Universidade de Brasília - UnB
Instituto de Geociências – IG

EVOLUÇÃO TECTONO-ESTRATIGRÁFICA DAS BACIAS RIFTE-SAG PALEO/MESOPROTEROZOICAS DOS ESTADOS DE GOIÁS E TOCANTINS

TESE DE DOUTORADO Nº 181

RAFAEL TOSCANI GOMES DA SILVEIRA

Orientador:
Prof. Dr. José Eloi Guimarães Campos

Programa de Pós Graduação em Geologia
Área de Concentração: Geologia Regional

Brasília, Novembro de 2021.

Universidade de Brasília - UnB
Instituto de Geociências – IG

EVOLUÇÃO TECTONO-ESTRATIGRÁFICA DAS BACIAS RIFTE-SAG PALEO/MESOPROTEROZOICAS DOS ESTADOS DE GOIÁS E TOCANTINS

TESE DE DOUTORADO Nº 181

RAFAEL TOSCANI GOMES DA SILVEIRA

Programa de Pós Graduação em Geologia
Área de Concentração: Geologia Regional

Banca Examinadora:

Prof. Dr. José Eloi Guimarães Campos (Universidade de Brasília)
Prof. Dr. Carlos Jorge de Abreu (Universidade de Brasília)
Prof. Dr. André Danderfer Filho (Universidade Federal de Ouro Preto)
Prof. Dr. Alexandre Uhlein (Universidade Federal de Minas Gerais)

Se Silveira, Rafael Toscani Gomes
EVOLUÇÃO TECTONO-ESTRATIGRÁFICA DAS BACIAS RIFTE-SAG PALEO/MESOPROTEROZOICAS DOS ESTADOS DE GOIÁS E TOCANTINS / Rafael Toscani Gomes Silveira; orientador José Eloi Guimarães Campos. -- Brasília, 2021.
134 p.

Tese (Doutorado - Doutorado em Geologia) -- Universidade de Brasília, 2021.

1. Geologia Regional. 2. Estratigrafia. 3. Geologia Isotópica. 4. Proveniência Sedimentar. 5. Sedimentologia. I. Guimarães Campos, José Eloi , orient. II. Título.

"It's not about how hard you hit. It's about how hard you can get hit and keep moving forward. How much you can take and keep moving forward."

Rocky Balboa, Sylvester Stallone.

"O importante é nunca desistir"
Mãe e Pai.

Agradecimentos

A minha esposa Débora pela extrema paciência, parceria e amor. Sem isso seria simplesmente impossível. Além disso, você me deu a coisa mais importante nessa vida, uma família, com o mais novo membro ainda na barriga, o Tomás e o seu irmão cachorro (Amendoim).

Aos meus pais e ao meu irmão por toda a base e apoio desde a infância, sempre foram meus primeiros, únicos e verdadeiros fãs. Obrigado também a todos que torceram por mim, especialmente aos tios, sogros, primos, geólogos e amigos.

Ao meu orientador por essa parceria que começou em 2013, desde o trabalho final de graduação, mestrado e doutorado.

Ao Prof. Marco Caçador e ao meu amigo Caio Aguiar pela disponibilidade para tirar dúvidas, especialmente nos domingos à noite. Ao meu amigo Deusavan pela preparação das amostras para geocronologia. Aos professores do Instituto de Geociências que contribuíram para minha formação.

Ao IG/UnB e a toda sua equipe de servidores pelas facilidades laboratoriais que contribuíram com esta pesquisa e ao Centro de Hidrografia da Marinha (DHN/MB) por todo suporte e estabilidade. Aos Comandantes Ivan e Peçanha pela compreensão, especialmente, na fase final dessa Tese.

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001, CAPES-PrInT (88881.312018/2018-01) e CNPq (MCTIC/CNPq 28/2018 - 420308/2018-0).

Por fim, a uma energia superior.

RESUMO

Esta pesquisa versa sobre a evolução tectono-estratigráfica das bacias rifte-sag Paleo/Mesoproterozoicas desenvolvidas na margem oeste do Cráton São Francisco e foi realizada com base em mapeamento geológico, estudo petrográfico, estratigráfico, geoquímico, sedimentológico, uso de dados magnetométricos e geocronologia de U/Pb em zircão. No Grupo Natividade, definiram-se onze litotipos que foram agrupados em quatro associações faciológicas: i) Areno-silto-carbonática; ii) Areno-conglomerática; iii) Arenosa; iv) Silto-argilosa. Deste modo, foi possível estabelecer quatro ambientes deposicionais para o Grupo Natividade: plataforma mista; plataforma interna siliciclástica; plataforma siliciclástica de mar aberto; e turbiditos de água rasa (depósitos de fluxo de massa). A Sequência Natividade seria mais rasa na porção sul com o predomínio de carbonatos e turbiditos de água rasa e mais profunda para o norte, com o predomínio de sedimentos finos, sendo o paleorelevo um fator controlador da sedimentação. Os dados de U/Pb, para a rocha metavulcânica observada na base da sucessão, indicam idade de 1824 Ma (amostra VU39), já a idade máxima de deposição nas rochas metassedimentares é de 1776 Ma (amostras T1, T3 e T4). Esses dados indicam que o Grupo Natividade foi depositado no Paleoproterozoico tardio (Estateriano), possivelmente englobando o Mesoproterozoico inicial (Calimiano), sendo posicionado na estratigrafia regional entre os grupos Araí e Traíras/Serra da Mesa. O vulcanismo do Grupo Natividade é bastante restrito e apresenta comportamento geoquímico semelhante ao observado no Grupo Araí, indicando que esses processos magmáticos são reflexos do rifteamento ocorrido mais ao sul (rifte Araí). O modelo geológico considera o Grupo Natividade (ao norte) como uma bacia do tipo sag sob efeito de subsidência termo-flexural que é separada do Grupo Araí (ao sul) pelo Bloco Almas interpretado como um paleorelevo elevado. A pesquisa também aborda a Formação Água Morna (Grupo Araí) que é uma sequência Paleoproterozoica com distribuição regional descontínua, pouco espessa e com homogeneidade lateral. Os principais registros sedimentares são compostos por quartzito feldspático/metarcósio, imaturo, frequentemente rico em seixos e com presença comum de estratificações cruzadas planares e acanaladas. Secundariamente, há deposição de metaconglomerados e metagrauvacas. Essas características indicam ambiente deposicional do tipo fluvial entrelaçado dominado por areia, com canais ativos, barras e canais abandonados. O modelo geotectônico proposto sugere uma bacia do tipo pré-rifte que faz parte dos estágios iniciais do rifte Araí. Nesse sentido, a sequência seria controlada por subsidência térmica resultante do resfriamento crustal após soerguimento astenosférico passivo. Dados geocronológicos de zircão detrítico indicam uma proveniência do embasamento local, com uma fonte no Sideriano (2,47 a 2,32 Ga) ligada ao Terreno Almas, e uma fonte mais significativa no Riaciano (2,28 a 2,05 Ga) relacionada especialmente ao Terreno Aurumina que é constituído pela Suíte Aurumina (2,11 a 2,16 Ga) e pela Formação Ticunzal (2,16 a 2,19 Ga). A idade máxima de deposição de 2,15 Ga (Marques, 2009), associada a dados sedimentológicos fornecem um argumento sólido para separar a Formação Água Morna da Formação Arraias (1,771 Ga) sobreposta, na base da estratigrafia do Grupo Araí.

Palavras-chave*: Bacias Paleo-Mesoproterozoicas; Grupo Natividade; Formação Água Morna; Grupo Araí; paleorelevo; plataforma mista; turbiditos de água rasa; estágio pré-rifte; sistema de rios entrelaçados.*

ABSTRACT

This research focus on the tectonostratigraphic evolution of the Paleo/Mesoproterozoic rift-sag basins developed on the western edge of the São Francisco Craton. The methodology was based on geological mapping, petrographic, stratigraphic and sedimentological studies, use of magnetometric data, and U/Pb geochronology, especially on detrital zircon. In the Natividade Group, it was possible to delimit eleven sedimentary rock types grouped into four rock assemblages: i) Sand-Silt-Carbonate; ii) Sand-Conglomerate; iii) Sand; and iv) Silt-Clay. Thus, it was possible to establish four depositional environments for the Natividade Group: mixed platform (siliciclastic-carbonate deposition); internal siliciclastic platform; open-marine siliciclastic platform; and a shallow water turbidite (mass flow slope deposition). The Natividade Sequence was shallower in the southern portion with a predominance of carbonate and gravitational flux deposits and deeper to the north, evidenced by the northward predominance of fine-grained sediments. The paleorelief would be a factor that controls sedimentation. The tectonostratigraphic evolution of the intracontinental Natividade Basin is evaluated by zircon U/Pb analysis. The U/PB age for the metavolcanic rock is 1,824 Ma (sample VU39), whereas the maximum depositional age for metasedimentary rocks is 1,776 Ma (samples T1, T3, and T4). These data indicate that the Natividade Group was deposited in the late Paleoproterozoic (Statherian), possibly entering the early Mesoproterozoic (Calymmian), positioned in the stratigraphy between the Araí and Traíras/Serra da Mesa groups. The volcanism of the Natividade Group is restricted and presents a geochemical characteristic similar to the Araí Group (further south), indicating that these magmatic processes are related to the Araí rift. The geological model considers the Natividade Group as a sag-type basin under the effect of thermo-flexural subsidence that is separated from the Araí Group (to the south) by the Almas Block, which was interpreted as an elevated paleorelief. The thesis also focuses on the Água Morna Formation (Araí Group), which is a Paleoproterozoic basin with discontinuous regional distribution, thin sedimentary packages, and high lateral homogeneity. The main sedimentary records are composed of immature, poorly sorted feldspar quartzite/metarkose, often rich in pebbles and trough/planar cross-stratification. More rarely, there is a deposition of metaconglomerates and metagreywacke. These characteristics were interpreted as a fluvial braided system with active channels, bars, and abandoned channels. The proposed geotectonic model suggests a pre-rift type basin that is part of the initial stages of the Araí rift. In this sense, the sequence would be controlled by thermal subsidence resulting from crustal cooling after passive asthenospheric uplift. Geochronological data of detrital zircon indicate a local basement provenance, with a source in the Siderian (2.47 to 2.32 Ga) linked to the Almas Terrane, and a more significant source in the Rhyacian (2.28 to 2.05 Ga) related mainly to the Aurumina Terrane (Aurumina Suite -2.11 to 2.16 Ga) and Ticunzal Formation (2.16 to 2.19 Ga). The maximum deposition age of 2.15 Ga (Marques, 2009), associated with sedimentological data, provides a solid argument to separate the Água Morna Formation from the overlying Arraias Formation (1.771 Ga), at the base of the Araí Group stratigraphy.

***Keywords**: Paleo-Mesoproterozoic basins; Natividade Group; Água Morna Formation; Araí Group; paleorelief; mixed platform; shallow water turbidite; pre-rift stage; braided river.*

SUMÁRIO

ANEXOS

Artigo 2: The Statherian Natividade basin evolution constrained by U-Pb geochronology, sedimentology, and paleogeography, central Brazil.

Supplementary Material 1 - Detrital Zircon LA-ICP-MS U-Pb data for T1, T3, T4 and VU39 samples. *(https://docs.google.com/spreadsheets/d/1RYxpp_oo3XXuor46W3yEmQll-cGI8I0jMA5QQWQc2Gc/edit?usp=sharing)*

Supplementary Material 2 – Geochemical Results for VU39 samples. *(https://docs.google.com/spreadsheets/d/1hzMbwGYIgFJzlwG-JY02zbz7svOILlw_GcZ55V-24VU/edit?usp=sharing)*

CAPÍTULO 1
INTRODUÇÃO E METODOLOGIA

1.1 Apresentação e Justificativa

As bacias rifte-sag Paleo-Mesoproterozoicas situadas no nordeste do estado de Goiás e sudeste do Tocantins são relacionadas aos grupos Araí, Traíras e Natividade as quais estão ancoradas entre os crátons Amazônico e São Francisco. Estes grupos, segundo Marques (2009), Saboia (2009) e Martins-Ferreira et al. (2018b) apresentam uma unidade tectônica formada a partir da evolução do rifte Araí.

O Grupo Natividade é uma sequência metassedimentar de idade Paleo-Mesoproterozoica situada no sudeste do estado do Tocantins, e ainda que seja conhecido desde a década de 60 (Moore, 1963), os principais trabalhos na região são essencialmente descritivos, sem aprofundar em aspectos sedimentológicos e na interpretação dos ambientes deposicionais, sem contar na quase ausência de dados geocronológicos.

Diversos autores tentaram compreender o empilhamento estratigráfico do Grupo Natividade por meio de colunas litoestratigráficas (Costa et al., 1976; Correia Filho & Sá, 1980; Costa et al., 1984; Gorayeb et al., 1988; Saboia, 2009), entretanto, devido à existência de descontinuidades laterais, estas não podem ser aplicadas de forma integral em escala regional.

Deste modo, é necessário aprofundar a interpretação dos ambientes e dos processos deposicionais do Grupo Natividade por meio de mapeamento geológico, estudos bibliográficos, petrográficos, paleogeográficos e estratigráficos. Além disso, realizar um trabalho sistemático de geocronologia (U/Pb) a fim de detalhar o preenchimento da sequência e determinar possíveis quebras no registro sedimentar, visto que existe somente uma datação realizada por meio do método U-Pb em zircão detrítico, com idade máxima de deposição de 1779 ± 6 Ma (Silva et al., 2005). Por fim esse estudo visa posicionar o Grupo Natividade na estratigrafia do Supergrupo Veadeiros, compreender a proveniência dos sedimentos, e propor um modelo geotectônico.

Em relação ao Supergrupo Veadeiros, que engloba os grupos Araí e Traíras os quais são compostos por um conjunto de rochas metassedimentares e metavulcânicas, com metamorfismo variável desde ausente a xisto-verde baixo (Dardenne et al., 1999; Martins-Ferreira et al., 2018a), houve um grande desenvolvimento ligado a geocronologia com trabalho de Martins-Ferreira et al. (2018a) que caracterizou o Grupo Araí (1,771 Ga) pertencendo à fase rifte do Estareriano com as formações Água Morna e Arraias. Já o Grupo Traíras foi classificado como uma sequência isolada do tipo sag Calimiana (1,54 Ga).

