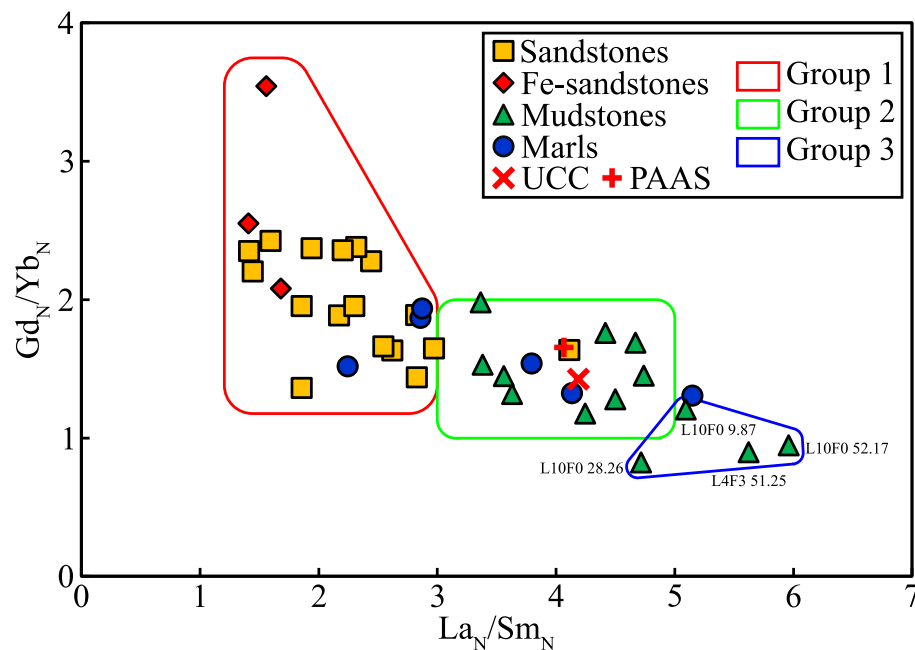


Figure 9. La_N/Sm_N vs. Gd_N/Yb_N diagram, after Bock et al. (1994). Group 1 comprise samples affected by sorting. Group 2 comprise samples not affected by sedimentary and/or post-depositional processes. Group 3 comprises samples affected by REE redistributions.

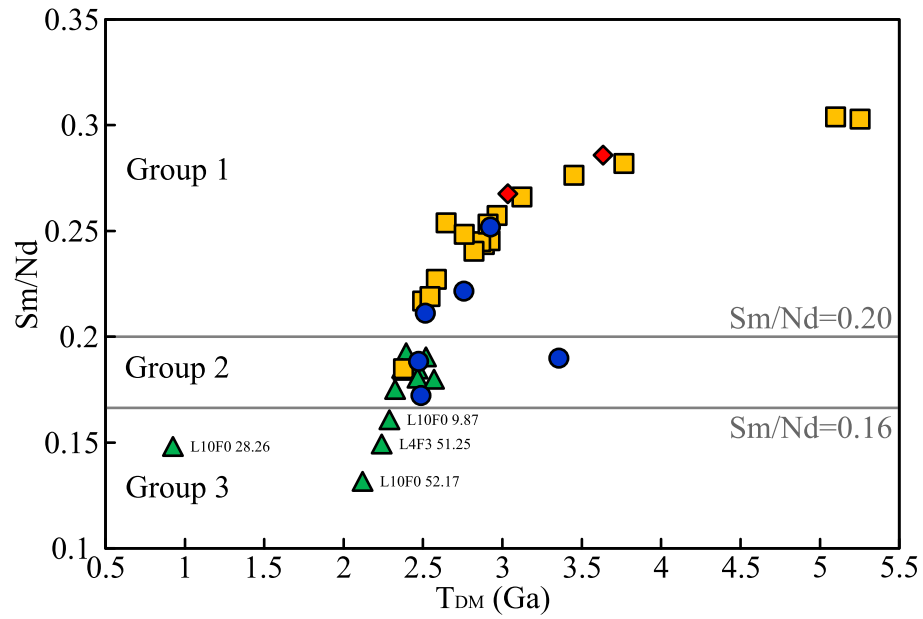


Figure 10. T_{DM} model age vs. Sm/Nd ratio diagram.

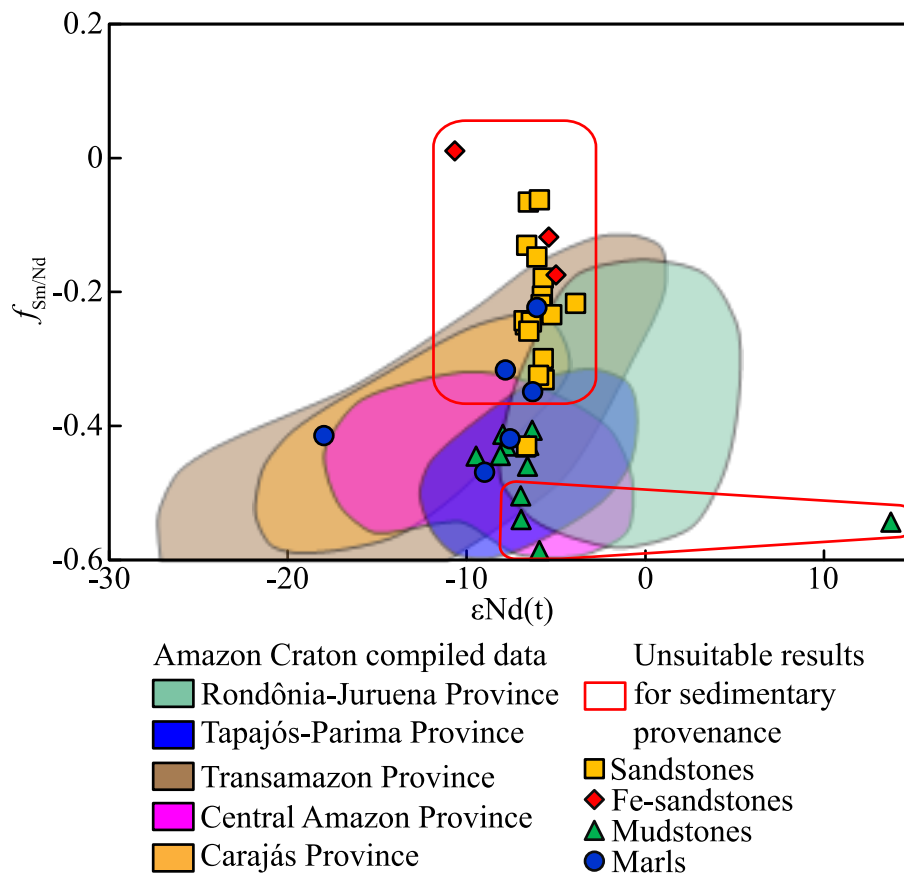


Figure 11. $\epsilon Nd(t)$ vs. $f_{Sm/Nd}$ diagram. (Nd Isotopic compositions after: Santos et al., 2000; Avelar, 2002; Payolla et al., 2002; Teixeira et al., 2002; Pinho et al., 2003; Lamarão et al., 2005;

Almeida, 2006; Rosa-Costa et al., 2006; Scandolara, 2006; Oliveira et al., 2008; Silva et al., 2008; Fernandes et al., 2011; Feio et al., 2012; Duarte et al., 2012; Heinonen et al., 2012; Rocha et al., 2012; Barreto et al., 2013; Feio et al., 2013; Barreto et al., 2014; Rosa-Costa, 2014; Assis, 2015; Almeida et al., 2016; Rocha, 2016; Semblano et al., 2016; Oliveira, 2017; Silva, 2017; Leal et al., 2018; Fernandes and Juliani, 2019; Silva et al., 2019; Cassini et al., 2020; Silva, 2020; Albuquerque et al., 2023).