Apesar desses avanços, não houve uma atenção no empilhamento sedimentar da Formação Água Morna associada à fase pré-rifte do Grupo Araí (Tanizaki et al., 2015). Deste modo, o presente estudo visa, por meio de dados de campo e reinterpretação de dados de geocronologia da literatura, esclarecer o ambiente deposicional da Formação Água Morna e posicioná-la na estratigrafia do Supergrupo Veadeiros. Além disso, é proposto um modelo geotectônico do tipo pré-rifte em um sistema de rios entrelaçados.

1.2 Localização da área de estudo

O presente trabalho situa-se na Província Tocantins, na Zona Externa da Faixa Brasília (Fig. 1). Os trabalhos de campo envolvendo o Grupo Natividade concentraram-se no sudeste do estado do Tocantins entre as cidades de Natividade e Almas. Já os estudos da Formação Água Morna (Grupo Araí) ocorreram entre as cidades do Paranã, ao sul do estado do Tocantins, e Alto Paraíso de Goiás (GO) (Figs. 1 e 2).

1.3 Objetivos

O presente trabalho visa aprofundar o conhecimento geológico do Grupo Araí e Natividade por meio de estudos petrográficos, estratigráficos e geocronológicos. Deste modo, torna-se necessário detalhar os seguintes objetivos:

i) Definir o ambiente e os processos sedimentares que originaram a deposição do Grupo Natividade, descrevendo os litotipos e agrupando em associações;
ii) Produzir um mapa geológico mais detalhado do Grupo Natividade, e construir colunas estratigráficas a partir dos dados de campo e das colunas estratigráficas anteriormente elaboradas por Costa et al. (1976), Correia Filho & Sá (1980), Costa et al. (1984), Gorayeb et al. (1988) e Saboia (2009);
iii) Compreender a relação entre o paleorelevo e a deposição do Grupo Natividade;
iv) Propor um modelo geotectônico para a sequência do Natividade;
v) Caracterizar as áreas-fonte e posicionar na estratigrafia do Supergrupo Veadeiros por meio de datação U-Pb em zircão de rochas de origem sedimentar e vulcânica;
vi) Aprofundar o conhecimento do ambiente sedimentar que originou a deposição da Formação Água Morna (Grupo Araí) por meio de dados de campo, petrografia, estratigrafia e reinterpretação de dados de geocronologia da literatura;
vii) Posicionar a Formação Água Morna na estratigrafia do Supergrupo Veadeiros e correlacionar com o Supergrupo Espinhaço; e
viii) Propor um o modelo geotectônico para a Formação Água Morna.

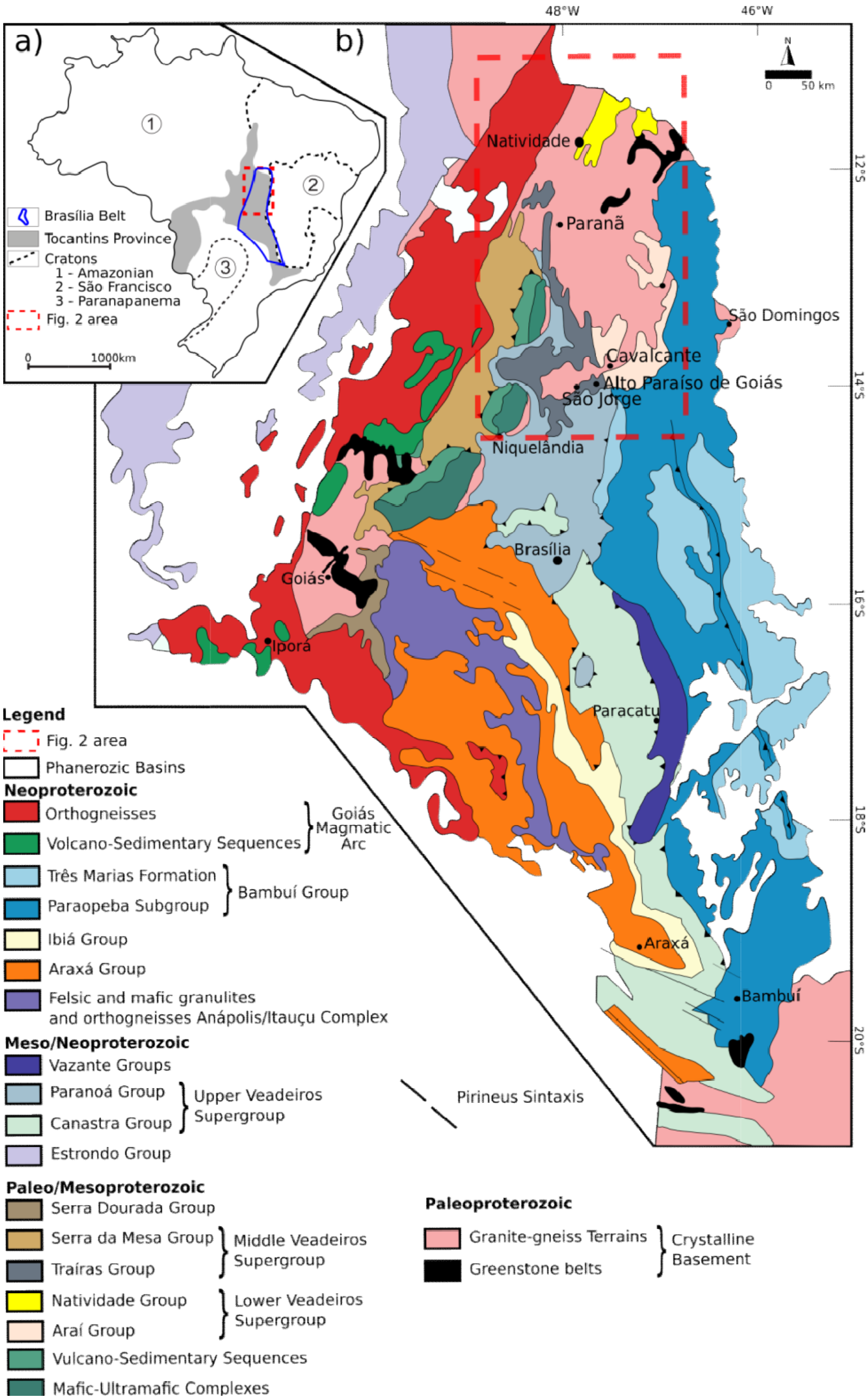


Fig. 1. Contexto geológico regional: a) localização da Faixa Brasília, Província Tocantins e os crátons: Amazônico, São Francisco e Paranapanema (modificado de Sousa et al., 2016), b) Mapa da Faixa Brasília, com os Grupos Natividade e Araí aflorando na porção nordeste (modificado de Dardenne, 2000; Fuck et al., 2017).

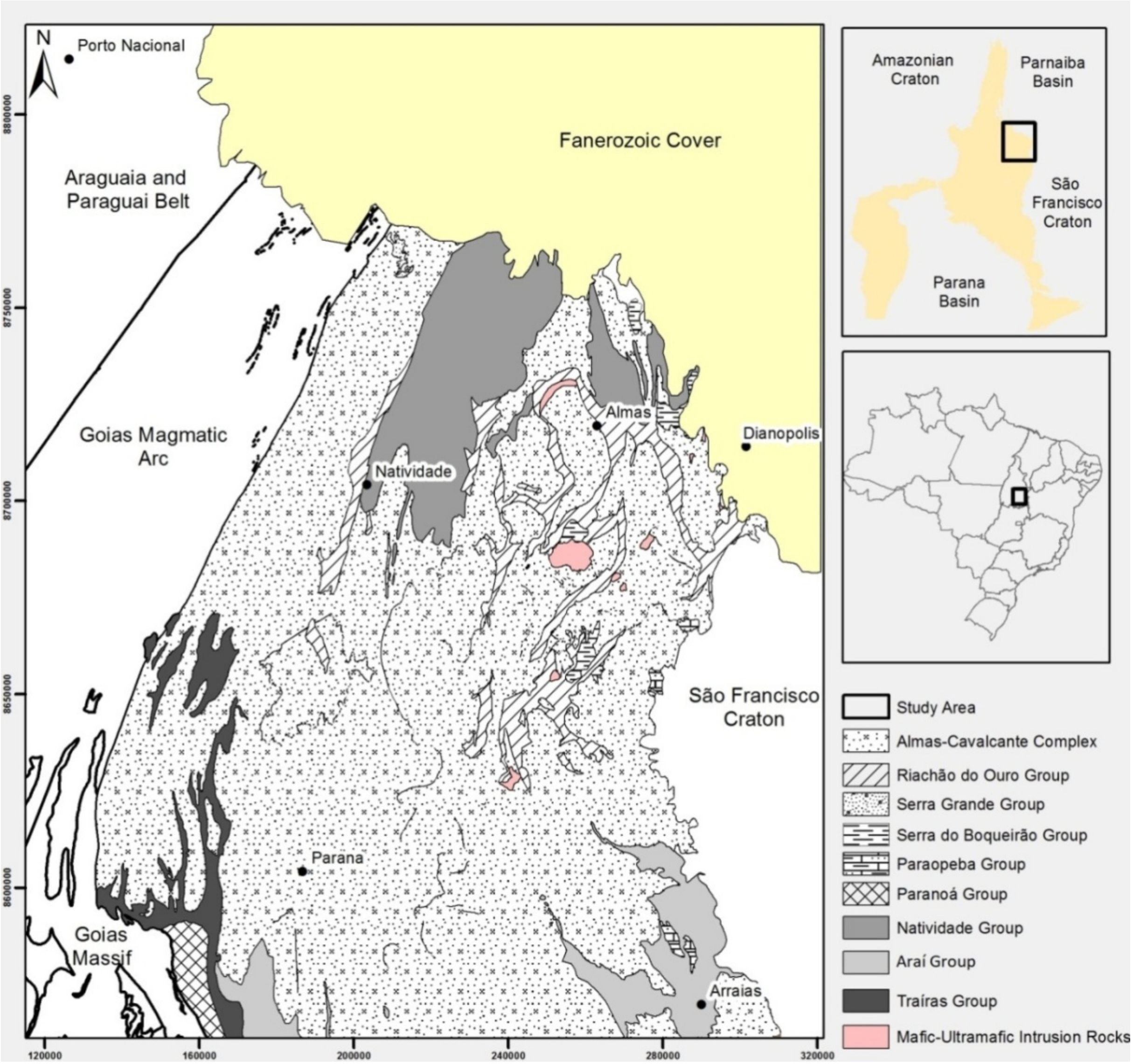


Fig. 2. Mapa geológico regional, onde se visualiza a área de interesse entre as cidades de Natividade, Almas, Paranã e Arraias (modificado de Schobbenhaus & Bellizia, 2001).

1.4 Materiais e Métodos

No presente estudo, para alcançar os objetivos descritos, realizaram-se as seguintes etapas:

i. Levantamento bibliográfico sobre as Bacias rifte-sag Paleo-Mesoproterozoicas dos Crátons Amazônico e São Francisco. Além disso, compilou-se a evolução do conhecimento dos Grupos Araí, Traíras e Natividade;
ii. Trabalhos de campo em sítios-chave onde afloram rochas da Formação Água Morna e do Grupo Natividade para coleta de amostras; descrição de afloramentos e empilhamento estratigráfico;
iii. Preparação de amostras e realização de análises de geocronologia (U/Pb) e geoquímica para o Grupo Natividade;
iv. Elaboração de mapas geológicos e colunas estratigráficas bem como definição de

litotipos, associação de rochas e ambientes sedimentares para o Grupo Natividade e a Formação Água Morna; e

v. Integração, interpretação, tratamento estatístico e geocronológico dos resultados com a elaboração do texto da Tese e de publicações.

1.4.1 Determinação isotópica pelo método U-Pb em zircão

O método de datação aplicado nesse trabalho é o U-Pb em zircão de rocha metassedimentar (amostras T1, T3, T4) e metavulcânica (amostra VU39). O zircão é um dos minerais mais utilizados em estudos relacionados à geocronologia, devido a suas características geoquímicas, que possibilitam a datação por diversos métodos radiométricos. Além disso, esse mineral apresenta ampla distribuição em diversos tipos de rochas, grande resistência física e química a processos de intemperismo, transporte sedimentar e eventos metamórficos (Bühn, 2009 e Teles, 2013).

No presente estudo realizaram-se as etapas tradicionais de britagem, moagem, peneiramento, concentrado de bateia e separação magnética (Frantz). A partir disso, foi realizada a separação de forma manual dos grãos de zircão por meio de microscópios binoculares. A seguir produziram-se *mounts* com resina epóxi que foram polidos para a exposição de seus núcleos. Os procedimentos para a datação foram conduzidos na Universidade de Brasília (amostras T1, T3, T4) e na Universidade de Ouro Preto (amostra VU39).

Na Universidade de Brasília, utilizou-se o MC-ICP-MS Finnigan Neptune acoplado ao laser ablation New Wave 213 μm Nd-YAG. Os isótopos de U, Th, Pb foram normalizados a partir do parâmetro primário GJ-1 (608.5 ± 1.5 Ma; Jackson et al., 2004). Os *spots* foram de 25 μm de diâmetro com frequência de 10 Hz e intensidade de 2.71–3.99 J/cm^2. O material pulverizado foi transportado por Hélio (He) (~0.40 L/min) e Argônio (Ar) (~1.00 L/min). O parâmetro secundário é o zircão 91,500. Para maiores detalhes de equipamento e metodologia verificar Bühn et al. (2009).

Na Universidade de Ouro Preto, os grãos de zircão foram analisados pelo sistema de ablação a laser CETAC 213 e o pelo espectrômetro LA-SFICP-MS (Thermo Scientific™ ELEMENT 2™). O diâmetro do laser foi de 20 μm, e os dados foram adquiridos com análise do *background* por 20 s seguido por 20 s de ablação da amostra. Os padrões de zircão GJ-1 e Plešovice (337 ± 1 Ma; Sláma et al., 2008) foram usados para avaliar a acurácia e a precisão dos resultados da ablação a laser. Para mais informações sobre os métodos analíticos e os tratamentos dos dados consultar Santos et al. (2017).

Por fim, a constante de decaimento de Jaffey et al. (1971) foi adotada e os softwares Chronus 1.4.3 (Oliveira, 2015) e Isoplot-Ex (Ludwig, 2003) foram utilizados para correção dos dados, cálculo da idade e elaboração dos histogramas (Supplementary Material 1). A correção do Chumbo (Pb) comum não foi necessária, e apenas grãos com pelo menos 90% de concordância foram usados nas amostras T1, T3 e T4. O Chumbo (Pb) comum foi contabilizado por 204Pb medido sendo descartados os grãos com altos valores (> 1000 cps). Vale ressaltar que apenas cinco grãos permaneceram com quantidades mais significativas de 204Pb variando de 364 a 860 cps (amostras T1, T3 e T4).

1.4.2 Geoquímica de rocha total

A geoquímica de rocha total foi realizada na amostra VU39. Os elementos maiores e elementos terras raras (ETR) foram analisados na Actlabs-Canadá, usando o pacote 4Litho Actlabs, e estão listados no Supplementary Material 2. O software GCDkit foi usado para manipulação de dados e criação de diagramas (Janousek et al., 2006).

1.4.3 Dados magnetométricos

Neste projeto foram utilizados os dados magnetométricos procedentes do levantamento aerogeofísico do Tocantins, realizado em 2006 por solicitação da CPRM. Os dados magnetométricos registrados em nanotesla (nT) foram processados no programa Oasis Montaj^{TM}, versão 9.6 (Geosoft, 2019). Cada banco de dados tinha como formato inicial a extensão .XYZ, e foi convertido para o formato de banco de dados do Oasis Montaj^{TM} (arquivo .GDB).

Em seguida, realizaram-se os procedimentos: i) análise do nível de ruído pelo filtro da quarta diferença (Geosoft, 2013); ii) remoção do International Geomagnetic Reference Field (IGRF) utilizando-se o software Oasis Montaj 9.6; iii) interpolação dos dados em malha regular com 1/4 do espaçamento entre as linhas de voo (Reeves, 2005). O método bidirecional apresentou os melhores resultados, fornecendo maior definição e correlação espacial dos dados amostrados. Este método leva em conta a distribuição dos dados orientados em linha e enfatiza tendências perpendiculares às linhas de voo (Geosoft, 2019).

Como resultado obteve-se o Campo Magnético Anômalo (CMA) e a partir deste foram produzidos: Gradiente Total (GT) e derivadas de primeira ordem nas direções X, Y e Z (Dx, Dy e Dz) para cada um dos aerolevantamentos.

Após a fase de processamento, os dados foram analisados e buscou-se dividir a área em domínios de respostas magnetométricas semelhantes, texturas e densidade de lineamentos, e para isso utilizou-se o Gradiente Total.

CAPÍTULO 2
REFERENCIAL TEÓRICO

2.1 Sequências rifte-sag Paleo/Mesoproterozoicas dos crátons Amazônico e São Francisco

As principais sequências de idade Paleo (2,5 - 1,6 Ga) a Mesoproterozoica (1,6 - 1,0 Ga) estão ancoradas na borda ou no interior dos crátons Amazônico e São Francisco e normalmente são envoltas por faixas dobradas Neoproterozoicas. Nesse contexto, destacam-se os supergrupos Roraima (RR), Espinhaço (MG-BA) e Veadeiros (GO-TO) e os Grupos Beneficente (PA) e Natividade (TO) (Fig. 3) (Schobbenhaus & Brito Neves, 2003; Uhlein et al., 2015).

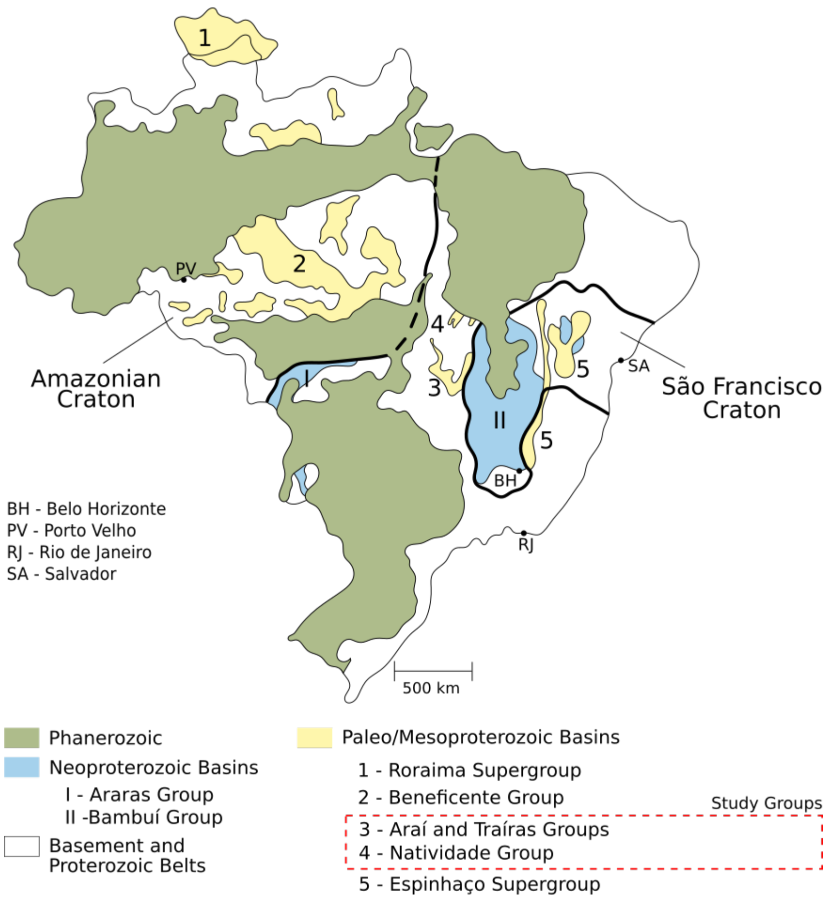


Fig. 3. Mapa geológico com destaque para as principais bacias rifte-sag Paleo-Mesoproterozoicas do Brasil (Modificado de Uhlein et al., 2015; Schobbenhaus et al., 1984; Schobbenhaus & Brito Neves, 2003).

2.1.2 Evolução das sequências rifte-sag Paleo/Mesoproterozoicas dos crátons Amazônico e São Francisco

Segundo Uhlein et al. (2015) é notável uma similaridade entre as bacias Paleo-Mesoproterozoicas desenvolvidas especialmente durante o processo global conhecido como Trafogênese Estateriana (Brito Neves et al., 1995). Há, de modo geral, um predomínio de quartzitos ou metarenitos originados em bacias rifte-sag com a deposição de sedimentos continentais na base e transicionais a marinhos no topo.

Mais especificamente, na base caracterizam-se por uma fase distensional com influência de falhas normais formadas por subsidência mecânica. Nesta fase, há formação de conglomerados e arenitos grossos em ambientes de leques aluviais e fluviais com abundantes estruturas sedimentares (estratificações cruzadas e marcas onduladas). Esse conjunto faciológico é típico de sedimentos continentais. Além disso, nessa porção basal, é comum a presença de rochas vulcânicas ácidas-intermediárias anorogênicas. Já as intrusivas básicas (diabásios e gabros) são frequentes em vários níveis estratigráficos (Uhlein et al., 2015).

Na porção intermediária, ocorre deposição majoritária de lutitos e arenitos finos com rara ocorrência de calcários estromatolíticos característicos de ambiente litorâneo a marinho plataformal, retrabalhados por marés e ondas (Uhlein et al., 2015).

Por fim, no topo, predominam sedimentos bem selecionados (quartzo-arenitos e subarcósios) indicando longo transporte, sendo provenientes de embasamentos gnáissicos. Essa fase é caracterizada por ambientes transicionais e marinhos correlacionados a ciclos transgressivos-regressivos (Uhlein et al., 2015).

2.2 Bacias Paleo/Mesoproterozoicas no Cráton São Francisco

No Cráton São Francisco estão ancorados três cinturões orogenéticos: faixas Brasília, Araguaia e Paraguai as quais hospedam diversas sequências proterozoicas separadas por inconformidades (Almeida, 1977; Alkmim & Martins Neto, 2012; Martins-Ferreira, 2017). Nesse contexto, destacam-se o Supergrupo Espinhaço e o Supergrupo Veadeiros os quais foram considerados como crono-correlatos, com seus estágios evolutivos ligados por eventos regionais ou por processos tectônicos globais (Figs. 3,4, 5 e 6) (Guadagnin & Chemale, 2015).

O Supergrupo Espinhaço situa-se entre o Cráton São Francisco e a Faixa Araçuaí, sendo uma feição que se inicia perto da cidade de Ouro Preto até o norte do estado da Bahia (Fig. 4). Apresenta normalmente dobramentos norte-sul e falhas reversas vinculadas ao tectonismo da Faixa Araçuaí (Pedreira, 1997; Martins Neto, 1998; Uhlein et al., 2015). É dividido geograficamente em três regiões: Serra do Espinhaço Meridional (*Southern Espinhaço range*), Serra do Espinhaço Setentrional (*Northern Espinhaço range*), e Chapada Diamantina (*Diamantina Plateau*) (Guadagnin et al., 2015) (Fig. 4).

Guadagnin et al. (2015) e Uhlein et al. (2015) subdividem o Supergrupo Espinhaço em três ciclos baciais: o basal Estateriano (~ 1,7 Ga), do tipo rifte, o médio Calimiano (1,5 - 1,4 Ga), com características de bacia intracratônica, e o superior Esteniano (1,2 - 1,1 Ga) com características rifte-sag (Fig. 5). Nesse contexto, destacam-se dois processos de rifteamento, o primeiro Estateriano (Tuxás) e o segundo Calimiano (Tupinaés) (Danderfer et al., 2015; Costa et al., 2018).

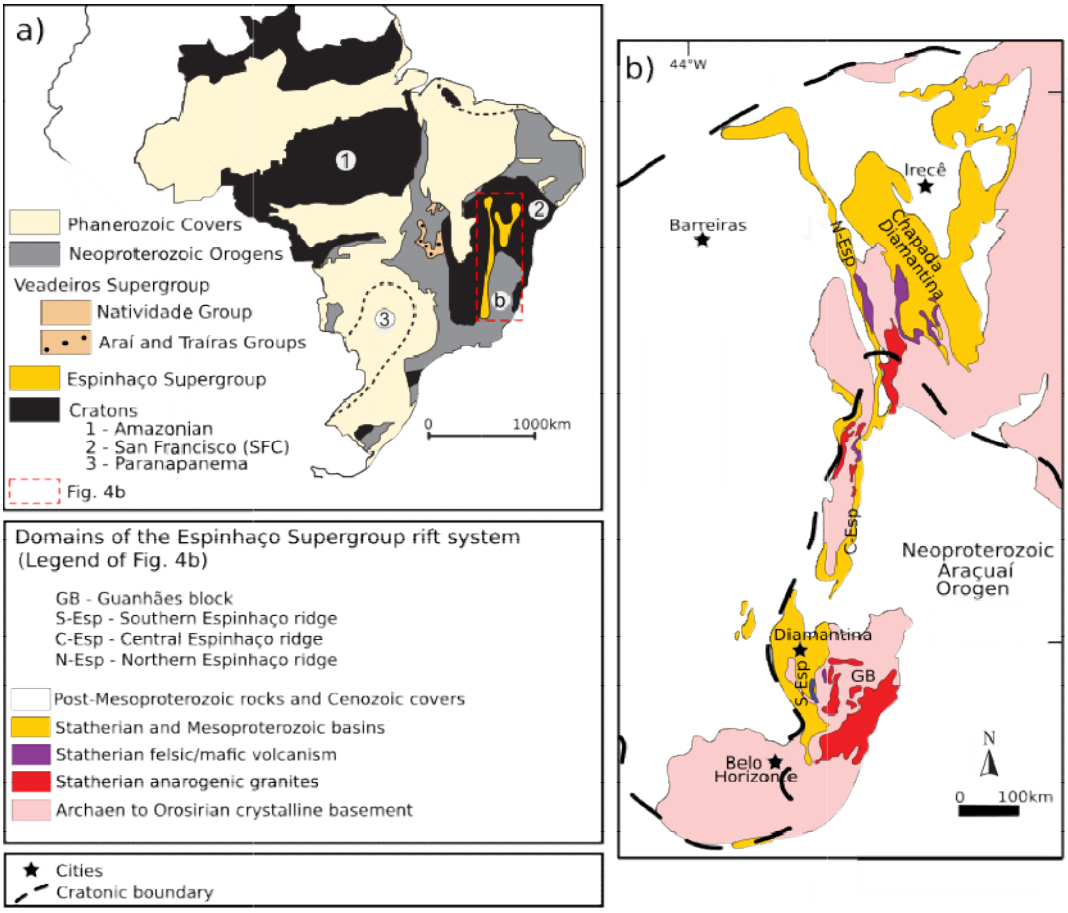
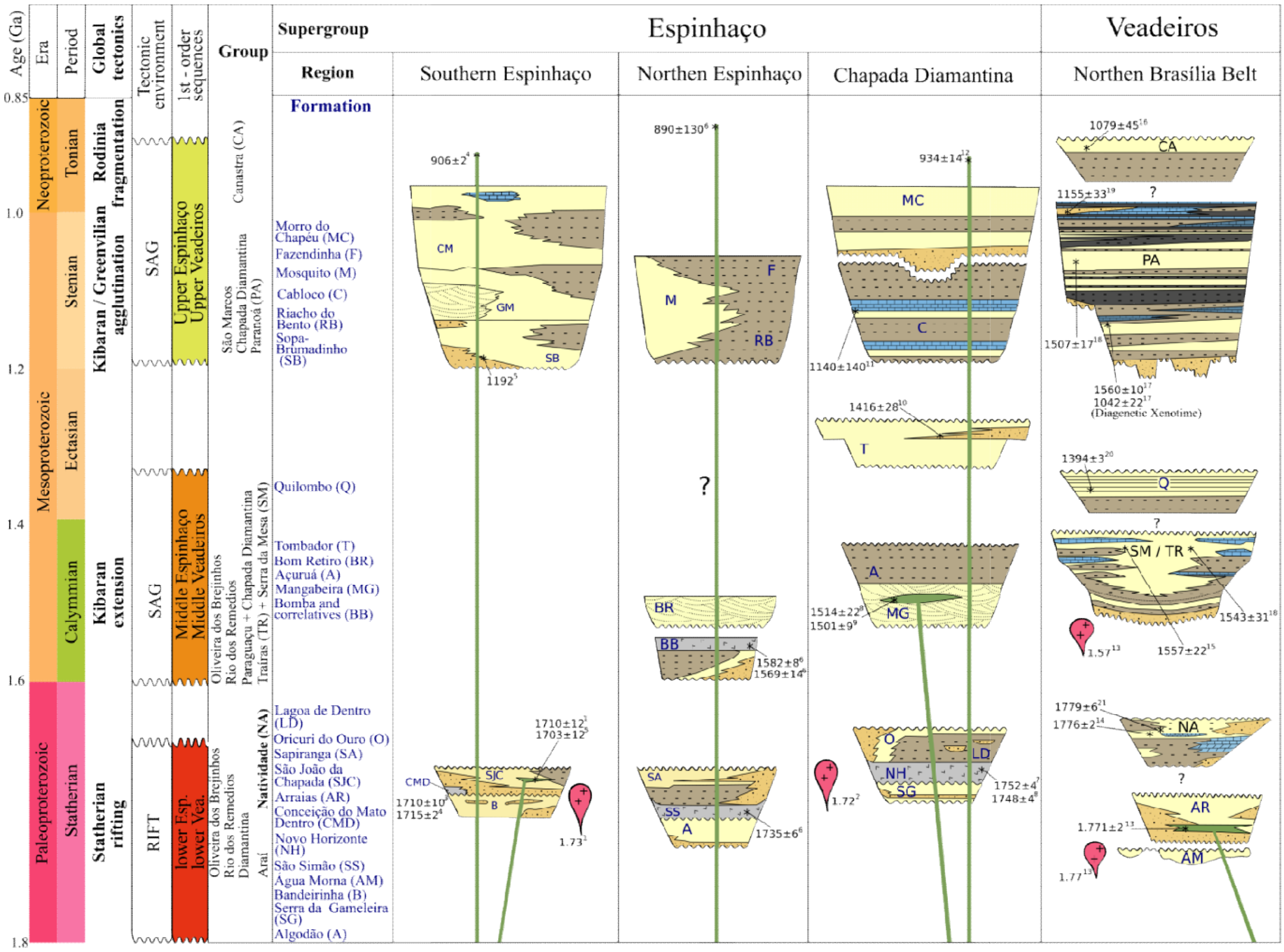