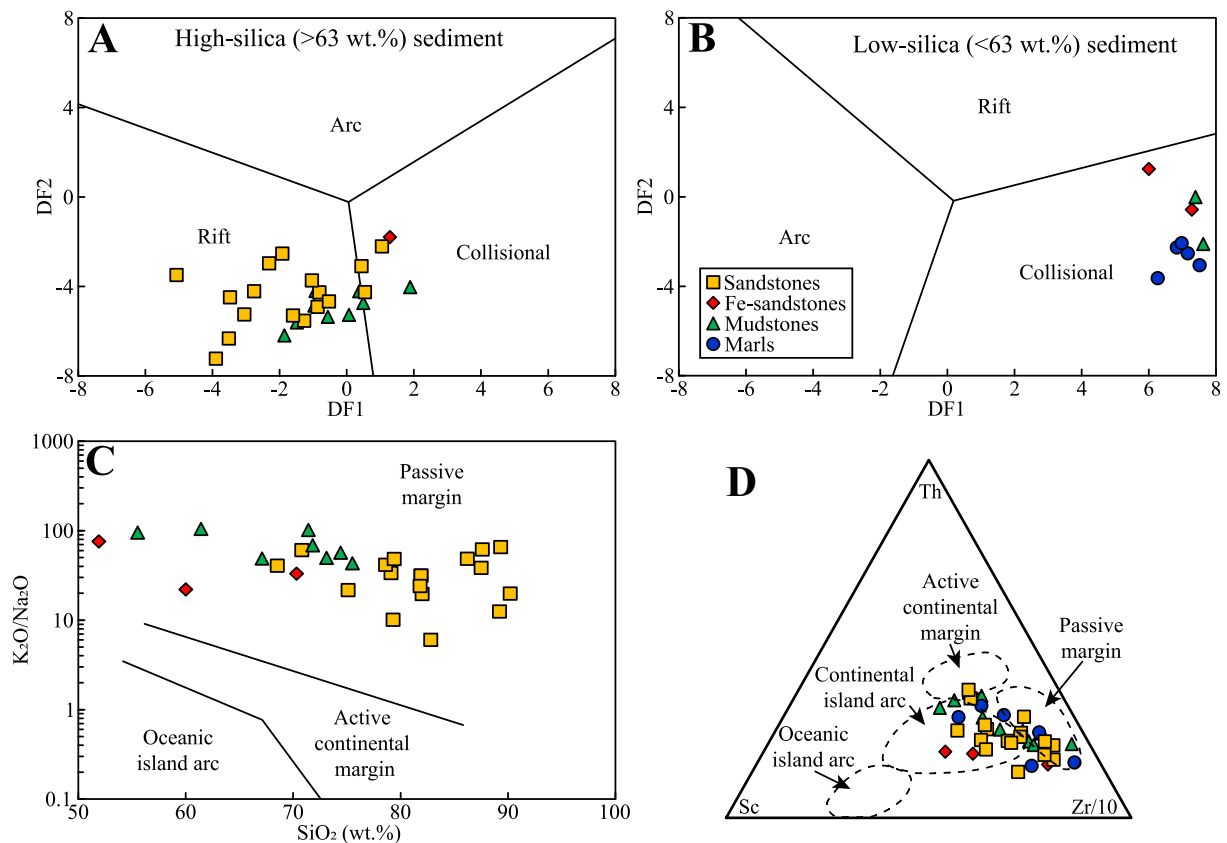


Figure 12. A-B) Discriminant function analysis diagrams using major elements concentrations of sedimentary rocks for tectonic setting discrimination (Verma and Armstrong-Altrin, 2013):
 (A) $DF1 = (-0.26269 \times \ln(TiO_2/SiO_2)_A) + (0.60369 \times \ln(Al_2O_3/SiO_2)_A) + (-0.72489 \times \ln(Fe_2O_3/SiO_2)_A) + (0.66042 \times \ln(MnO/SiO_2)_A) + (2.19128 \times \ln(MgO/SiO_2)_A) + (0.14421 \times \ln(CaO/SiO_2)_A) + (-1.30432 \times \ln(Na_2O/SiO_2)_A) + (0.05449 \times \ln(K_2O/SiO_2)_A) + (-0.33002 \times \ln(P_2O_5/SiO_2)_A) + 1.58815$; $DF2 = (-1.19586 \times \ln(TiO_2/SiO_2)_A) + (1.06399 \times \ln(Al_2O_3/SiO_2)_A) + (0.30341 \times \ln(Fe_2O_3/SiO_2)_A) + (0.43567 \times \ln(MnO/SiO_2)_A) +$

$(0.83805 \times \ln (\text{MgO}/\text{SiO}_2)\text{A}) + (-0.40665 \times \ln (\text{CaO}/\text{SiO}_2)\text{A}) + (1.02140 \times \ln (\text{Na}_2\text{O}/\text{SiO}_2)\text{A})$
 $+ (-1.70582 \times \ln (\text{K}_2\text{O}/\text{SiO}_2)\text{A}) + (-0.12643 \times \ln (\text{P}_2\text{O}_5/\text{SiO}_2)\text{A}) - 1.06801.$

(B) $\text{DF1} = (0.60809 \times \ln (\text{TiO}_2/\text{SiO}_2)\text{A}) + (-1.85447 \times \ln (\text{Al}_2\text{O}_3/\text{SiO}_2)\text{A}) + (0.29904 \times \ln$
 $(\text{Fe}_2\text{O}_3/\text{SiO}_2)\text{A}) + (-0.54964 \times \ln (\text{MnO}/\text{SiO}_2)\text{A}) + (0.12026 \times \ln (\text{MgO}/\text{SiO}_2)\text{A}) + (0.19377$
 $\times \ln (\text{CaO}/\text{SiO}_2)\text{A}) + (-1.51036 \times \ln (\text{Na}_2\text{O}/\text{SiO}_2)\text{A}) + (1.94074 \times \ln (\text{K}_2\text{O}/\text{SiO}_2)\text{A}) +$
 $(0.00343 \times \ln (\text{P}_2\text{O}_5/\text{SiO}_2)\text{A}) - 0.29378; \text{DF2} = (-0.55404 \times \ln (\text{TiO}_2/\text{SiO}_2)\text{A}) + (-0.99528 \times$
 $\ln (\text{Al}_2\text{O}_3/\text{SiO}_2)\text{A}) + (1.76467 \times \ln (\text{Fe}_2\text{O}_3/\text{SiO}_2)\text{A}) + (-1.39149 \times \ln (\text{MnO}/\text{SiO}_2)\text{A}) +$
 $(-1.03363 \times \ln (\text{MgO}/\text{SiO}_2)\text{A}) + (0.22482 \times \ln (\text{CaO}/\text{SiO}_2)\text{A}) + (0.71313 \times \ln (\text{Na}_2\text{O}/\text{SiO}_2)\text{A})$
 $+ (0.33022 \times \ln (\text{K}_2\text{O}/\text{SiO}_2)\text{A}) + (0.63684 \times \ln (\text{P}_2\text{O}_5/\text{SiO}_2)\text{A}) - 3.63056.$

C) SiO_2 vs. $\text{K}_2\text{O}/\text{Na}_2\text{O}$ diagram for tectonic setting discrimination (Roser and Korsch, 1986);

D) Th-Zr/10-Sc ternary diagram for tectonic setting discrimination (Bhatia and Crook, 1986).