Fig. 4. Mapas geológicos com: a) localização dos principais crátons Arqueanos/Paleoproterozoicos, cinturões Neoproterozoicos e sequências Paleo-Mesoproterozoicas (modificado de Sousa et al., 2016), b) domínios do Supergrupo Espinhaço (modificado de Alkmim, 2004; Pinto & Silva, 2014; Magalhães et al., 2018).

No presente estudo, vale destacar a Formação Bandeirinha, que é considerada por alguns autores como uma unidade basal do Supergrupo Espinhaço, caracterizada por depósitos continentais (250 m de espessura), compostos por arenitos laminados intercalados com camadas de conglomerados (Simplicio & Basilici, 2015).

Segundo Silva (1998), essa unidade é o resultado de processos costeiros e de rios entrelaçados, sendo os conglomerados oriundos de fluxos de massa em área proximal, ou leques aluviais relacionados a processos tectônicos. Simplicio & Basilici (2015) entendem que os arenitos são depositados em ambiente eólico, enquanto os conglomerados são oriundos de rios efêmeros de alta energia.



1. Dussin (1994) 2. Turpin et al. (1988) 3. Brito Neves et al. (1979) 4. Abreu (1991) 5. Chemale (2012) 6. Danderfer et al. (2009) 7. Schobbenhaus et al. (1994) 8. Babinski et al. (1999) 9. Silveira et al. (2013) 10. Guadagnin & Chemale (2015) 11. Babinski et al. (1993) 12. Loureiro et al. (2008) 13. Pimentel et al. (1991) 14. Toscani et al. (2021b) 15. Marques (2009) 16. Rodrigues et al. (2010) 17. Matteini et al. (2012) 18. Martins-Ferreira et al. (2018a) 19. Seraine et al. (2020) 20. Campos et al. (2020) 21. Silva et al. (2005)

Fig. 5. Carta cronoestratigráfica correlacionando os Supergrupos Veadeiros e Espinhaço (depois de Guadagnin & Chemale, 2015; Martins-Ferreira et al., 2018a; Toscani et al., 2021a; Toscani et al., 2021b). Escala geológica do tempo de Cohen et al. (2013).

2.3 Contexto Geotectônico dos Grupos Araí, Traíras e Natividade

O presente estudo localiza-se na porção norte da zona externa da Faixa de Dobramentos Brasília (Fig. 1), que é caracterizada por um cinturão de dobras e empurrões com direção NE-SW compostos por sequências supracrustais de baixo grau metamórfico e unidades do embasamento, os quais foram alçados tectonicamente em direção ao Cráton São Francisco (Dardenne, 2000; Marques, 2009). As referidas sequências supracrustais são representadas pelo Supergrupo Veadeiros (Grupos Araí, Traíras/Serra da Mesa e Paranoá) e pelos Grupos Natividade e Bambuí (Martins-Ferreira et al., 2020).

Segundo Cordeiro & Oliveira (2017), o embasamento é caracterizado por todas as rochas do Pré-Neoproterozoico e é denominado de Maciço de Goiás, sendo dividido em quatro domínios tectônicos distintos: Domínio Arqueano-Paleoproterozoico Crixás-Goiás e os Domínios Paleoproterozoicos Almas-Conceição do Tocantins (ACT); Cavalcante-Arraias e Campinorte.

No presente estudo, utilizamos a nomenclatura de Martins-Ferreira et al. (2020), que definiram os termos: Terreno Almas para o ACT e Terreno Aurumina para o Domínio Cavalcante-Arraias (Fig. 6).

O embasamento da área em estudo é formado pelos Terrenos Almas e Aurumina, o primeiro consiste em um conjunto de rochas greenstone-TTG em fácies anfibolito (Cruz, 2001; Martins-Ferreira et al., 2020). Já o Terreno Aurumina é caracterizado por granitos peraluminosos e tonalitos/granodioritos da Suíte Aurumina (2,11 a 2,16 Ga) (Cuadros et al., 2017a) e sequências de biotita-granada paragnaisses e xistos grafitosos da Formação Ticunzal (2,16 a 2,19 Ga) (Cuadros et al., 2017b).

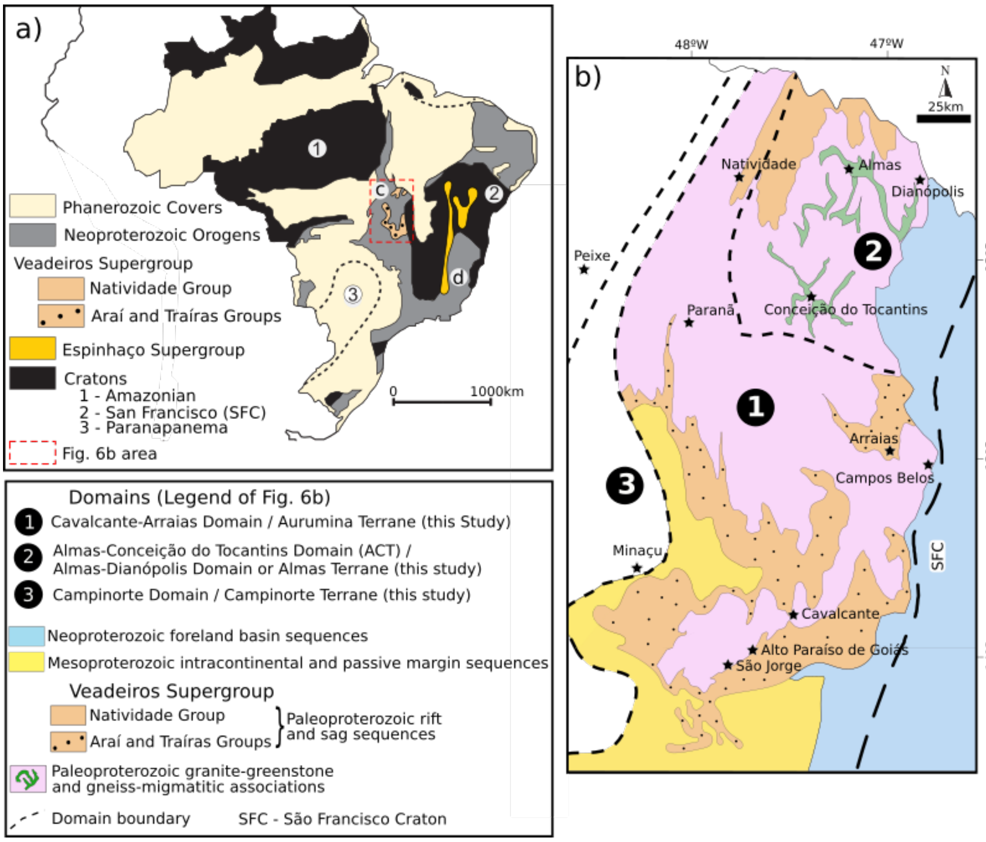


Fig. 6. Mapas geológicos com: a) principais crátons Arqueanos/Paleoproterozoicos, cinturões Neoproterozoicos e bacias Paleo-Mesoproterozoicas (modificado de Sousa et al., 2016), b) porção nordeste da Faixa Brasília com três domínios tectônicos (modificado de Fuck et al., 2014; Cordeiro & Oliveira, 2017; Martins-Ferreira et al., 2020).

2.3.1 Arcabouço estrutural do Grupo Araí e Traíras

O embasamento dos grupos Araí e Traíras é formado essencialmente pelo Terreno Aurumina (Suíte Aurumina e Formação Ticunzal). Esse terreno foi afetado por processos tectônicos distensionais relacionados à Tafrogênese Estateriana (~1,7Ga) que impôs uma tectônica essencialmente rúptil, em escala continental. O falhamento, em geral, apresenta direção NS a N20E, que possivelmente atingiu grandes profundidades, atravessando a crosta continental (Tanizaki, 2013).

As estruturas secundárias existentes nos Grupos Araí e Traíras são reflexos da Orogênese Brasiliana. Segundo Tanizaki (2013), a foliação S1 é discreta, o que evidencia o início dos processos de deformação por movimentos de fluxo intraestratal. As sequências apresentam grandes dobras regionais assimétricas, fechadas a isoclinais, com foliação de plano axial S2 e direção variada devido ao redobramento dessas estruturas por dobras normais flexurais abertas, de eixo aproximadamente NS, horizontal a sub-horizontal as quais possuem clivagem espaçada de direção geral NS. Por fim, há grandes zonas de cisalhamento denominadas de sistemas: i) Cavalcante-Teresina; ii) Arraias-Campos Belos; iii) Colinas do Sul; iv) Rio Maranhão (Tanizaki, 2013).

2.3.2 Arcabouço estrutural do Grupo Natividade

O embasamento do Grupo Natividade é constituído essencialmente pelo Terreno Almas, que apresenta sequências metavulcanossedimentares do tipo greenstone belt que em geral estão dispostos em contato curvilíneo (N-S) com corpos elipsoidais plutônicos das unidades graníticas/TTG (Fig. 6) (Ress et al., 2016; Martins-Ferreira et al.2020).

As rochas desse Grupo atingiram fácies xisto verde baixo. Localmente, a presença de minerais como cloritoide e cianita no quartzito indicam um grau metamórfico mais elevado (Gorayeb et al., 1988; Saboia, 2009). De acordo com Gorayeb et al. (1988), as dobras no Grupo Natividade são isoclinais com planos axiais sub-verticais a NS-20NE. Perto da cidade de Natividade, as dobras são assimétricas, fechadas ou isoclinais, com planos axiais e ângulos de mergulho de 60NW.

As falhas do Grupo Natividade são divididas em dois grupos principais: o primeiro transcorrente dextral com direção de 50 a 60NE e sinistral variando de 60NW a 35SW, relacionado à compressão E-W (Colagem Brasiliana), e o segundo com falhas normais N/S, NNE e NNW relacionadas à reativação posterior (Gorayeb et al., 1988).

Localmente, associada a dobras há xistosidade ou clivagem ardosiana plano-axial nos metapelitos ou clivagem de fratura em leque nos quartzitos e mármores. Nos metaconglomerados, os seixos estão orientados de forma plano paralela com os eixos das dobras (Gorayeb et al., 1988).

2.3.3 Evolução do conhecimento dos Grupos Araí e Traíras

Historicamente, o Grupo Araí englobava as formações Arraias e Traíras, entretanto, devido aos estudos de Martins-Ferreira (2017) e Martins-Ferreira et al. (2018a), foi possível estabelecer um lapso temporal de no mínimo 228 Ma entre essas formações por meio de datação U-Pb em zircão detrítico. Consequentemente, a Formação Traíras foi elevada a categoria de

Grupo e relacionada à bacia do tipo sag Calimiana, já o Grupo Araí, ficou limitado à bacia do tipo rifte de idade Estateriana englobando as Formações Água Morna e Arraias (Fig. 5).

Deste modo, esses autores propuseram a denominação de Supergrupo Veadeiros, que engloba três pulsos extensionais registrados na margem oeste do Cráton São Francisco, representados pelas sequências de primeira ordem Araí (Veadeiros Inferior), Traíras (Veadeiros Médio) e Paranoá (Veadeiros Superior) (Fig. 5). O presente tópico dará enfoque aos grupos Araí e Traíras e é baseado especialmente nos trabalhos de Tanizaki (2013), Marques (2009) e Martins-Ferreira (2017).