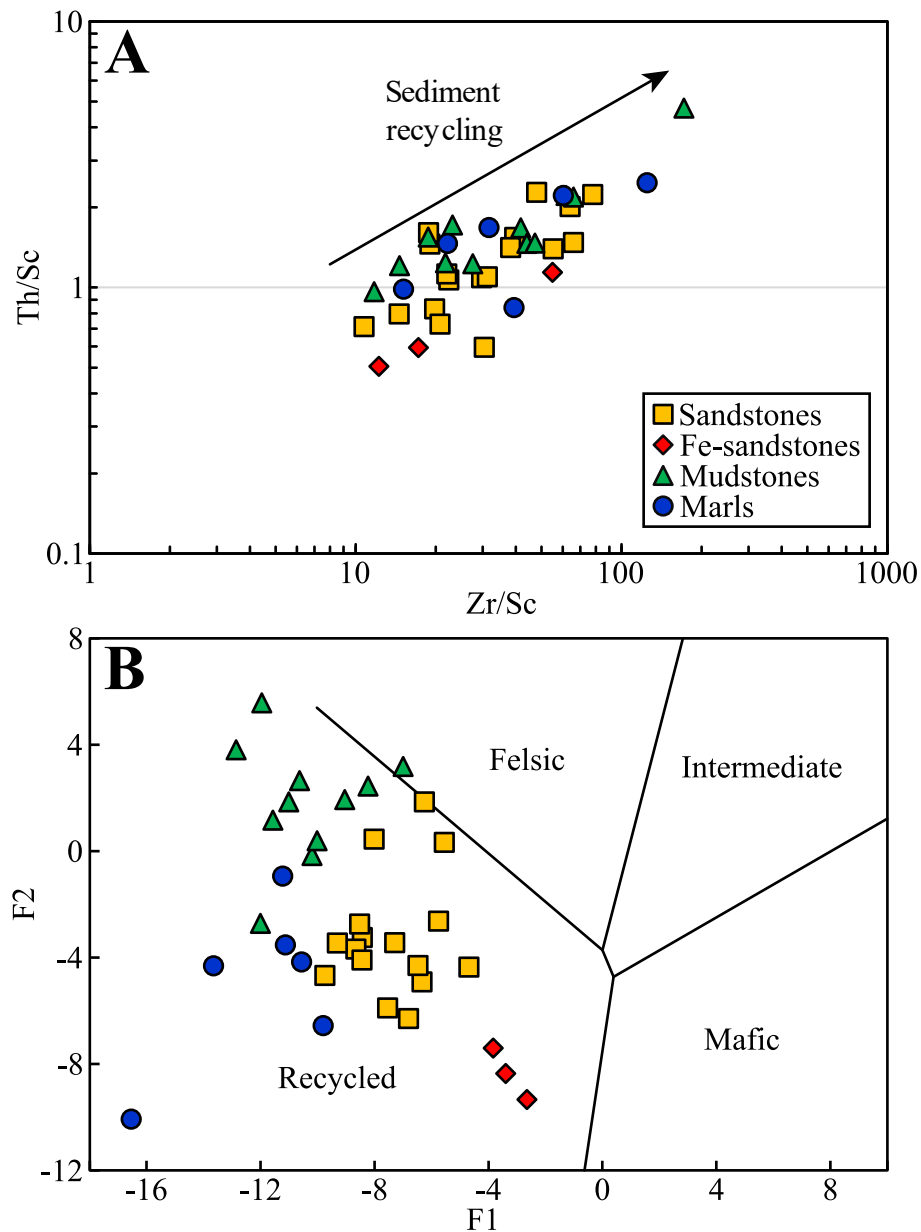


Figure 13. A) Zr/Sc vs. Th/Sc diagram for evaluation of sedimentary sorting and recycling/zircon addition (McLennan et al., 1993). B) Discriminant function analysis diagram for provenance signatures (Roser and Korsch, 1988): $F1 = -1.773(\text{TiO}_2) + 0.607(\text{Al}_2\text{O}_3) + 0.760(\text{Fe}_2\text{O}_3) - 1.500(\text{MgO}) + 0.616(\text{CaO}) + 0.509(\text{Na}_2\text{O}) - 1.224(\text{K}_2\text{O}) - 9.090$; $F2 = 0.445(\text{TiO}_2) + 0.070(\text{Al}_2\text{O}_3) - 0.250(\text{Fe}_2\text{O}_3) - 1.142(\text{MgO}) + 0.438(\text{CaO}) + 1.475(\text{Na}_2\text{O}) + 1.426(\text{K}_2\text{O}) - 6.861$.

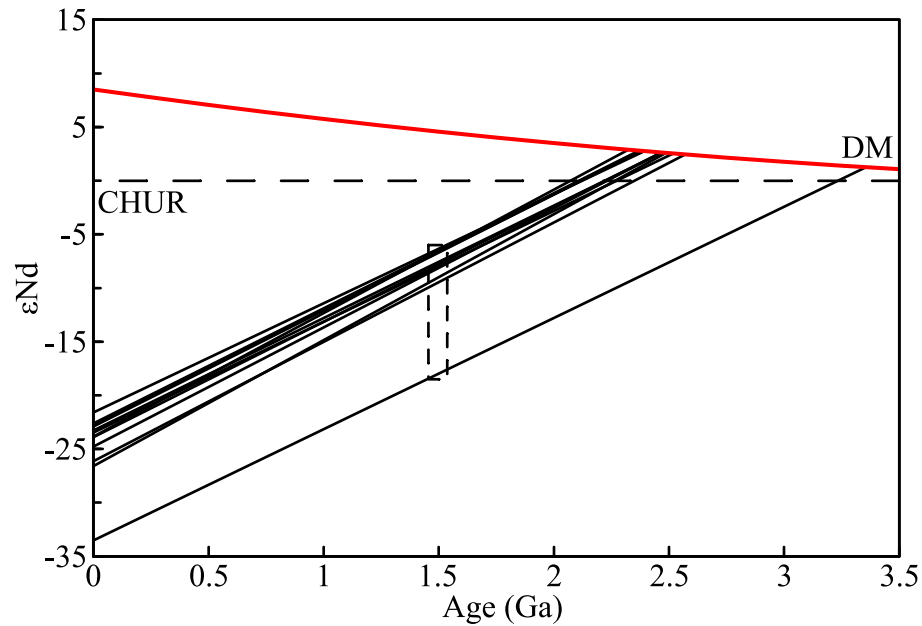


Figure 14. ϵNd vs. age evolution diagram. Dashed rectangle at the estimate deposition age (1.5 Ga).

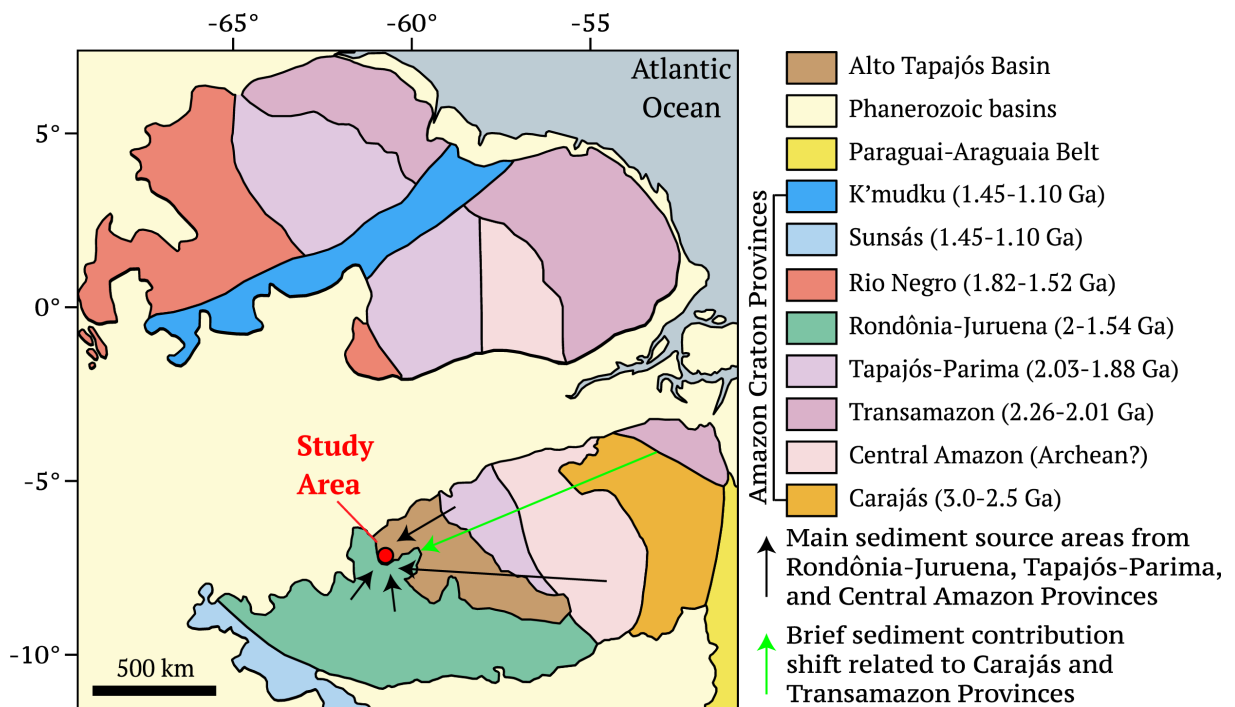


Figure 15. Summary of possible sediment source areas for the studied sections. It is interpreted a main sediment contribution from more proximal areas, related to Rondônia-Juruena, Tapajós-Parima and Central-Amazon Provinces, with a brief sediment contribution shift from eastern distal areas, related to Carajás and Transamazon Provinces, or unknown proximal units.

Tables

Table 1: Lithofacies summary, with descriptions, depositional processes, and facies associations interpretations.

Code	Facies	Description	Interpretation	Facies association
F1	Massive sandstones	Centimetric to decametric massive medium-grained sandstones. Rarely coarse grained.	Gravity flows and/or high intensity combined flows	Lower shoreface
F2	Normal-graded sandstones	Centimetric to decametric beds of fine to medium-grained sandstones. Normal graded beds with erosive bases. From base to top - massive, planar, quasi-planar, to low-angle cross laminated, and sometimes symmetric ripples at the top.	Waning gravity or high intensity combined flows	Lower shoreface
F3	Sandstones with mudstone interbeds	Centimetric sandstone beds with mudstone interbeds. Normal-graded beds of sandstones to mudstones, ending on erosive contacts. Planar, quasi-planar, low-angle, and hummocky cross laminated.	Cycles of waning oscillatory-dominant combined flows followed by suspended load settling at fair-weather conditions	Inner shelf
F4	Mudstones	Planar laminated or massive siltstones and shales.	Shelf mud – Suspended load settling	Outer shelf
F5	Marls	Light gray to white marls.	Shelf fine-grained mixed sediments – Suspended load settling	Outer shelf
F6	Impure dolostones	White dolostones. Recrystallized/fine-grained.	Mainly carbonate deposition – Suspended load settling	Outer shelf
F7	Breccias	Carbonate and terrigenous breccias.	Tectonism/seismicity	-

Table 2: Electron microprobe selected analysis for siderite components. Table upper part presents the oxides weight percentage (wt%) and table lower part present the carbonate endmembers molecular percentages.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Mean
FeO	43.19	43.06	39.87	39.51	40.21	38.23	39.23	41.65	40.05	46.75	41.97	38.76	38.00	40.39	40.35	41.03	38.41	39.30	36.59	40.34
MnO	3.13	2.78	2.54	2.52	2.37	2.71	3.25	4.06	2.69	1.94	2.47	2.58	1.76	2.69	2.34	2.95	2.05	2.18	3.23	2.64
MgO	7.96	8.98	11.83	13.04	11.93	14.54	13.50	9.01	12.55	6.43	10.97	13.56	15.13	12.13	12.43	11.57	15.38	13.68	15.13	12.09
CaO	0.71	0.12	1.57	0.40	0.75	0.32	0.49	0.89	0.91	1.44	0.65	0.43	1.32	0.56	0.60	0.75	0.21	0.38	0.50	0.68
CO _{2-calc}	37.64	38.00	40.14	40.30	39.71	41.23	41.17	38.56	40.62	37.99	39.71	40.48	41.93	40.08	40.21	40.18	41.75	40.65	41.32	40.09
Total	92.63	92.94	95.95	95.76	94.96	97.05	97.65	94.17	96.82	94.56	95.76	95.81	98.14	95.85	95.94	96.47	97.80	96.18	96.77	95.85
FeCO ₃	70.28	69.42	60.83	60.04	62.03	56.79	58.36	66.14	60.40	75.38	64.72	58.65	55.51	61.72	61.46	62.55	56.34	59.21	54.23	61.64
MnCO ₃	5.15	4.54	3.92	3.88	3.70	4.08	4.90	6.53	4.11	3.17	3.85	3.96	2.60	4.16	3.61	4.55	3.05	3.32	4.84	4.09
MgCO ₃	23.10	25.80	32.19	35.33	32.81	38.52	35.80	25.52	33.75	18.47	30.16	36.57	39.41	33.03	33.76	31.45	40.22	36.74	39.99	32.94
CaCO ₃	1.47	0.25	3.07	0.77	1.48	0.61	0.94	1.81	1.75	2.98	1.27	0.83	2.48	1.09	1.17	1.46	0.39	0.73	0.95	1.34

Table 3: Electron microprobe selected analysis of glauconitic minerals. Table upper part presents the oxides weight percentages (wt%) and lower part presents the calculated results for the structural formula and charge.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Mean
SiO ₂	52.09	52.77	48.32	53.10	53.60	51.81	51.77	52.77	52.73	51.81	51.76	50.27	51.82	48.05	48.46	48.97	51.26
TiO ₂	0.29	0.13	0.34	0.19	0.00	0.16	0.01	0.00	0.79	0.00	0.02	0.08	0.00	0.00	0.00	0.00	0.12
Al ₂ O ₃	9.83	12.00	12.41	13.07	16.81	13.23	17.35	13.99	15.74	8.84	8.17	12.82	12.77	18.80	14.89	11.98	13.29
Cr ₂ O ₃	0.10	0.03	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.01	0.14	0.02	0.01	0.02	0.04	0.03
Fe ₂ O ₃	13.23	10.51	7.95	9.65	10.30	13.05	8.49	9.53	8.38	10.36	11.85	8.94	10.57	6.02	7.51	9.93	9.77
MnO	0.03	0.06	0.00	0.06	0.01	0.06	0.00	0.14	0.08	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.03
MgO	4.53	4.27	6.20	5.17	2.99	3.92	2.62	5.37	4.80	9.11	8.40	5.66	5.63	3.03	4.00	4.87	5.03
CaO	0.96	0.28	0.20	0.24	0.12	0.11	0.21	0.13	0.45	0.20	0.12	0.96	0.64	0.15	0.05	0.05	0.30
Na ₂ O	0.25	0.40	0.08	0.08	0.07	0.09	0.07	0.04	0.09	0.04	0.06	0.09	0.05	0.07	0.08	0.15	0.11
K ₂ O	6.73	6.68	6.08	6.53	6.43	7.34	7.06	7.90	7.88	7.91	8.09	7.69	7.81	7.30	7.74	7.81	7.31
F	1.12	1.06	1.71	0.90	0.62	0.39	0.33	1.05	0.77	1.80	2.38	0.76	1.18	0.35	0.62	0.48	0.97
Cl	0.02	0.02	0.02	0.01	0.02	0.03	0.00	0.07	0.06	0.02	0.05	0.05	0.06	0.02	0.01	0.01	0.03
Total	89.17	88.20	83.30	88.98	90.97	90.19	87.89	91.12	91.76	90.10	90.91	87.45	90.54	83.84	83.39	84.30	88.26
Structural formula and charge																	
Si	3.84	3.86	3.76	3.82	3.75	3.73	3.73	3.76	3.70	3.80	3.82	3.74	3.74	3.63	3.73	3.77	3.76
^{IV} Al	0.16	0.14	0.24	0.18	0.25	0.27	0.27	0.24	0.30	0.20	0.18	0.26	0.26	0.37	0.27	0.23	0.24
Σ ^{IV}	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
TC	-0.16	-0.14	-0.24	-0.18	-0.25	-0.27	-0.27	-0.24	-0.30	-0.20	-0.18	-0.26	-0.26	-0.37	-0.27	-0.23	-0.24
Ti	0.02	0.01	0.02	0.01	0.00	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
^{VI} Al	0.69	0.90	0.89	0.93	1.13	0.85	1.21	0.93	1.00	0.57	0.52	0.86	0.83	1.30	1.09	0.86	0.91
Fe ³⁺	0.73	0.58	0.47	0.52	0.54	0.71	0.46	0.51	0.44	0.57	0.66	0.50	0.57	0.34	0.44	0.58	0.54
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.50	0.47	0.72	0.55	0.31	0.42	0.28	0.57	0.50	1.00	0.92	0.63	0.61	0.34	0.46	0.56	0.55
Σ ^{VI}	1.94	1.96	2.10	2.03	1.99	1.99	1.95	2.03	1.99	2.14	2.11	2.00	2.01	1.99	1.98	2.00	2.01
OC	-0.65	-0.59	-0.40	-0.47	-0.35	-0.44	-0.43	-0.50	-0.49	-0.58	-0.60	-0.63	-0.57	-0.37	-0.51	-0.57	-0.51
Ca	0.08	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.03	0.02	0.01	0.08	0.05	0.01	0.00	0.00	0.02
Na	0.04	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
K	0.63	0.62	0.60	0.60	0.57	0.67	0.65	0.72	0.71	0.74	0.76	0.73	0.72	0.70	0.76	0.77	0.68
Σ ^{XII}	0.74	0.70	0.63	0.63	0.59	0.70	0.68	0.73	0.75	0.76	0.78	0.82	0.78	0.73	0.78	0.79	0.72
IC	0.82	0.73	0.65	0.65	0.60	0.71	0.69	0.74	0.79	0.78	0.79	0.89	0.83	0.74	0.78	0.80	0.75

Notes: TC = tetrahedral charge; OC = octahedral charge; IC = interlayer charge; Σ^{IV} = cations on tetrahedral sites; Σ^{VI} = cations on octahedral sites; Σ^{XII} = interlayer cations.

Table 4: Electron microprobe selected analysis of phosphatic particles, results in oxides weight percentages (wt%).

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Mean
SiO ₂	0.35	0.15	0.15	0.20	0.15	0.83	0.02	0.01	0.43	0.91	0.13	0.95	0.37	0.15	0.34
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.18	0.10	0.00	0.02	0.03
Al ₂ O ₃	0.13	0.02	0.06	0.05	0.02	0.25	0.01	0.02	0.17	0.05	0.02	0.43	0.29	0.13	0.12
FeO	0.55	1.62	0.40	0.40	0.47	0.57	0.64	0.82	0.48	0.84	1.22	0.96	2.14	0.95	0.86
MnO	0.06	0.03	0.01	0.08	0.24	0.13	0.06	0.00	0.13	0.26	0.35	0.09	0.04	0.13	0.11
MgO	0.11	0.06	0.07	0.07	0.03	0.13	0.12	0.02	0.12	0.08	0.12	0.11	0.07	0.28	0.10
CaO	53.57	51.46	52.19	53.81	52.36	51.61	55.57	55.46	54.07	51.69	51.00	50.13	49.39	51.07	52.38
Na ₂ O	0.37	0.28	0.34	0.26	0.42	0.41	0.39	0.43	0.35	0.72	0.70	0.23	0.21	0.27	0.38
K ₂ O	0.05	0.03	0.06	0.04	0.03	0.11	0.04	0.02	0.11	0.06	0.04	0.22	0.16	0.08	0.07
BaO	0.03	0.00	0.07	0.06	0.10	0.15	0.05	0.05	0.13	0.02	0.05	0.06	0.01	0.14	0.06
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P ₂ O ₅	42.27	41.57	42.19	43.03	42.32	41.99	42.72	42.43	42.70	41.47	40.50	40.10	39.48	40.03	41.63
F	4.44	5.33	6.72	5.61	7.51	5.16	6.46	5.42	4.57	5.84	6.24	6.36	6.24	5.27	5.80
Cl	0.05	0.04	0.03	0.05	0.04	0.02	0.05	0.02	0.00	0.05	0.05	0.05	0.04	0.07	0.04
V ₂ O ₃	0.04	0.00	0.08	0.10	0.00	0.05	0.00	0.01	0.00	0.00	0.01	0.06	0.01	0.00	0.03
NiO	0.00	0.15	0.09	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.01	0.01	0.04	0.00	0.03
Cr ₂ O ₃	0.00	0.00	0.00	0.05	0.00	0.00	0.04	0.00	0.04	0.00	0.11	0.09	0.08	0.00	0.03
O=F-Cl	1.88	2.25	2.84	2.37	3.17	2.18	2.73	2.29	1.93	2.47	2.64	2.69	2.64	2.23	2.45
Total	100.12	98.48	99.61	101.41	100.51	99.23	103.43	102.50	101.45	99.51	98.07	97.26	95.93	96.33	99.56

Table 5: Whole-rock major oxides weight percentages (wt.%).