Os grupos Araí e Traíras situam-se na porção nordeste do estado de Goiás e ao sul do estado do Tocantins no contexto geotectônico da porção norte da Zona Externa da Faixa Brasília (Figs. 1, 3 e 6). Resumem-se a um conjunto de rochas metassedimentares e metavulcânicas de grau anquimetamórfico a xisto verde baixo (Dardenne et al., 1999; Martins, 1999; Tanizaki, 2013; Tanizaki et al., 2015). Esses grupos depositam-se sobre a Suíte Aurumina e a Formação Ticunzal (Terreno Aurumina) (Fig. 6) e são recobertos pelos grupos Paranoá e Bambuí.

O Grupo Araí foi inicialmente descrito por Barbosa et al. (1969) e Dyer (1970). Este último autor definiu dez unidades litoestratigráficas mapeáveis e as agrupou em duas formações (Fig. 7): Formação Arraias (Unidades 1 a 3) com 1.000 m de espessura constituída principalmente por sedimentos arenosos (metaconglomerados, quartzitos conglomeráticos, quartzitos feldspáticos, com ocorrências locais de efusivas básicas e metassiltitos) depositadas em ambiente fluvial e a Formação Traíras (Unidades 4 a 10) com 1.200 m de espessura e formada por uma sequência intercalada por arenitos, lutitos e carbonatos de ambiente marinho (Martins, 1999; Tanizaki, 2013; Tanizaki et al., 2015).

Braun (1980) faz uma profunda revisão do trabalho de Dyer (1970) e propõe a categoria de Supergrupo Araí (Fig. 7). Neste estudo a região seria dividida em cinco subgrupos (A-E). O Grupo A apresenta história independente das demais, com deformações e intrusões vulcânicas antes da sedimentação do resto da sequência em ambiente flúvio-lacustre, já os demais grupos (B-E) são uma sequência harmônica de plataforma com raras instabilidades penecontemporâneas e uma sucessão de transgressões e regressões.

Mais precisamente, Braun (1980) dividiu os grupos (A-E) da seguinte forma: Grupo A, denominado de Grupo Arraias, corresponde à unidade 1 de Dyer (1970); Grupo B, formado por sedimentos arenosos e conglomeráticos da frente transgressiva costeira (Unidades 2 e 3); Grupo C denominado de Grupo Traíras constituído por lutitos e carbonatos da frente transgressiva nerítica (Unidades 4, 5 e 6); Grupo D denominado também de Grupo Paranoá, correspondente as Unidades 7 a 9 com lutitos e arenitos da cunha transgressiva costeira; e Grupo E, correspondente à unidade 10 composta de rochas areno-carbonatadas. Todas sobrepostas pelo Grupo F, denominado Grupo Bambuí, por discordância angular.

O trabalho de Martins (1999) definiu especialmente na região do Parque Nacional da Chapada dos Veadeiros duas sequências sedimentares delimitadas por descontinuidades regionais: uma Sequência Continental e uma Sequência Transicional/Marinha. A primeira é relacionada com sistemas deposicionais fluvial, eólico e fluvio-deltaico (fase sin-rifte). A segunda é interpretada como sistemas deposicionais litorâneos (fase pós-rifte) e de plataforma rasa e aberta, interpretada como progressivamente marinha em direção ao topo.

No mesmo ano, Dardenne et al. (1999) dividiram o Grupo Araí em três Unidades principais. A Unidade Continental Basal relacionada à fase pré-rifte composta de quartzitos fluviais e eólicos. A Unidade Continental Intermediária, relacionada à fase rifte, composta por brechas e conglomerados intraformacionais na base e por quartzitos grossos com níveis conglomeráticos no topo, além de uma intercalação de rochas vulcânicas ácidas e básicas. Por fim, a Unidade Marinha Superior constituída de metassiltitos intercalados com quartzitos finos, representando a fase pós-rifte acompanhada de uma transgressão marinha regional.

Marques (2009) realizou estudos nos grupos Araí e Serra da Mesa e correlacionaram as colunas estratigráficas mais significativas (Fig. 7). Além disso, propôs que o Grupo Araí pertence a uma bacia do tipo rifte-sag, que corresponde a uma Megasequência de primeira ordem e pode ser subdividido em quatro estágios: pré-rifte, rifte, transicional e pós-rifte flexural. O estágio pré-rifte é formado por conglomerados polimíticos (A1) e quartzitos eólicos e conglomerados oligomíticos (A2), o estágio sin-rifte é composto por metapiroclásticas (A3). Essas três unidades apresentam sedimentação continental. A fase transicional é composta por intercalações de quartzitos, conglomerados oligomíticos e, localmente, metagrauvacas (A4), e também, por quartzitos, metalutitos e subordinadamente conglomerados oligomíticos (A5). Por fim, a sequência pós-rifte é representada pelas unidades A6 e A7, que consistem em sedimentos depositados em uma plataforma marinha mista (siliciclástica-carbonatada), marcada por dois ciclos deposicionais, cada um com granodecrescência ascendente (A6 e A7).

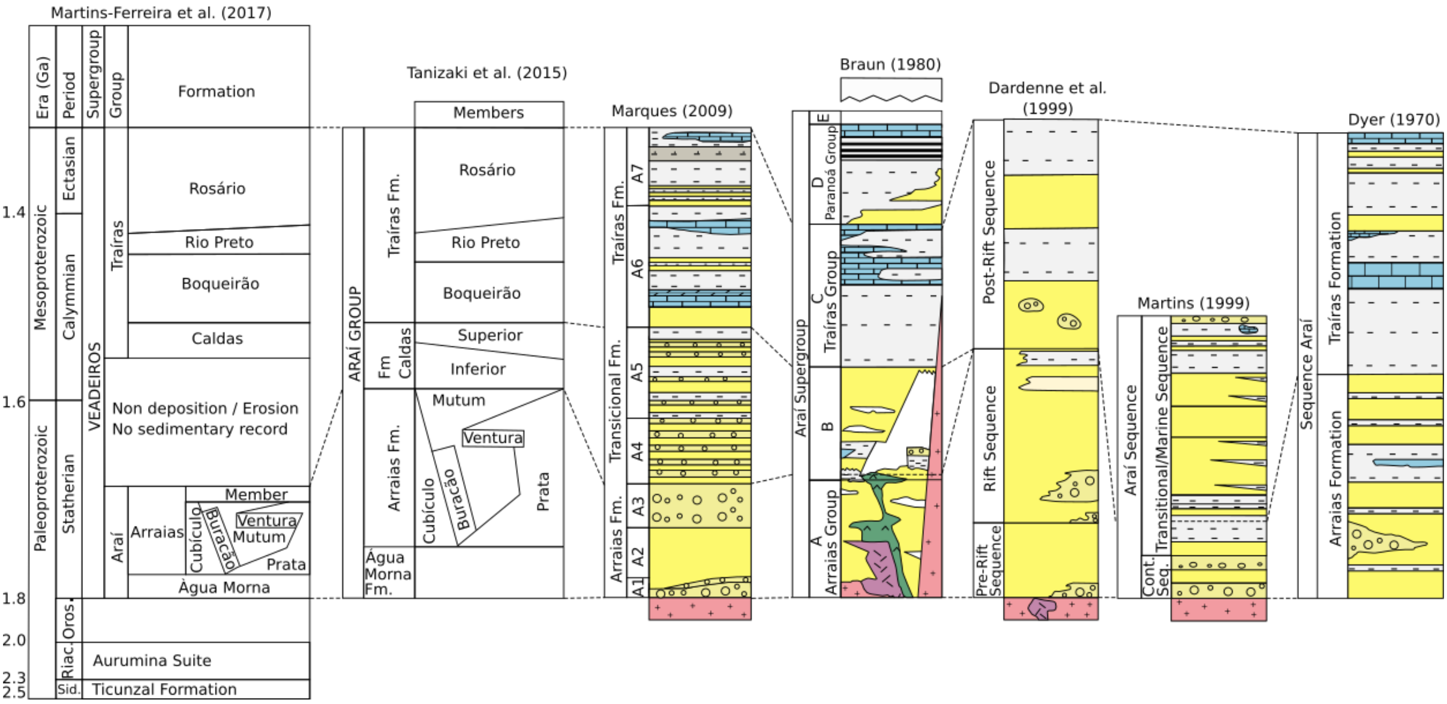


Fig. 7. Correlação das principais colunas estratigráficas para o Grupo Araí (modificado de Marques, 2009; Tanizaki et al., 2015; Martins-Ferreira, 2017).

Tanizaki et al. (2015) com base em trabalhos de campo e em ampla bibliografia existente integraram esses dados, definindo nomenclaturas formais para compreender os aspectos genéticos e as características de cada uma das unidades (Fig. 7). Deste modo, foram caracterizadas quatro formações para o Grupo Araí: Água Morna, Arraias, Caldas e Traíras.

Entretanto, Martins-Ferreira et al. (2018a) obtiveram idade U-Pb em grãos de zircão detríticos de 1,54 Ga para o que era anteriormente chamado de Formação Traíras, o que resultou em mudanças significativas na nomenclatura do Grupo Araí. Assim, no presente momento, o Grupo Araí é constituído apenas pelas formações Água Morna e Arraias correspondente à bacia do tipo rifte Estateriana. Já o Grupo Traíras engloba as formações Caldas; Boqueirão; Rio Preto e Rosário relativas à bacia do tipo sag Calimiana. Esses dois grupos, juntamente com o Grupo Paranoá constituem o Supergrupo Veadeiros (Figs. 5 e 7).

Deste modo, integrando os estudos de Tanizaki et al. (2015); Martins-Ferreira (2017) e Martins-Ferreira et al. (2018a), os Grupos Araí e Traíras poderiam ser assim divididos:

O **Grupo Araí** é subdivido nas Formações:

1. *Formação Água Morna*: constituída por metarcósios grossos e quartzitos feldspáticos. Secundariamente, há quartzitos micáceos e metaconglomerados. Esta formação pode ser classificada como uma tectonossequência depositada em condições continentais em sistemas de rios entrelaçados dominados por areias. Todos esses processos ocorreram antes da nucleação das falhas e da individualização dos meio-grábens que hospedam as unidades sobrepostas, como produto da fase pré-rifte da bacia. Esta unidade poderia ser considerada uma bacia do tipo sag-intracontinental.

2. *Formação Arraias*: foi subdividida nos membros: Cubículo, Prata, Mutum, Ventura e Buracão. Pode ser interpretada como uma tectonossequência constituída por uma associação dos sistemas deposicionais de leques aluviais, fluviais, eólicos e lacustres, acumulados durante a fase sin-rifte da Bacia Araí. Essa sedimentação foi intercalada com vulcanismo bimodal típico de sistemas rifte. É relacionada essencialmente à subsidência mecânica da bacia.
    - Membro Cubículo**:** caracterizado por metaconglomerados matriz-suportados e, secundariamente, por metaconglomerados clasto-suportados, quartzitos feldspáticos e metarcósios;
    - Membro Prata**:** possui espessos pacotes de metarcósios e quartzitos feldspáticos com lentes de metaconglomerado matriz-suportado, metaconglomerado clasto-suportado e muscovita filito;
    - Membro Mutum**:** é composto por quartzitos puros que sustentam o relevo de serras mais elevadas no norte de Goiás e sul de Tocantins;
    - Membro Ventura**:** é composto por metaconglomerados, quartzitos e intercalações métricas de metamarga e metagrauvacas; e
    - Membro Buracão**:** é representado por pequenos derrames de basalto, riolitos, riodacitos e dacitos, além de rochas piroclásticas e brechas, distribuídos em diferentes regiões.

O **Grupo Traíras** é dividido nas formações:

1. *Formação Caldas*: constituída por intercalações de quartzitos com metaconglomerados clasto-suportados na base. Ainda ocorrem metagrauvacas e metarcósios em áreas restritas. Na porção superior há intercalações de quartzitos puros com metalutitos.
2. *Formação Boqueirão*: é composto por siltitos calcíferos interdigitados com quartzitos que, por sua vez, são intercalados com material carbonoso, além de uma unidade superior composta por quartzitos e filitos com lentes de mármores.
3. *Formação Rio Preto*: é composto principalmente por quartzitos puros médios, bem selecionados. Subordinadamente ocorrem metaconglomerados, além de horizontes de metassiltitos.
4. *Formação Rosário*: é composto por uma sequência areno-lutítica e uma sequência areno-lutito-carbonatada.

2.3.4 Evolução do conhecimento do Grupo Natividade

No sudeste do estado do Tocantins aflora uma sequência metassedimentar denominada de Grupo Natividade de idade Paleo-Mesoproterozoica que foi inicialmente reconhecida por Moore (1963) com o nome de Série Natividade. Posteriormente, foi reclassificada como Grupo por

Costa et al. (1976).

Nas décadas de 60 e 70 os estudos na região eram bastante descritivos, porém já indicavam uma correlação entre os grupos Natividade e Araí ainda que fosse de maneira bastante especulativa (Moore, 1963; Dyer, 1970; Costa et al.,1976).

Na década de 80 e início de 90 os trabalhos eram mais completos, com dados importantes e com ideias interpretativas sobre o ambiente de deposição. Correia Filho & Sá (1980) sugeriram que o ambiente de deposição seja plataformal com ligeiros períodos de instabilidade dando origem a uma sequência areno-lamosa fina com fácies conglomeráticas e carbonáticas sendo o pacote arenoso depositado em condições estáveis. Estes autores citam também um aporte sedimentar moderado que possibilitou a sedimentação mista (siliciclástico-carbonática). Gorayeb et al. (1988) afirmam que o Grupo Natividade desenvolveu-se em bacia ensiálica com dobramento simples e que foi submetido a metamorfismo de baixo grau. Já Hasui et al. (1990) acreditavam que o Grupo pertencia a um pacote depositado na borda de uma bacia ensiálica que se abria para leste. Sua borda oeste (Porto Nacional-Gurupi) era responsável pelo aporte de detritos para a bacia que pra leste dava lugar aos sedimentos lutito-carbonatados em ampla plataforma carbonática.

As principais colunas litoestratigráficas do Grupo Natividade foram agrupadas por Saboia (2009) e podem ser verificados na Fig. 8 (Costa et al., 1976; Correia Filho & Sá, 1980; Costa et al., 1984; Gorayeb et al., 1988).