Drill Core	Depth (m)	Rock type	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3T}	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	LOI	Total
L4F3	27.80	Sandstone	89.30	3.20	0.59	0.01	0.16	1.86	0.03	1.96	0.14	1.34	1.17	99.78
L4F3	30.85	Sandstone	87.50	3.67	0.80	0.02	0.26	2.06	0.06	2.30	0.20	1.52	1.33	99.75
L4F3	36.70	Sandstone	86.20	1.63	2.34	0.11	0.48	3.41	0.02	0.97	0.12	2.52	2.39	100.21
L4F3	40.58	Sandstone	79.30	1.68	2.92	0.13	0.70	5.56	0.09	0.91	0.08	3.91	2.85	98.15
L4F3	45.16	Sandstone	79.10	1.17	3.67	0.17	0.90	6.93	0.02	0.67	0.05	5.09	3.58	101.36
L4F3	51.25	Siltstone	71.80	11.90	2.28	0.03	1.12	0.81	0.10	6.85	0.55	0.56	2.86	98.94
L4F3	54.35	Sandstone	70.80	9.60	4.50	0.16	1.50	1.04	0.10	6.06	0.52	0.70	4.11	99.16
L4F3	56.46	Fe-Sandstone	51.90	4.96	13.75	0.74	4.28	4.53	0.04	3.03	0.25	3.14	12.30	98.95
L4F3	60.83	Sandstone	81.90	2.51	4.74	0.28	1.63	1.40	0.06	1.88	0.11	0.95	4.54	100.02
L4F3	62.45	Siltstone	71.40	9.94	4.93	0.14	2.01	1.06	0.06	6.10	0.61	0.75	4.65	101.70
L4F3	65.44	Marl	31.50	5.77	6.86	0.47	9.01	14.80	0.04	3.65	0.33	0.66	25.20	98.32
L4F3	69.49	Dolomitic siltstone	55.50	11.00	2.89	0.12	3.92	5.95	0.07	6.65	0.58	0.78	10.60	98.11
L10F0	9.87	Siltstone	61.40	20.00	2.98	0.02	1.38	0.15	0.07	7.32	0.79	0.14	-	94.34
L10F0	12.90	Siltstone	74.40	13.00	2.19	0.04	0.79	0.17	0.11	6.23	0.48	0.13	3.48	101.11
L10F0	21.05	Sandstone	94.10	1.53	0.42	0.01	0.10	0.50	<0.01	0.71	0.07	0.38	0.78	98.61
L10F0	28.26	Mudstone	67.10	15.15	2.06	0.01	1.10	1.07	0.13	6.34	0.68	0.72	4.33	98.77
L10F0	32.24	Sandstone	89.20	1.12	1.96	0.08	0.40	2.33	0.04	0.50	0.07	1.60	2.08	99.39
L10F0	36.07	Sandstone	78.60	5.66	2.21	0.06	0.73	1.52	0.06	2.49	0.22	1.00	3.22	95.81
L10F0	38.05	Sandstone	87.60	4.88	1.16	0.03	0.44	1.95	0.03	1.85	0.19	1.42	2.37	101.94
L10F0	41.80	Sandstone	90.20	3.50	0.90	0.02	0.32	0.83	0.09	1.78	0.15	0.58	0.96	99.36
L10F0	45.94	Fe-Sandstone	70.30	3.64	9.76	0.44	1.76	1.51	0.06	1.98	0.15	1.00	7.87	98.51
L10F0	52.17	Siltstone	68.50	13.35	2.44	0.05	1.28	1.62	0.15	6.07	0.58	1.08	4.31	99.49
L10F0	54.47	Sandstone	82.00	2.28	1.45	0.07	0.36	4.38	0.07	1.37	0.09	3.00	2.43	97.52
L10F0	58.55	Sandstone	79.40	7.49	2.09	0.05	0.71	1.88	0.10	4.82	0.33	1.34	1.94	100.21
L10F0	62.34	Sandstone	75.10	3.61	4.28	0.22	1.04	5.15	0.12	2.59	0.23	3.57	4.10	100.05
L10F0	67.20	Fe-Sandstone	60.00	1.88	11.20	0.62	2.96	4.32	0.05	1.10	0.06	2.85	10.30	95.35
FE6	10.85	Sandstone	82.80	0.86	0.78	0.04	0.15	4.88	0.07	0.42	0.04	3.39	1.72	95.16
FE6	24.46	Sandstone	81.80	2.03	0.87	0.02	0.33	4.58	0.05	1.20	0.09	3.16	1.87	96.01
FE6	35.96	Mudstone	73.10	10.10	4.02	0.14	1.58	0.95	0.12	5.94	0.63	0.64	3.86	101.15
FE6	46.27	Marl	54.30	4.62	3.32	0.27	5.84	10.70	0.08	3.48	0.23	0.62	16.15	99.65
FE6	55.15	Marl	50.50	8.48	3.21	0.19	5.27	9.11	0.10	5.48	0.43	0.69	15.20	98.72
FE6	79.95	Siltstone	75.50	8.20	1.78	0.04	1.04	1.86	0.14	6.04	0.29	0.94	2.24	98.13
FE6	99.31	Mudstone	61.20	12.85	5.87	0.04	4.84	1.35	0.09	6.53	0.45	0.47	5.48	99.22
FE6	119.10	Marl	49.00	8.87	3.88	0.12	7.73	9.15	0.08	5.22	0.33	0.21	16.05	100.67
FE6	140.77	Mudstone	62.20	13.40	3.73	0.03	1.88	1.97	0.12	9.34	0.48	1.44	3.59	98.24
FE6	160.07	Siltstone	66.90	12.25	4.67	0.12	2.52	1.28	0.10	9.10	0.38	0.54	6.08	103.94
FE6	179.68	Dolostone	24.40	2.89	1.73	0.22	13.75	21.20	0.07	2.30	0.10	0.37	32.50	99.54
FE6	195.60	Marl	57.90	4.36	1.81	0.20	5.73	11.30	0.07	3.44	0.14	1.28	15.55	101.81
FE6	200.07	Siltstone	78.90	7.75	0.53	0.03	0.30	0.49	0.08	6.36	0.26	0.13	2.12	97.10

Table 6: Whole-rock trace elements concentrations (ppm).

Drill Core	Depth (m)	Rock type	Ba	Co	Cu	Cr	Cs	Ga	Hf	Li	Nb	Ni	Pb	Rb	Sc	Sn	Sr	Ta	Th	U	V	W	Y	Zn	Zr
L4F3	27.80	Sandstone	175.5	280	5	27	2.15	3.9	5.54	10	4.13	23	29	58.6	3	0.6	53.1	3.0	6.70	2.18	13	1890	33.1	5	234
L4F3	30.85	Sandstone	209.0	206	15	67	2.57	4.3	6.60	20	4.20	17	20	62.6	4	0.7	54.9	2.4	5.90	2.46	17	1340	30.9	8	264
L4F3	36.70	Sandstone	91.1	288	8	24	1.20	2.7	3.19	10	3.69	28	38	30.9	3	0.9	52.4	3.3	4.63	2.70	11	2120	19.5	4	119
L4F3	40.58	Sandstone	98.3	201	9	26	2.32	3.3	1.70	20	2.52	35	48	39.2	5	<0.5	77.5	2.1	3.97	3.52	14	1285	24.1	9	73
L4F3	45.16	Sandstone	61.9	194	13	19	1.93	4.5	1.08	30	1.74	27	29	34.5	4	0.5	67.9	2.1	2.85	3.05	14	1395	20.7	8	43
L4F3	51.25	Siltstone	483.0	61	7	72	9.66	16.5	11.20	30	13.15	20	12	216.0	7	2.8	67.5	1.6	15.50	3.71	55	489	17.7	11	433
L4F3	54.35	Sandstone	417.0	63	15	65	6.68	11.5	6.75	30	8.80	19	48	153.0	8	1.9	62.6	1.3	8.70	2.31	55	354	19.7	12	238
L4F3	56.46	Fe-Sandstone	201.0	108	11	45	4.55	11.3	4.06	70	4.58	36	31	103.5	8	0.8	76.8	1.0	4.75	2.05	34	594	32.1	23	138
L4F3	60.83	Sandstone	185.0	199	5	23	1.17	2.8	3.18	30	2.40	13	18	41.4	4	0.8	36.2	2.2	2.38	0.91	13	1290	17.6	69	122
L4F3	62.45	Siltstone	363.0	92	5	68	5.67	13.8	6.94	40	10.35	21	12	158.0	6	1.5	58.9	1.7	10.05	2.81	58	598	19.0	55	251
L4F3	65.44	Marl	171.0	19	12	47	5.09	8.1	2.32	20	5.69	12	7	100.0	6	1.1	63.3	0.8	5.91	1.84	43	88	15.8	10	91
L4F3	69.49	Dolomitic siltstone	348.0	31	18	82	10.60	13.9	5.02	60	10.30	24	10	195.0	9	2.1	86.5	1.0	11.15	3.15	63	164	25.6	21	196
L10F0	9.87	Siltstone	442.0	18	23	103	26.10	26.7	6.45	20	16.85	30	10	311.0	16	3.9	261.0	1.5	19.30	4.08	95	46	27.8	15	234
L10F0	12.90	Siltstone	509.0	84	18	57	10.70	13.4	6.83	10	10.95	18	12	202.0	9	2.7	163.0	1.7	11.05	2.36	50	453	28.5	10	248
L10F0	21.05	Sandstone	68.1	275	3	16	1.27	2.1	3.29	20	2.80	7	8	25.8	2	0.6	34.0	3.5	4.02	1.41	7	2140	19.4	2	128
L10F0	28.26	Mudstone	456.0	78	4	94	18.80	19.4	15.95	20	16.50	30	24	249.0	14	2.7	167.5	2.1	20.50	5.32	83	459	45.8	13	616
L10F0	32.24	Sandstone	68.0	278	6	13	0.97	1.8	3.37	10	2.86	18	25	20.5	4	<0.5	52.4	3.2	5.65	3.00	8	2100	40.6	3	153
L10F0	36.07	Sandstone	244.0	167	4	36	5.55	8.4	2.68	10	5.60	18	18	107.0	6	0.6	75.8	2.1	8.72	2.51	31	1435	27.6	6	114
L10F0	38.05	Sandstone	115.5	197	4	41	5.75	7.7	2.85	10	5.91	20	24	86.4	6	1.3	76.8	2.8	9.63	4.18	31	1740	40.7	5	113
L10F0	41.80	Sandstone	264.0	222	2	24	3.82	4.3	3.62	10	4.79	11	12	63.2	3	0.8	51.5	3.0	6.84	1.80	21	1625	26.5	4	144
L10F0	45.94	Fe-Sandstone	240.0	178	9	23	2.57	5.3	7.77	10	4.43	20	21	68.9	6	0.5	57.2	2.4	6.84	2.36	16	1460	31.8	6	330
L10F0	52.17	Siltstone	369.0	54	3	88	16.25	17.0	7.63	30	13.60	24	19	235.0	13	3.1	115.0	1.8	13.85	4.57	77	342	22.7	13	291
L10F0	54.47	Sandstone	104.5	231	8	18	1.26	3.2	2.90	10	3.15	25	40	45.6	4	<0.5	91.2	2.8	4.38	3.56	11	1960	24.6	5	125
L10F0	58.55	Sandstone	362.0	124	11	66	3.76	9.4	8.04	30	7.30	28	23	133.0	6	1.3	79.5	1.8	8.37	3.03	34	1060	25.5	8	332
L10F0	62.34	Sandstone	196.0	187	6	46	2.22	4.7	2.79	20	4.70	34	39	63.5	6	1.2	87.4	2.1	4.98	3.57	22	1095	22.0	8	119
L10F0	67.20	Fe-Sandstone	93.7	148	6	11	2.83	7.1	1.37	50	1.96	9	12	54.6	4	<0.5	68.4	1.8	2.02	1.90	14	1380	18.7	9	49
FE6	10.85	Sandstone	68.6	244	10	11	0.97	2.0	2.11	10	2.00	29	47	18.4	4	<0.5	72.1	2.8	4.49	3.72	8	1935	34.6	5	88
FE6	24.46	Sandstone	78.5	220	8	19	2.73	6.0	2.02	50	2.63	13	14	52.8	4	<0.5	48.0	2.5	2.91	2.20	18	1810	15.6	8	83
FE6	35.96	Mudstone	441.0	56	14	90	7.56	13.7	11.10	40	11.75	20	12	182.0	9	2.6	67.5	1.4	13.20	3.18	65	344	22.4	15	426
FE6	46.27	Marl	266.0	67	5	41	2.54	4.1	4.86	30	4.29	9	57	78.6	5	1.3	52.7	1.1	4.20	1.61	25	412	16.0	126	197
FE6	55.15	Marl	386.0	32	16	55	6.92	12.2	5.80	40	9.49	22	19	153.0	7	1.7	87.2	1.0	11.75	3.49	45	181	22.8	52	222
FE6	79.95	Siltstone	410.0	79	10	29	1.65	6.8	7.06	30	7.72	10	15	121.5	4	1.3	63.5	1.4	8.75	2.58	27	537	18.6	145	264
FE6	99.31	Mudstone	277.0	17	1	60	8.51	17.5	3.46	150	10.75	33	13	159.5	11	1.7	62.4	0.9	10.60	2.55	60	18	19.6	33	129
FE6	119.10	Marl	222.0	12	22	47	5.16	12.8	3.50	90	7.61	12	8	119.5	6	1.9	59.2	0.8	8.79	2.42	39	61	16.4	25	133
FE6	140.77	Mudstone	332.0	24	26	61	6.04	18.7	5.14	80	12.80	25	33	176.5	9	3.1	64.9	1.3	13.90	4.53	70	66	27.6	278	169
FE6	160.07	Siltstone	254.0	34	24	56	4.10	17.2	4.31	70	10.35	25	20	158.0	7	2.0	43.0	1.1	12.00	4.76	77	186	21.8	505	162
FE6	179.68	Dolostone	100.5	13	8	14	0.66	3.9	3.32	10	2.65	3	6	41.1	2	0.7	39.9	0.4	4.43	0.75	13	56	11.0	23	121
FE6	195.60	Marl	228.0	58	8	15	0.96	5.7	9.51	10	3.91	4	11	63.4	3	0.5	51.5	1.0	7.42	2.99	18	460	21.1	77	375
FE6	200.07	Siltstone	1355.0	224	6	24	1.32	7.9	12.90	<10	7.80	3	18	122.5	3	0.7	64.8	3.2	14.15	2.70	16	1675	21.0	16	515

Table 7: Whole-rock rare-earth elements concentrations (ppm) and element ratios.