Um dos estudos mais importantes na região foi realizado por Gorayeb et al. (1988) onde o Grupo Natividade foi dividido em quatro formações (Fig. 8d): i) **Formação Santa Clara -** compreende de um pacote de quartzitos puros na base, passando a micáceos com intercalações descontínuas de metaconglomerados polimíticos, mármores dolomíticos, filitos e quartzitos com cianita e cloritóide. Feições primárias estão preservadas; ii) **Formação Mato Virgem-** constituída predominantemente por mármores dolomíticos com intercalações de filitos e quartzitos micáceos na base; iii) **Formação Córrego Fundo -** inicia com quartzitos passando para filitos e ardósias, com delgados leitos de metalutitos carbonosos e hematíticos, e quartzitos micáceos em direção ao topo; iv) **Formação Jacuba -** apresenta na base quartzitos puros e micáceos com níveis arcosianos, gradando lateral e verticalmente para quartzitos arcosianos, filitos e mármores alternados.

Outra descrição litológica interessante é dada por Hasui et al. (1990), em que o grupo é dividido em três porções baseado nas colunas de Correia Filho & Sá (1980), Costa et al. (1984) e Gorayeb et al. (1988). A **Porção Ocidental** sobrepõem às rochas do embasamento. Sua estratigrafia da base para o topo é resumida em: i) metaconglomerados com seixos de quartzo e quartzito; ii) quartzitos puros com seixos e grânulos de quartzo; iii) quartzitos micáceos com intercalações de tremolita-actinolita xistos; iv) filitos; v) quartzitos micáceos com lentes de filito (Costa et al.,1984), (Fig. 8c). Na **Porção Central** afloram da base para o topo, as formações classificadas por Gorayeb et al. (1988). Já a **Porção Oriental** apresenta um pacote de 120 metros definido da base para o topo por: i) Filitos com lentes de quartzitos conglomeráticos, tendo seixos de quartzo e quartzito em matriz de quartzo e mica; ii) Filitos carbonáticos, ou não, com lentes de mármores impuros; iii) Mármores impuros, com intercalações de metabrechas sin-sedimentares e filitos; iv) Filitos localmente carbonáticos; v) Quartzitos micáceos (Correia Filho & Sá, 1980) (Fig. 8b).

Um dos trabalhos mais recentes a respeito da região foi realizado por Saboia (2009) e divide o Grupo Natividade em oito unidades litoestratigráficas (Fig. 8e):

- **Unidade 1 -** parte basal do Grupo Natividade, composta por metadolomitos que passam para metassiltitos em direção ao topo. Apresentam contato discordante com o embasamento gnáissico;
- **Unidade 2 -** apresenta na base um espesso pacote de quartzitos que em porções superiores intercalam com metaconglomerados oligomíticos;
- **Unidade 3 -** constituída essencialmente por metadolomitos que em sua porção superior tem intercalação com metacalcários cinza;
- **Unidade 4 -** composta essencialmente por metassiltitos intercalados com quartzitos e lentes de metadolomitos. Nessa unidade por vezes é possível verificar intercalação com quartzo xisto e a presença de estromatólitos colunares;
- **Unidade 5 -** formada essencialmente por quartzitos, sendo na base quartzitos felsdspáticos grossos a muito grossos, por vezes conglomeráticos e com raras intercalações de metalutitos;
- **Unidade 6 -** apresenta metassiltitos esverdeados, microdobrados com intercalações de quartzitos e lentes de metadolomitos. Por vezes apresentam-se silicificados;

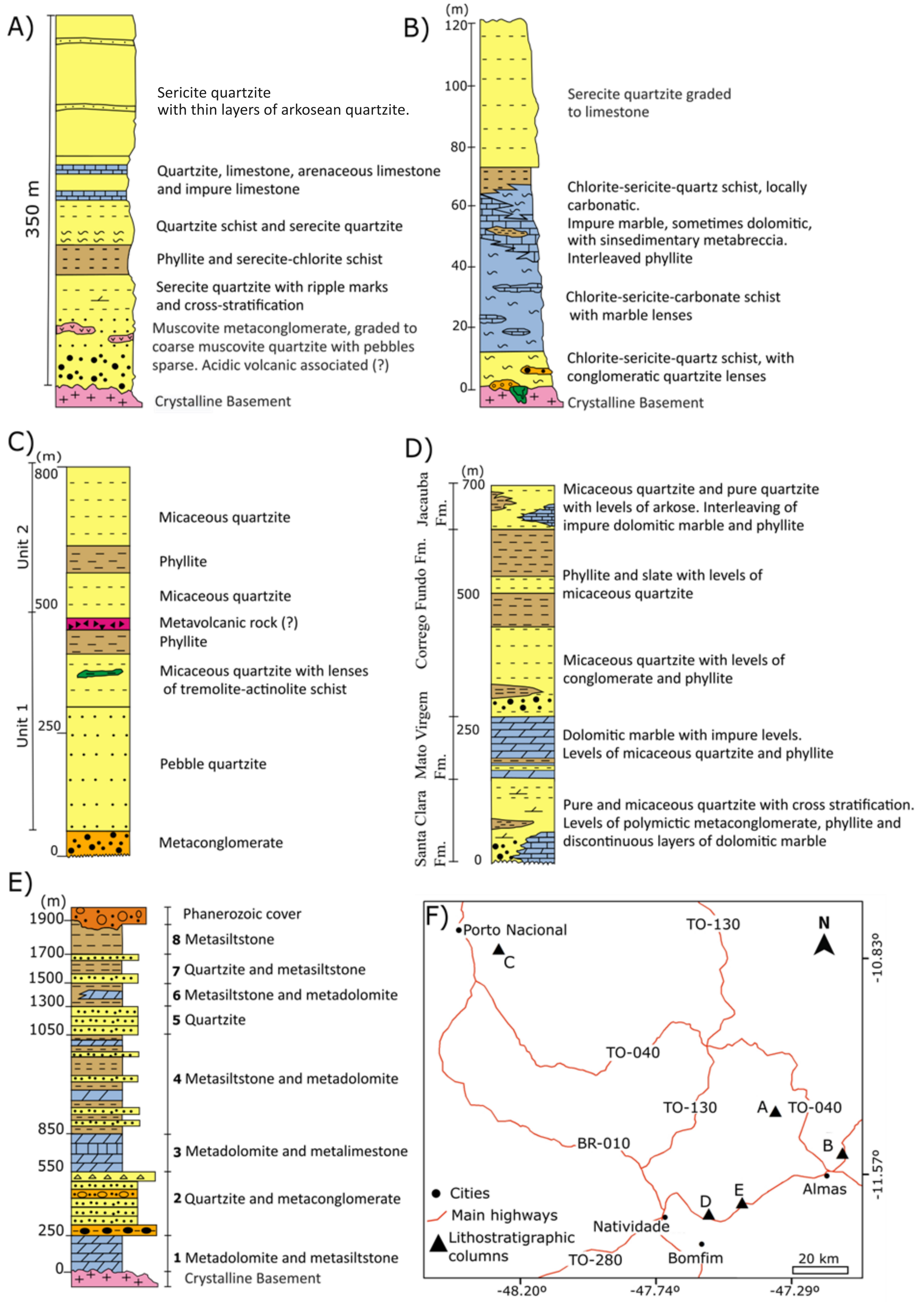


Fig. 8. Principais colunas litoestratigráficas do Grupo Natividade e respectivas localizações (posterior a Saboia, 2009). (A) Costa et al. (1976); (B) Correia Filho & Sá (1980); (C) Costa et al. (1984); (D) Gorayeb et al. (1988); (E) Saboia (2009); (F) localização das colunas estratigráficas (triângulos pretos).

- **Unidade 7 -** representada por quartzitos e metassiltitos laminados extremamente microdobrados. Os quartzitos são finos a médios, feldspáticos por vezes ricos em sericita. Apresenta localmente clorita xisto e estruturas como estratificações plano-paralelas e cruzadas; e
- **Unidade 8** - topo da sucessão sedimentar do Grupo Natividade. Apresenta metassiltitos que geralmente ocupam áreas de relevo arrasado.

Como conclusão, Saboia (2009) sugere que a deposição ocorreu em um ambiente de plataforma marinha, sendo afastada a hipótese da presença de uma fase rifte no início da formação do Grupo Natividade na região. O Grupo Natividade foi relacionado à fase pós-rifte de subsidência térmica, que se desenvolveu no Grupo Araí (ao sul).

Ainda, o Grupo Natividade foi influenciado pela deformação ocorrida no Sistema Transbrasiliano de falhamentos transcorrentes dextrais, orientados segundo a direção NNE, desenvolvido no final do ciclo Brasiliano (Schobbenhaus et al., 1984). Esta deformação gerou milonitização e dobramentos frequentes, com grau metamórfico de fácies xisto verde baixo. Além disso, existe um recobrimento discordante por sedimentos paleozoicos da Bacia do Parnaíba (Grupo Serra Grande e Formação Pimenteiras).

Por fim, as rochas metassedimentares do Grupo Natividade carecem de maior volume de dados geocronológicos devido à ausência de intercalações de rochas vulcânicas. Existe apenas um único dado disponível por meio do método Pb-Pb em zircão detrítico com idade máxima de deposição de 1779 ± 6 Ma para a deposição dos sedimentos desta unidade (Silva et al., 2005).

2.4 Considerações sobre o modelo geotectônico do rifte Araí

Os modelos geotectônicos para o rifte Araí que envolve o Grupo Araí (Formação Água Morna e Arraias) e o Grupo Natividade serão abordados mais detalhadamente nos capítulos 3, 4 e 5. Entretanto, vale ressaltar que o presente trabalho baseou-se no estudo de Falvey (1974) que atribuiu as seguintes fases para a formação de um rifte: pré-rifte, rifte e pós-rifte.

No modelo de Falvey (1974) o estágio pré-rifte indica atividade tectônica regional muito precoce (termal), que é precursor do estágio rifte. Essa fase também é conhecida como estágio inicial do rifte (Falvey, 1974; Bueno et al., 2007; Bosence, 1998; Mounguengui et al., 2002; Staton, 2009; Rapozo et al., 2021), sendo formado por sedimentos gerados antes da nucleação das falhas principais (Bosence, 1998; Miall, 2000).

Nesse estudo, a fase pré-rifte é caracterizada por uma bacia ampla e rasa, com a predominância de sistemas fluviais (rios entrelaçados) e influência de subsidência termal (Falvey, 1974; McKenzie, 1978).

A fase rifte é iniciada com os primeiros falhamentos que ocasionam a depressão na superfície da crosta (Kifumbi, 2017). O ápice desse processo é conhecido como clímax e há proeminentes e numerosas falhas transversais com aumento da área deposicional. Por fim, a fase pós-rifte é compreendida pelo fim do tectonismo ativo e pela máxima extensão da bacia, onde nos depósitos centrais ocorre apenas a deposição de lama lacustre (Prosser, 1993; Kuchle, 2010; Henstra et al., 2016; Kifumbi et al., 2017; Matenco & Haq, 2020).

2.5 Correlação entre os grupos Araí/Traíras e o Grupo Natividade

Nas décadas de 60 e 70 os estudos na região eram basicamente descritivos, porém, já indicavam uma correlação entre os grupos Natividade e Araí (Moore, 1963; Dyer, 1970; Costa et al., 1976).

Essa correlação era dada especialmente pela proximidade geográfica, sendo que autores como Costa et al. (1976), Araújo & Alves (1979) e Correia Filho & Sá (1980) acreditavam que o Grupo Natividade era correspondente às unidades basais do Grupo Araí. Entretanto, Schobbenhaus (1993) já alertava para a não ocorrência de vulcânicas associadas ao Grupo Natividade, ao contrário do que ocorria no Grupo Araí.

Marini et al. (1981) acreditavam que os grupos Natividade e Araí eram penecontemporâneos ainda que exibissem colunas estratigráficas distintas. Isso era explicado pelos seus sedimentos terem sido depositados em bacias isoladas ou em uma bacia de amplas dimensões com compartimentos distintos (Martins, 1999).

Marques (2009) e Saboia (2009) afirmam que o Grupo Araí e Natividade constituem uma unidade tectônica formada a partir da evolução da bacia rifte Araí. As variações faciológicas de cada grupo são relacionadas à paleogeografia da bacia. Assim, mais ao sul na região da Chapada dos Veadeiros dominam rochas sin-rifte representando o local de abertura. E mais para o norte passariam a prevalecer rochas do estágio transicional e pós-rifte com maior presença de carbonatos (dolomitos e calcários) do Grupo Natividade. Esses autores ainda fazem uma correlação provável entre o Grupo Serra da Mesa e o Grupo Natividade, ambos sendo depositados no mesmo estágio e numa plataforma siliciclástica-carbonática.

Silva et al. (2005) fazem um dos estudos mais complexos sobre a correlação entre os Grupos Araí e Natividade. Nesse trabalho, os autores estudaram uma amostra de quartzito com 74 grãos de zircão detrítico pelo método de evaporação de Pb, sendo que 37 tiveram resultados adequados. As idades obtidas são de um amplo espectro relativo a todo o período do Paleoproterozoico de 1779 ± 6 Ma a 2476 ± 8 Ma.

Com esses dados, Silva et al. (2005) calculam a idade máxima de deposição do Grupo Natividade de 1779 ± 6 Ma. Deste modo, evidenciou-se um diacronismo entre os grupos

Natividade e Araí. Segundo esses autores, o fato dessas duas unidades terem sido formadas em um mesmo ambiente geotectônico, torna possível uma correlação lito-estratigráfica entre eles.

Assim, Silva et al. (2005) sugerem que o rifteamento afetou toda a porção setentrional da Zona Externa da Faixa Brasília, sendo o estilo tectônico distinto entre os grupos Araí e Natividade, visto que nesse último não existem intercalações de rochas vulcânicas na base. Uma interpretação plausível é que a abertura tenha se iniciado de sul para norte durante um período relativamente longo.