Drill Core	Depth (m)	Rock type	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	ΣLREE	ΣMREE	ΣHREE	(La/Sm) _N	La/Yb _N	(Gd/Yb) _N
L4F3	27.80	Sandstone	15.1	36.5	4.60	21.4	6.72	1.42	7.04	0.99	6.00	1.22	3.37	0.42	2.47	0.39	107.6	92.8	22.2	14.9	0.34	0.45	1.65
L4F3	30.85	Sandstone	17.0	42.6	5.29	26.5	7.40	1.47	7.21	1.06	6.11	1.05	3.11	0.44	2.70	0.43	122.4	107.5	23.3	14.9	0.34	0.46	1.55
L4F3	36.70	Sandstone	12.8	27.3	3.07	12.8	3.07	0.78	3.56	0.52	3.11	0.72	1.85	0.29	1.80	0.25	71.9	63.4	11.0	8.5	0.63	0.52	1.15
L4F3	40.58	Sandstone	13.6	31.8	3.83	16.3	3.50	1.00	4.03	0.58	3.61	0.65	2.06	0.30	1.46	0.21	82.9	74.1	12.7	8.9	0.58	0.68	1.60
L4F3	45.16	Sandstone	15.2	32.5	4.03	18.8	4.92	0.84	4.28	0.64	3.26	0.65	1.78	0.27	1.49	0.21	88.9	80.6	13.9	8.3	0.46	0.75	1.66
L4F3	51.25	Siltstone	32.4	66.1	7.45	26.4	3.62	0.70	2.94	0.48	3.14	0.66	2.21	0.34	2.71	0.34	149.5	139.6	10.9	9.9	1.34	0.88	0.63
L4F3	54.35	Sandstone	27.1	56.2	5.85	24.4	4.14	0.85	4.14	0.60	3.62	0.69	1.81	0.30	2.09	0.28	132.1	122.7	13.4	9.4	0.98	0.95	1.15
L4F3	56.46	Fe-Sandstone	22.1	46.7	6.25	32.9	8.91	1.92	8.29	1.10	5.88	1.06	2.79	0.37	1.93	0.25	140.5	127.1	26.1	13.4	0.37	0.84	2.49
L4F3	60.83	Sandstone	12.9	25.4	3.13	15.0	3.50	0.82	3.46	0.47	2.80	0.51	1.40	0.21	1.20	0.14	70.9	64.2	11.1	6.7	0.55	0.79	1.67
L4F3	62.45	Siltstone	25.7	52.3	5.95	22.2	4.45	0.79	3.50	0.56	3.21	0.71	2.00	0.31	2.19	0.35	124.2	114.9	12.5	9.3	0.87	0.86	0.93
L4F3	65.44	Marl	19.1	37.3	4.75	18.4	4.20	0.67	3.42	0.45	2.78	0.46	1.47	0.19	1.51	0.23	94.9	87.8	11.5	7.1	0.68	0.93	1.31
L4F3	69.49	Dolomitic siltstone	36.1	74.2	8.84	33.7	6.74	1.22	5.57	0.81	4.74	0.92	2.52	0.38	2.32	0.36	178.4	166.4	19.1	12.1	0.80	1.14	1.39
L10F0	9.87	Siltstone	56.9	109.5	11.95	44.6	7.02	1.07	4.54	0.80	4.33	1.07	3.03	0.45	3.11	0.54	248.9	235.6	17.8	13.3	1.22	1.34	0.85
L10F0	12.90	Siltstone	33.0	68.6	7.86	32.2	6.13	1.13	5.08	0.74	4.97	0.88	2.97	0.40	2.74	0.48	167.2	154.0	18.1	13.2	0.81	0.88	1.07
L10F0	21.05	Sandstone	9.8	24.5	2.87	13.0	3.86	0.88	4.88	0.75	3.73	0.63	1.67	0.27	1.66	0.24	68.7	59.8	14.1	9.0	0.38	0.43	1.70
L10F0	28.26	Mudstone	57.2	123.0	12.95	50.8	7.62	1.19	6.16	1.00	7.07	1.34	5.00	0.67	6.18	0.80	281.0	258.9	23.0	22.1	1.13	0.68	0.58
L10F0	32.24	Sandstone	15.9	39.7	4.58	19.9	5.38	1.10	6.47	1.02	5.72	1.36	3.85	0.57	3.92	0.48	110.0	93.0	19.7	16.9	0.44	0.30	0.96
L10F0	36.07	Sandstone	24.6	56.0	6.50	26.2	5.48	0.98	5.79	0.80	4.67	0.96	2.57	0.36	2.53	0.32	137.8	125.6	17.7	12.2	0.67	0.71	1.32
L10F0	38.05	Sandstone	28.8	67.7	7.96	33.3	6.40	1.42	6.83	1.10	6.66	1.40	4.34	0.60	3.92	0.59	171.0	152.4	22.4	18.6	0.68	0.54	1.01
L10F0	41.80	Sandstone	15.9	39.1	4.23	18.4	4.60	0.98	5.23	0.84	4.52	0.84	2.80	0.37	2.29	0.32	100.4	88.4	16.2	12.0	0.52	0.51	1.32
L10F0	45.94	Fe-Sandstone	16.7	41.0	5.08	22.1	7.46	1.44	8.04	1.12	5.80	1.08	2.84	0.35	2.60	0.45	116.1	101.8	23.9	14.2	0.34	0.47	1.79
L10F0	52.17	Siltstone	38.9	83.6	8.49	29.7	4.10	0.66	3.20	0.54	3.39	0.65	2.26	0.42	2.79	0.36	179.1	168.7	11.9	10.4	1.42	1.02	0.66
L10F0	54.47	Sandstone	16.2	34.8	4.11	18.1	4.00	0.99	4.23	0.66	3.72	0.77	2.14	0.30	2.10	0.30	92.4	82.4	13.6	10.0	0.61	0.57	1.17
L10F0	58.55	Sandstone	25.6	53.9	6.50	26.5	5.41	1.07	4.97	0.77	4.45	0.92	2.62	0.38	2.49	0.37	136.0	124.0	16.7	12.0	0.71	0.75	1.16
L10F0	62.34	Sandstone	17.2	35.1	4.47	21.4	4.70	1.15	5.04	0.66	4.15	0.82	2.06	0.26	2.13	0.22	99.4	89.1	15.7	10.3	0.55	0.59	1.37
L10F0	67.20	Fe-Sandstone	11.1	24.1	3.34	16.3	4.15	0.86	3.53	0.59	2.86	0.61	1.60	0.18	1.40	0.20	70.8	63.4	12.0	7.4	0.40	0.58	1.46
FE6	10.85	Sandstone	17.1	38.1	4.42	20.9	5.79	1.26	6.30	0.98	5.46	1.09	3.10	0.39	2.66	0.40	108.0	93.9	19.8	14.1	0.44	0.47	1.37
FE6	24.46	Sandstone	12.3	25.9	3.12	12.3	3.51	0.65	3.37	0.45	2.69	0.48	1.46	0.19	1.18	0.19	67.8	61.2	10.7	6.6	0.53	0.76	1.65
FE6	35.96	Mudstone	31.3	59.5	6.91	26.1	4.15	0.74	3.46	0.52	3.66	0.66	2.32	0.38	1.97	0.34	142.0	132.2	12.5	9.9	1.13	1.17	1.02
FE6	46.27	Marl	12.8	25.8	3.12	13.7	2.80	0.87	3.33	0.50	2.70	0.45	1.28	0.22	1.42	0.21	69.2	62.4	10.2	6.8	0.69	0.66	1.36
FE6	55.15	Marl	31.7	64.0	7.52	28.1	5.25	0.94	4.21	0.65	4.00	0.71	2.34	0.33	2.26	0.31	152.3	141.7	15.1	10.6	0.91	1.03	1.08
FE6	79.95	Siltstone	21.2	45.9	5.19	20.9	3.74	0.80	3.30	0.51	3.03	0.56	1.92	0.28	1.88	0.24	109.5	101.0	11.4	8.4	0.85	0.83	1.02
FE6	99.31	Mudstone	26.5	53.1	5.55	21.9	3.70	0.66	3.21	0.51	3.03	0.62	2.28	0.32	2.07	0.31	123.8	114.6	11.1	9.1	1.07	0.94	0.90
FE6	119.10	Marl	24.1	47.5	5.02	19.4	2.94	0.63	2.94	0.37	2.58	0.51	1.74	0.22	1.86	0.24	110.1	102.5	9.5	7.5	1.23	0.95	0.92
FE6	140.77	Mudstone	39.0	77.1	8.49	35.2	5.55	0.89	5.50	0.81	4.84	0.91	2.82	0.40	2.58	0.30	184.4	171.7	17.6	12.7	1.05	1.11	1.23
FE6	160.07	Siltstone	34.2	63.2	6.80	24.0	4.60	0.69	3.89	0.56	3.24	0.80	2.13	0.29	1.90	0.28	146.6	137.4	13.0	9.2	1.12	1.32	1.19
FE6	179.68	Dolostone	10.2	23.0	2.54	9.9	1.55	0.33	1.57	0.28	1.48	0.28	1.07	0.15	0.98	0.13	53.5	49.1	5.2	4.4	0.99	0.76	0.93
FE6	195.60	Marl	16.5	38.1	4.82	20.4	4.62	0.70	3.81	0.58	3.53	0.73	1.96	0.26	2.07	0.25	98.3	89.0	13.2	9.4	0.54	0.58	1.07
FE6	200.07	Siltstone	22.5	45.1	5.27	16.8	3.33	0.59	3.22	0.51	3.37	0.65	2.37	0.34	2.26	0.36	106.7	96.8	11.0	9.9	1.01	0.73	0.82

Table 8: Whole-rock element ratios commented along the text and used on diagrams.

Drill Core	Depth (m)	Rock type	Th/Sc	Zr/Sc	Al/Si	Zr/10	K ₂ O/Na ₂ O	Zr/Hf
L4F3	27.80	Sandstone	2.23	78.00	0.04	23.40	65.33	42.24
L4F3	30.85	Sandstone	1.48	66.00	0.05	26.40	38.33	40.00
L4F3	36.70	Sandstone	1.54	39.67	0.02	11.90	48.50	37.30
L4F3	40.58	Sandstone	0.79	14.60	0.02	7.30	10.11	42.94
L4F3	45.16	Sandstone	0.71	10.75	0.02	4.30	33.50	39.81
L4F3	51.25	Siltstone	2.21	61.86	0.19	43.30	68.50	38.66
L4F3	54.35	Sandstone	1.09	29.75	0.15	23.80	60.60	35.26
L4F3	56.46	Fe-Sandstone	0.59	17.25	0.11	13.80	75.75	33.99
L4F3	60.83	Sandstone	0.60	30.50	0.03	12.20	31.33	38.36
L4F3	62.45	Siltstone	1.68	41.83	0.16	25.10	101.67	36.17
L4F3	65.44	Marl	0.99	15.17	0.21	9.10	91.25	39.22
L4F3	69.49	Dolomitic siltstone	1.24	21.78	0.22	19.60	95.00	39.04
L10F0	9.87	Siltstone	1.21	14.63	0.37	23.40	104.57	36.28
L10F0	12.90	Siltstone	1.23	27.56	0.20	24.80	56.64	36.31
L10F0	21.05	Sandstone	2.01	64.00	0.02	12.80	-	38.91
L10F0	28.26	Mudstone	1.46	44.00	0.26	61.60	48.77	38.62
L10F0	32.24	Sandstone	1.41	38.25	0.01	15.30	12.50	45.40
L10F0	36.07	Sandstone	1.45	19.00	0.08	11.40	41.50	42.54
L10F0	38.05	Sandstone	1.61	18.83	0.06	11.30	61.67	39.65
L10F0	41.80	Sandstone	2.28	48.00	0.04	14.40	19.78	39.78
L10F0	45.94	Fe-Sandstone	1.14	55.00	0.06	33.00	33.00	42.47
L10F0	52.17	Siltstone	1.07	22.38	0.22	29.10	40.47	38.14
L10F0	54.47	Sandstone	1.10	31.25	0.03	12.50	19.57	43.10
L10F0	58.55	Sandstone	1.40	55.33	0.11	33.20	48.20	41.29
L10F0	62.34	Sandstone	0.83	19.83	0.05	11.90	21.58	42.65
L10F0	67.20	Fe-Sandstone	0.51	12.25	0.04	4.90	22.00	35.77
FE6	10.85	Sandstone	1.12	22.00	0.01	8.80	6.00	41.71
FE6	24.46	Sandstone	0.73	20.75	0.03	8.30	24.00	41.09
FE6	35.96	Mudstone	1.47	47.33	0.16	42.60	49.50	38.38
FE6	46.27	Marl	0.84	39.40	0.10	19.70	43.50	40.53
FE6	55.15	Marl	1.68	31.71	0.19	22.20	54.80	38.28
FE6	79.95	Siltstone	2.19	66.00	0.12	26.40	43.14	37.39
FE6	99.31	Mudstone	0.96	11.73	0.24	12.90	72.56	37.28
FE6	119.10	Marl	1.47	22.17	0.20	13.30	65.25	38.00
FE6	140.77	Mudstone	1.54	18.78	0.24	16.90	77.83	32.88
FE6	160.07	Siltstone	1.71	23.14	0.21	16.20	91.00	37.59
FE6	179.68	Dolostone	2.22	60.50	0.13	12.10	32.86	36.45
FE6	195.60	Marl	2.47	125.00	0.09	37.50	49.14	39.43
FE6	200.07	Siltstone	4.72	171.67	0.11	51.50	79.50	39.92

Table 9: Whole-rock Nd isotopic results.