Mais precisamente, segundo esses autores, o rifteamento iniciaria nas adjacências da atual cidade de Niquelândia (GO) composta por uma bacia isolada (Bacia Araí), que imediatamente passaria para uma transgressão, evoluindo para um mar restrito limitado por falhas normais. Esse falhamento mais ao sul alcançaria níveis crustais profundos, ocasionando vulcanismo na superfície junto com a presença de arcósios e evaporitos que marcam os estágios iniciais de um rifte. Assim que ocorre a inundação formam-se rochas como argilitos, arenitos e carbonatos.

Já na região de Natividade (TO), a abertura seria relacionada a um simples fraturamento em superfície. Deste modo, a distensão na porção da Bacia Natividade seria de menor intensidade e a própria bacia mais rasa, o que é corroborado pela falta de vulcanismo e pela predominância de sedimentos arenosos.

Por fim, Silva et al. (2005) afirmam que o Terreno Almas foi à principal fonte de sedimentos e que há uma discreta participação de rochas ígneas com idade de 1,78 Ga (vulcanitos da base do Grupo Araí e granitos associados) no fornecimento de sedimentos à Bacia Natividade.

Ainda, vale citar as conclusões de Martins-Ferreira (2017) que relatam que os grupos Natividade e Serra da Mesa são correlatos ao Grupo Traíras, possivelmente pertencentes ao mesmo sistema de bacia tipo sag, com diferenças metamórficas e variações laterais oriundas de fontes de sedimentos distintas e do paleorelevo.

Referências bibliográficas

Abreu, F.R. 1991. Estudo das Mineralizações Auríferas Filoneanas da região da cidade de Diamantina/MG (Unpublished Msc. dissertation). Universidade de Campinas.

Aerogeophysica Latinoamerica - AGP-LA. 2006. Levantamento Aerogeofísico do Estado do Tocantins. Programa Geologia do Brasil - CPRM. Relatório Final do Levantamento e Processamento dos Dados Magnetométricos e Gamaespectrométricos. Vol. 1. 478p.

Alkmim F.F. 2004. O que faz de um cráton um cráton? O Cráton do São Francisco e as revelações almeidianas ao delimita-lo. In: Mantesso-Neto V., Bartorelli A., Carneiro C.D.R., Brito Neves B.B. (eds.), Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida. Brasil, Beca, 17-35p.

Alkmim, F.F. & Martins Neto, M.A. 2012. Proterozoic first order sedimentary sequences of the São Francisco Craton, eastern Brazil. Marine and Petroleum Geology, 33(1):127-139. https://doi.org/10.1016/j.marpetgeo.2011.08.011.

Almeida, F.F.M. 1977. O Cráton do São Francisco. Revista Brasileira de Geociências, 7(4):349-364.

Araújo, V.A. & Alves A.C. 1979. Projeto Canabrava-Porto Real, Relatório Final. CPRM, Goiânia, 191p.

Babinski, M., Pedreira, A.J., Brito Neves, B.B., Van Schmus, W.R. 1999. Contribuição à geocronologia da Chapada Diamantina. In: VII Simpósio Nacional de Estudos Tectônicos. Lençóis, Brazil, Anais, 2:118-120.

Babinski, M., Van Schmus, W.R., Chemale, F., Brito Neves, B.B., Rocha, A.J.D. 1993. Idade isocrônica Pb/Pb em rochas carbonáticas da Formação Caboclo, em Morro do Chapéu. In: Pedreira, A.J., Misi, A., Dominguez, J.M.L. (Eds.), II Simpósio sobre o Craton do São Francisco. Brazilian Geological Society, Salvador, 160-163p.

Barbosa O., Baptista M.B., Braun O.P., Dyer R.G., Cotta J.C. 1969. Geologia e inventário dos recursos minerais do Projeto Brasília. Rio de Janeiro, PROSPEC/DNPM, 225p.

Bosence, D.W.J. 1998. Stratigraphic and sedimentological models of rift basins. In: Purser, B.H. & Bosence, D.W.J. (ed.). Sedimentation and tectonics of rift basins: Red Sea - Gulf of Aden. London: Chapman & Hall, 9-25p.

Braun, O.P.G. 1980. Revisão Estratigráfica na Área Central de Goiás – Anais do XXXI Congresso Brasileiro de Geologia, v. 2SBG, Camboriú, Santa Catarina, 705-719p.

Brito Neves, B.B., Kawashita, K., Cordani, U.G., Delhal, J. 1979. A evolução geocronológica da Cordilheira do Espinhaço; dados novos e integração. Revista Brasileira de Geociências, 9(1):71-85.

Brito Neves, B.B., Sá, J.M., Nilson, A.N., Botelho, N.F. 1995. A Tafrogênese Estateriana nos blocos Paleoproterozoicos da América do Sul e processos subsequentes. Geonomos, 3:1-21.

Bueno, G.V., Zacharias, A.A., Oreiro, S.G., Cupertino, J.A., Falkenhein, F.U.H., Neto, M.A.M. 2007. Bacia de Pelotas. Boletim de Geociências da Petrobras, 15(2):551-559.

Bühn, B., Pimentel, M.M., Matteini, M., Dantas, E.L. 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). An. Acad. Bras. Cienc. 81:1-16. DOI: https://doi.org/10.1590/S0001-37652009000100011

Campos, J.E.G., Martins Ferreira, M.A.C., Moura, F.G., Chemale Jr, F. 2020. Discovery of Precambrian deep-water turbidites and submarine volcanism in the Brasilia Belt, central Brazil: The Quilombo Formation. Journal of South American Earth Sciences, 108:103226. DOI: https://doi.org/10.1016/j.jsames.2021.103226

Chemale Jr., F., Dussin, I.A., Alkmim, F.F., Martins, M.S., Queiroga, G., Armstrong, R., Santos, M.N. 2012. Unravelling a Proterozoic basin history through detrital zircon geochronology: the case of the Espinhaço Supergroup, Minas Gerais, Brazil. Gondwana Res. 22:200-206.

Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X. 2013. Updated. The ICS International Chronostratigraphic Chart. Episodes 36:199-204.

Cordeiro, P.F.O., & Oliveira, C.G. 2017. The Goiás Massif: implications for a pre-Columbia 2.2-2.0 Ga continent-wide amalgamation cycle in central Brazil. Precambrian Res. 298:403-420. Https://doi.org/10.1016/j.precamres.2017.06.021.

Correia Filho, F. C. L., & Sá, A. M. 1980. Projeto Natividade. Relatório Final. Goiânia, DNPM/CPRM, 6:256p.

Costa, A.F.O., Danderfer, A., Bersan, S.M. 2018. Record of a Statherian rift-sag basin in the Central Espinhaço Range: Facies characterization and geochronology. Journal of South American Earth Sciences, 82:311-328. DOI: https://doi.org/10.1016/j.jsames.2017.10.014

Costa, J. B. S. 1984. Aspectos litoestruturais e evolução crustal da região centro-norte de Goiás. Tese de Doutorado. Centro de Geociências da Universidade Federal do Pará, Belém, 210p.

Costa, L.A.M., Portela, A.C., Nilson, A.A., Vale, C.R.O., Marchetto, C.L.M., Santos, E.L., Meneghesso, G., Inda, H.A.V., Sterna, R., Marchetto, P., Baptista, M.B., Fratin, O., Mosmann, R., Oliveira, T.F.D., Silva, W.E. 1976. Projeto Natividade Área VI. Projeto Leste do Tocantins, Oeste do Rio São Francisco. Conv. DNPM/CPRM/PROPESC. (relatório final), Rio de Janeiro, 151p.

Cruz, E.L.C.C. 2001. A gênese e o contexto tectônico da mina Córrego Paiol, Terreno Almas-Conceição: um depósito de ouro hospedado em anfibolito do embasamento da Faixa de Dobramento Brasília. Doctoral dissertation, PhD thesis. Universidade de Brasília, 189p.

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017a. The peraluminous Aurumina Granite Suite in central Brazil: An example of mantle-continental crust interaction in a Paleoproterozoic cordilleran hinterland setting? Precambrian Research, 299:75-100. DOI: https://doi.org/10.1016/j.precamres.2017.07.029

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017b. The Ticunzal formation in central Brazil: record of Rhyacian sedimentation and metamorphism in the western border of the São Francisco Craton. J. S. Am. Earth Sci. 79:307-325. DOI: https://doi.org/10.1016/j.jsames.2017.08.014

Danderfer, A., De Waele, B., Pedreira, A.J., Nalini, H.A. 2009. New geochronological constraints on the geological evolution of Espinhaço basin within the São Francisco Craton - Brazil. Precambrian Research 170:116-128. DOI: https://doi.org/10.1016/j.precamres.2009.01.002.

Danderfer, A., Lana, C.C., Nalini, H.A., Costa, A.F.O. 2015. Constraints on the Statherian evolution of the intraplate rifting in a Paleo-Mesoproterozoic paleocontinent: New stratigraphic and geochronology record from the eastern São Francisco Craton. Gondwana Research, 28:668-688. https://doi.org/10.1016/j.gr.2014.06.012

Dardenne, M. A., Campos J.E.G., Alvarenga C.J.S., Martins F.A.L., Botelho, N.F. 1999. A sequência sedimentar do Grupo Araí na região da Chapada dos Veadeiros, Goiás. In: Simpósio de Geologia do Centro Oeste, 7, e Simpósio de Geologia de Minas Gerais, 10, Brasília., Atas, 100 p.

Dardenne, M.A. 2000. The Brasília Fold Belt. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 31st International Geological Congress, 231-263.

Dussin, T.M., Dussin, I.A., Rossi, P., Charvet, J. 1994. Dating of the Mesoproterozoic tensional event in the Espinhaço Range, Southeastern of the São Francisco Craton (SE Brazil). in: Dussin, I.A.: Evolution structurale de la region de l'Espinhaço Meridional, bordure sud-est du craton São Francisco, Brésil. - Tese de Doutoramento, Univ. Orléans, 105-133.

Dyer, R.C. 1970. Grupo Araí - Um Grupo de Metamorfitos do Centro-Leste de Goiás. Revista da Escola de Minas. Ouro Preto, 28(2):55-63.

Falvey, D.A. 1974. The development of continental margins in plate tectonic theory. Australian Petroleum Exploration Journal, 14:95-106.

Fuck, R.A., Dantas, E.L., Pimentel, M.M., Botelho, N.F., Armstrong, R., Laux, J.H., Junges, S.L., Soares, J.E., Praxedes, I.F. 2014. Paleoproterozoic crust-formation and reworking events in the Tocantins Province, central Brazil: A contribution for Atlantica supercontinent reconstruction. Precambrian Research, 244:53-74. DOI: https://doi.org/10.1016/j.precamres.2013.12.003

Fuck, R.A., Pimentel, M.M., Alvarenga, C.J.S., Dantas, E.L. 2017. The Northern Brasília Belt. In: São Francisco Craton, Eastern Brazil. Tectonic Genealogy of a Miniature Continent. Editors: Heilbron, M., Cordani, U.G., Alkmim, F.F. Regional Geology Reviews. Springer, 1ed, 205-220. DOI:10.1007/978-3-319-01715-0.

Geosoft. 2013. Oasis Montaj 7.5 Mapping and Processing System. In: Quick Start Tutorials. Geosoft Incorporated, 258 p.

Geosoft. 2019. Oasis MontajTM 9.6 Geosoft Inc. Toronto: Canadá.

Gorayeb, P.S.S., Costa, J.B.S., Lemos, R.L., Gama, J.R.T., Bemerguy, R.L., Hasui, Y. 1988. O Pré-Cambriano da Região de Natividade, GO. Revista Brasileira de Geociências, 18:391-397.

Guadagnin, F., & Chemale, F. 2015. Detrital zircon record of the Paleoproterozoic to Mesoproterozoic cratonic basins in the São Francisco Craton. Journal of South American Earth Sciences, 60:104-116. DOI: https://doi.org/10.1016/j.jsames.2015.02.007

Guadagnin, F., Chemale, F., Magalhães, A.J., Santana, A., Dussin, I., Takehara, L. 2015. Age constraints on crystal-tuff from the Espinhaço Supergroup - Insight into the Paleoproterozoic to Mesoproterozoic intracratonic basin cycles of the Congo-São Francisco Craton. Gondwana Research, 27(1): 363-376. DOI: https://doi.org/10.1016/j.gr.2013.10.009

Hasui, Y., Costa, J.B.S., Saad, A.R., Campanha, V.A. 1990. O Grupo Natividade e sua correlação com o Grupo Bambuí. Geociências (UNESP. Impresso), São Paulo, v. Esp., n. Especial, 299-316p.

Henstra, G.A., Grundvag, S.-A., Johannessen, E.P., Kristensen, T.B., Midtkandal, I., Nystuen, J.P., Rotevatn, A., Surlyk, F., Sather, T., Windelstad, J. 2016. Depositional processes and stratigraphic architecture within a coarse-grained rift-margin Turbidite system: the Wollaston Forland Group, east Greenland. Mar. Petrol. Geol. 76:187-209.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A. 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. Chem. Geol. 211: 47-69. DOI: https://doi.org/10.1016/j.chemgeo.2004.06.017

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., Essling, A.M. 1971. Precision measurement of the half-lives and specific activities of 235U and 238U. Physical Review C 4, 1889-1906.

Janousek, V., Farrow, C.M., Erban, V. 2006. Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). J. Petrol. 47:1255-1259. https://doi.org/10.1093/petrology/ egl013

Kifumb, C. 2017. Estratigrafia de alta resolução dos estágios iniciais de rifteamento, Bacia de Sergipe-Alagoas, Dissertação de Mestrado, Universidade Federal do Rio Grande do Sul, 74p.

Kifumbi, C., Scherer, C.M.D.S., Jones, F.H., Kuchle, J. 2017. High resolution stratigraphy of initial stages of rifting, Sergipe-Alagoas Basin, Brazil. Brazilian Journal of Geology, 47(4):657-671.

Kuchle, J. 2010. Análise tectono-estratigráfica de bacias rifte. Tese de doutorado. Universidade Federal do Rio Grande do Sul. 186p.