Drill Core	Depth (m)	Petrology	Sm (ppm)	Nd (ppm)	Sm/Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	2SE (*10 ⁻⁶)	f _{Sm/Nd}	EpsNd(0)	EpsNd(t)	T _{DM} (Ga)
L4F3	27.80	Sandstone	6.64	21.94	0.30	0.1831	0.512168	5	-0.07	-9.01	-6.38	5.25*
L4F3	30.85	Sandstone	7.80	25.67	0.30	0.1837	0.512206	11	-0.06	-8.27	-5.77	5.10*
L4F3	36.70	Sandstone	3.52	14.47	0.24	0.1472	0.511808	9	-0.25	-16.03	-6.08	2.89*
L4F3	40.58	Sandstone	4.19	17.08	0.25	0.1483	0.511815	22	-0.24	-15.90	-6.17	2.92*
L4F3	45.16	Sandstone	5.20	20.50	0.25	0.1535	0.512013	5	-0.22	-12.04	-3.36	2.65*
L4F3	51.25	Siltstone	3.72	24.91	0.15	0.0903	0.511237	7	-0.54	-27.17	-5.59	2.24*
L4F3	54.35	Sandstone	4.70	25.42	0.18	0.1118	0.511463	17	-0.43	-22.76	-5.57	2.38
L4F3	56.46	Fe-Sandstone	9.83	34.38	0.29	0.1729	0.512126	4	-0.12	-9.83	-5.11	3.63*
L4F3	60.83	Sandstone	3.74	15.25	0.24	0.1480	0.511833	13	-0.24	-15.55	-5.76	2.86*
L4F3	62.45	Siltstone	4.36	23.55	0.19	0.1119	0.511471	12	-0.43	-22.61	-5.45	2.37
L4F3	65.44	Marl	3.89	18.40	0.21	0.1277	0.511637	7	-0.35	-19.37	-5.42	2.51
L4F3	69.49	Dolomitic siltstone	6.92	35.97	0.19	0.1163	0.511524	7	-0.41	-21.58	-5.32	2.39
L10F0	9.87	Siltstone	7.47	46.45	0.16	0.0972	0.511303	5	-0.50	-25.89	-5.72	2.29*
L10F0	12.90	Siltstone	5.96	32.36	0.18	0.1114	0.511457	9	-0.43	-22.88	-5.61	2.38
L10F0	21.05	Sandstone	3.89	13.78	0.28	0.1704	0.512039	9	-0.13	-11.53	-6.31	3.77*
L10F0	28.26	Mudstone	7.79	52.66	0.15	0.0895	0.512290	12	-0.54	-6.63	15.12	0.92*
L10F0	32.24	Sandstone	6.03	26.53	0.23	0.1373	0.511762	9	-0.30	-16.93	-4.95	2.58*
L10F0	36.07	Sandstone	5.05	18.99	0.27	0.1609	0.511993	9	-0.18	-12.43	-5.25	3.12*
L10F0	38.05	Sandstone	6.55	30.17	0.22	0.1311	0.511703	6	-0.33	-18.08	-4.84	2.50*
L10F0	41.80	Sandstone	5.07	19.71	0.26	0.1556	0.511939	14	-0.21	-13.48	-5.23	2.97*
L10F0	45.94	Fe-Sandstone	7.33	22.38	0.33	0.1980	0.512104	13	0.01	-10.26	-10.68	-
L10F0	52.17	Siltstone	4.17	31.65	0.13	0.0797	0.511185	9	-0.59	-28.19	-4.44	2.12*
L10F0	54.47	Sandstone	4.36	18.15	0.24	0.1453	0.511799	9	-0.26	-16.21	-5.87	2.82*
L10F0	58.55	Sandstone	5.56	25.39	0.22	0.1324	0.511700	11	-0.32	-18.14	-5.17	2.54*
L10F0	62.34	Sandstone	5.33	21.06	0.25	0.1531	0.511911	10	-0.22	-14.03	-5.27	2.91*
L10F0	67.20	Fe-Sandstone	4.45	16.62	0.27	0.1618	0.512039	12	-0.17	-11.53	-4.55	3.03*
FE6	10.85	Sandstone	5.71	20.64	0.28	0.1671	0.512035	8	-0.15	-11.61	-5.70	3.45*
FE6	24.46	Sandstone	3.26	13.11	0.25	0.1502	0.511912	12	-0.23	-14.01	-4.65	2.76*
FE6	35.96	Mudstone	4.57	26.11	0.18	0.1058	0.511408	9	-0.46	-23.84	-5.43	2.32
FE6	46.27	Marl	3.52	13.98	0.25	0.1523	0.511890	10	-0.22	-14.44	-5.51	2.92*
FE6	55.15	Marl	5.13	27.04	0.19	0.1148	0.510912	19	-0.41	-33.51	-16.94	3.35
FE6	79.95	Siltstone	4.00	21.00	0.19	0.1152	0.511428	9	-0.41	-23.45	-6.95	2.52
FE6	99.31	Mudstone	3.05	16.48	0.18	0.1117	0.511405	9	-0.43	-23.90	-6.69	2.47
FE6	119.10	Marl	3.13	18.18	0.17	0.1041	0.511268	10	-0.47	-26.57	-7.81	2.49
FE6	140.77	Mudstone	6.27	34.79	0.18	0.1090	0.511361	5	-0.44	-24.75	-7.00	2.47
FE6	160.07	Siltstone	-	-	-	-	-	-	-	-	-	-
FE6	179.68	Dolostone	1.97	10.46	0.19	0.1139	0.511437	19	-0.42	-23.27	-6.51	2.47
FE6	195.60	Marl	4.49	20.26	0.22	0.1339	0.511620	10	-0.32	-19.70	-7.04	2.76*
FE6	200.07	Siltstone	3.20	17.76	0.18	0.1088	0.511290	6	-0.44	-26.14	-8.34	2.57

Note: *Model ages of altered samples that do not reflect provenance. See text for further explanations.

CAPÍTULO 5

CONSIDERAÇÕES FINAIS

5 CONSIDERAÇÕES FINAIS

A sucessão estudada é interpretada como depositada em ambiente marinho raso, em uma plataforma dominada por tempestades. A porção basal compreende lamitos, margas e dolomitos impuros associados a Formação Terra Preta. A porção superior é relacionada a Formação São Benedito, compreendendo essencialmente arenitos e lamitos. As associações de fácies e a paragênese mineral autigênica de siderita, glauconita, fluorapatita, pirita e dolomita sugerem condições anóxicas e deposição entre a plataforma externa e *shoreface* inferior.

As composições isotópicas de Nd, principalmente dos arenitos, não podem ser utilizadas para a proveniência, devido a contaminação por fluorapatita autigênica. Lamitos levemente empobrecidos em elementos terras raras médios sugerem redistribuição diagenética quando comparados aos arenitos, enriquecidos nos mesmos elementos. O processo de redistribuição ocorreu por meio da dessorção de argilominerais, nos lamitos, e posterior absorção em fluorapatita, nos arenitos, durante a migração de fluidos conatos. Uma amostra de lamito apresentou idade modelo de 0,92 Ga, incomparável às assinaturas conhecidas para o Cráton Amazônico. Esse valor pode ser um produto de fracionamento isotópico, causado durante a remobilização dos elementos terras raras.

Dados faciológicos e geoquímicos apontam rochas félsicas e sedimentares como fontes dos sedimentos terrígenos da sucessão. Os mesmos dados são favoráveis a classificação da bacia como de rifte intracratônico. Isótopos de Nd em rocha total indicam áreas proximais, relacionadas as províncias Rondônia-Juruena, Tapajós-Parima e Amazônia Central, como fontes dos sedimentos, ao menos no extremo noroeste da bacia. Uma única amostra rendeu idade modelo distinta de 3,35 Ga, sugerindo breve mudança na proveniência para áreas ao leste do Cráton Amazônico, relacionadas as Províncias Carajás e Transamazônia, ou a rochas desconhecidas.

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