Loureiro, H.S.C., Lima, E.S., Macedo, E.R., Silveira, F.V., Bahiense, I.C., Arcanjo, J.B.A., Moraes Filho, J.C., Neves, J.P., Guimarães, J.T., Teixeira, L.R., Abram, M.B., Santos, R.A., Melo, R.C. 2008. Projeto Barra-Oliveira dos Brejinhos Geological map. Brazilian Geological Survey and Bahia Mineral Research Company, scale 1:200000.

Ludwig, K.R., 2003. User's Manual for Isoplot/Ex Version 3.00dA Geochronology Toolkit for Microsoft Excel, No. 4. Berkeley Geochronological Center Special Publication, 70p.

Magalhães, J.R., Pedrosa-Soares, A., Dussin, I., Müntener, O., Pinheiro, M.A.P., Silva L.C., Knauer, L.G., Bouvier, A., Baumgartner, L. 2018. First Lu-Hf, δ18O and trace elements in zircon signatures from the Statherian Espinhaço anorogenic province (Eastern Brazil): geotectonic implications of a silicic large igneous province. Brazilian Journal of Geology, 48(4):735-759. DOI: 10.1590/2317-4889201820180046.

Marini, O.J., Fuck, R.A., Danni, J.C. 1981. A evolução geotectônica da Faixa Brasília e seu embasamento. In: Simpósio sobre o Cráton do São Francisco e suas faixas marginais. Salvador. Anais. Salvador, SBG/BA, 100-113p.

Marques, G.C. 2009. Geologia dos grupos Araí e Serra da Mesa e seu embasamento no sul do Tocantins. Dissertação de Mestrado, Universidade de Brasília, 116p.

Martins Neto, M.A. 1998. O Supergrupo Espinhaço em Minas Gerais: registro de uma bacia rifte-sag do Paleo/Mesoproterozóico. Revista Brasileira de Geociências, São Paulo, 28:151-168.

Martins, F.A.L. 1999. Análise faciológica e estratigráfica do Paleo-Mesoproterozóico: Sequência Araí no Parque Nacional Chapada dos Veadeiros, Goiás. Dissertação de Mestrado. IG-UnB, 137 p.

Martins-Ferreira, M.A.C. 2017. Evolução tectônica das bacias Araí, Traíras e Paranoá na Faixa Brasília Norte. Tese de Doutorado. Instituto de Geociências. Universidade de Brasília, 202p.

Martins-Ferreira, M.A.C., Campos, J.E.G., Von Huelsen, M.G. 2018b. Tectonic evolution of the Paranoá basin: New evidence from gravimetric and stratigraphic data. Tectonophysics, 734:44-58. DOI: 10.1016/j.tecto.2018.04.004

Martins-Ferreira, M.A.C., Chemale, F., Coelho Dias, A.N., Campos, J.E.G. 2018a. Proterozoic intracontinental basin succession in the western margin of the São Francisco Craton: Constraints from detrital zircon geochronology. Journal of South American Earth Sciences, 81:165-176. DOI: 10.1016/j.jsames.2017.11.018.

Martins-Ferreira, M.A.C., Dias, A.N.C., Chemale., F., Campos, J.E.G., Seraine, M., Novais-Rodrigues, E. 2020. Multistage crustal accretion by magmatic flare-up and quiescence intervals in the western margin of São Francisco Craton: U-Pb-Hf and geochemical constraints from the Almas Terrane. Gondwana Research. 85:32-54. DOI: https://doi.org/10.1016/j.gr.2020.04.005

Matenco, L.C., & Haq, B.U. 2020. Multi-scale depositional successions in tectonic settings. Earth Sci. Rev. 200:102991. https://doi.org/10.1016/j.earscirev.2019.102991.

Matteini, M., Dantas, E.L., Pimentel, M.M., Alvarenga, C.J.S., Dardenne, M.A. 2012. U-Pb and Hf isotope study on detrital zircons from the Paranoá Group, Brasília Belt Brazil: Constraints on depositional age at Mesoproterozoic-Neoproterozoic transition and tectono-magmatic events in the São Francisco Craton. Precambrian Research, 206:168-181. DOI: 10.1016/j.precamres.2012.03.007

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters, 40:25-32.

Miall, A.D. 2000. Principles of sedimentary basin analysis. 3. ed. New York: SpringerVerlag, 616p.

Moore B. 1963. Geological reconnaissance of the southwest corner of the Maranhão Basin. Relatório nº 1854, PETROBRÁS/DEPEX, RJ.

Mounguengui, M.M., Lang, J., Guiraud, M., Jocktane, O. 2002. Sedimentary dynamics and structural geology of pre-rift deposits of the Cretaceous Interior Basin of Gabon. J. Afr. Earth Sci 35:315-329. DOI: https://doi.org/10.1016/S0899-5362(02)00035-0

Oliveira F.V. 2015. Um novo suplemento para a redução de dados U-Pb obtidos por LA-MC-ICPMS. Dissetação (Mestrado em Geonciência). Instituto de Geociências. Universidade de Brasília, 91p.

Pedreira, A.J. 1997. Sistemas deposicionais da Chapada Diamantina Centro Oriental, Bahia. Revista Brasileira de Geociências, 27 (3): 229-240.

Pimentel, M.M., Heaman, L., Fuck, R.A., Marini, O.J. 1991. U-Pb zircon chronology of Precambrian tin-bearing continental-type acid magmatism in central Brazil. Precambrian Research, 52(3-4):321-335. DOI: https://doi.org/10.1016/0301-9268(91)90086-P

Pinto C.P., Silva M.A. 2014. Mapa Geológico do Estado de Minas Gerais, Brasil. Escala 1:1.000.000. Belo Horizonte, CODEMIG - CPRM.

Prosser, S. 1993. Rift-related linked depositional systems and their seismic expression. Geological Society, London, Special Publications, 71:35-66.

Rapozo, B. F., Córdoba V.C., Antunes, A.F. 2021. Tectono-stratigraphic evolution of a cretaceous intracontinental rift: Example from Rio do Peixe Basin, north-eastern Brazil. Marine and Petroleum Geology 126:104899 https://doi.org/10.1016/j.marpetgeo.2021.104899

Reeves, C. 2005. Aeromagnetic surveys: principles, practice and interpretation. Delft: Geosoft, 155p.

Ress, C.B., Oliveira, L.M.C., Ribeiro, T.G.R., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea IX. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Rodrigues, J.B., Pimentel, M.M., Dardenne, M.A., Armstrong, R.A. 2010. Age, provenance and tectonic setting of the Canastra and Ibiá Groups (Brasília Belt, Brazil): Implications for the age of a Neoproterozoic glacial event in central Brazil. Journal of South American Earth Sciences, 29(2):512-521. DOI: 10.1016/j.jsames.2009.08.008

Saboia, A.M. 2009. O Vulcanismo em Monte do Carmo e Litoestratigrafia do Grupo Natividade, Estado de Tocantins. Dissertação (Mestrado em Geociências) – Universidade de Brasília, Brasília, 96 p.

Santos, M.M., Lana, C., Scholz, R., Buick, I., Schmitz, M.D., Kamo, S.L., Gerdes, A., Cirfu, F., Tapster, S., Lancaster, P., Storey, C.D., Basei, M.A.S., Tohver, E., Alkmim, A., Nalini, H., Krambrock, K., Fantini, C., Wiedenbeck, M. 2017. A New Appraisal of Sri Lankan BB Zircon as a Reference Material for LA-ICP-MS U-Pb Geochronology and Lu-Hf Isotope Tracing. Geostandards and Geoanalytical Research, 1-24.

Schobbenhaus C. 1993. O Proterozóico Médio no Brasil com ênfase à região Centro-Leste: uma revisão. Tese de Doutorado, Univ. Albert-Ludwig, Freiburg, Alemanha, 166 p.

Schobbenhaus, C. & Bellizzia, A. (coords.). 2001. Mapa geológico da América do Sul, 1: 5.000.000. CGMW - CPRM - DNPM - UNESCO, Brasília.

Schobbenhaus, C. & Brito Neves, B.B. 2003. A Geologia do Brasil no contexto da plataforma Sul-Americana. In: Bizzi, L.A., Schobbenhaus, C., Vidoti, R.M., Gonçalves, J.H. (Eds). Geologia, Tectônica e Recursos Minerais do Brasil, CPRM, Serviço Geológico do Brasil, Brasília, 169-226p.

Schobbenhaus, C., Campos, D.A., Derze, G.R., Asmus, H.E. 1984. Mapa Geológico do Brasil e da Área Oceânica Adjacente, Incluindo Depósitos Minerais, escala 1:2500000. MME/DNPM, Brasília.

Schobbenhaus, C., Hoppe, A., Baumann, A., Lork, A. 1994. Idade U/Pb do vulcanismo Rio dos Remédios, Chapada Diamantina, Bahia. In: Congresso Brasileiro de Geologia, 38, Balneário Camboriú, Anais, 2:397-399.

Seraine, M., Campos, J.E.G., Martins-Ferreira, M.A.C., Giorgioni, M., Angelo, T.V. 2020. Tectonic significance of abrupt immature sedimentation in a shallow cratonic margin basin: The Arkose Level, Mesoproterozoic Paranoá Group. Journal of South American Earth Sciences, 97:102397. https://doi.org/10.1016/j.jsames.2019.102397

Silva, R.R. 1998. As bacias proterozóicas do Espinhaço e São Francisco em Minas Gerais: Uma abordagem do ponto de vista da estratigrafia de sequências. Geonomos, 6:1-12.

Silva, W.L., Kotschoubey, B., Lafon, J.M., Gallarza, M.A. 2005. Grupo Natividade e Grupo Araí: correlatos, mas diacrônicos. In: X Congresso Brasileiro de Geoquímica e II Simpósio de Geoquímica dos Países do Mercosul. Estratigrafia do Grupo Araí: registro de rifteamento Paleoproterozoico no Brasil Central de Galinhas, Pernambuco, Brasil, 2:1-4.

Silveira, E.M., Söderlund, U., Oliveira, E.P., Ernst, R.E., Menezes Leal, A.B. 2013. First precise U-Pb baddeleyite ages of 1500 Ma mafic dykes from the São Francisco Craton, Brazil, and tectonic implications. Lithos, 144-156.

Simplicio, F. & Basilici, G. 2015. Unusual thick eolian sand sheet sedimentary succession: Paleoproterozoic Bandeirinha Formation, Minas Gerais. Braz. J. Geol. 45(1):3-11. DOI: • https://doi.org/10.1590/2317-4889201530133

Sláma J., Košler J., Condon D.J., Crowley J.L., Gerdes A., Hanchar J.M., Horstwood M.S.A., Morris G.A., Nasdala L., Norberg N., Schaltegger U., Schoene B., Tubrett M.N., Whitehouse M.J. 2008. Plešovice zircon – a new natural reference material for U–Pb and Hf isotopic microanalysis. Chem. Geol., 249:1-35. Doi: https://doi.org/10.1016/j.chemgeo.2007.11.005

Sousa I.M.C., Giustina M.E.S.D., Oliveira C.G. 2016. Crustal evolution of the northern Brasília Belt basement, central Brazil: A Rhyacian orogeny coeval with a pre-Rodinia supercontinent assembly. Precambrian Research, 273:129-150. https://doi.org/10.1016/j.precamres.2015.12.007

Stanton, N. 2009. Caracterização Crustal da Margem Sudeste Brasileira através de Magnetometria e suas Implicações Tectônicas. Tese de Doutorado, Universidade do Estado do Rio de Janeiro, 164p.

Tanizaki M.L.N. 2013. Geologia Do Grupo Araí: Registro de Rifteamento Crustal No Brasil Central. Dissertação de Mestrado, Universidade de Brasília, 133 p.

Tanizaki, M.L.N., Campos, J.E.G., Dardenne, M.A. 2015. Stratigraphy of the Araí Group: Record of Paleoproterozoic rifting in Central Brazil. Brazilian Journal of Geology, 45(1):95-108. DOI: 10.1590/23174889201500010007.

Teles, G.S. 2013. Proveniência e idades de deposição dos sedimentos auríferos da Bacia de Jacobina: implicações sobre a evolução da bacia durante o Paleoarqueano e a gênese da mineralização. Dissertação (Mestrado em Geologia), Universidade de Brasília, Brasília, 120 p.

Toscani, R., Campos, J.E.G., Martins-Ferreira, M.A.C., Matos, D.R., Borges, C.C.A., Dias, A.N.C., Chemale Jr, F. 2021b. The Statherian Natividade basin evolution constrained by U-Pb geochronology, sedimentology, and paleogeography, central Brazil. Journal of South merican Earth Sciences. Submitted.

Toscani, R., Campos, J.E.G., Matos, D.R., Martins-Ferreira, M.A.C. 2021a. Complex depositional environments on a siliciclastic carbonate platform with shallow-water turbidites: The Natividade Group, central Brazil, Journal of South American Earth Sciences. DOI: http:/doi.org/10.1016/j.jsames.2020.102939

Turpin, L., Maruejol, P., Cuney, M. 1988. U-Pb, Rb-Sr and Sm-Nd chronology of granitic basement hydrothermal albitites and uranium mineralizations (Lagoa Real, South Bahia, Brazil). Contrib. Mineral. Petrol. 98:139-147.

Uhlein, A., Paim, P.S.G., Tassinari, C.C.G., Pedreira, A.J. 2015. Análise estratigráfica de bacias rifte Paleo-Mesoproterozoicas dos crátons Amazônico e São Francisco, Brasil. Geonomos, 23(2):1-13. DOI: 10.18285/geonomos.v23i2.707.

CAPÍTULO 3

ARTIGO 1

Published in Journal of South American Earth Sciences: https://doi.org/10.1016/j.jsames.2020.102939

Journal of South American Earth Sciences 107 (2021) 102939

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

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

ELSEVIER

Complex depositional environments on a siliciclastic-carbonate platform with shallow-water turbidites: The Natividade Group, Central Brazil

Toscani, R.[1]*; Campos, J.E.G.[2]; Matos, D.R.[3]; Martins-Ferreira, M.A.C.[4]

[1] Centro de Hidrografia da Marinha, Diretoria de Hidrografia e Navegação, Marinha do Brasil, Niteroi, Rio de Janeiro, RJ, Brazil.
[2]Instituto de Geociências, Universidade de Brasília, Campus Univ. Darcy Ribeiro, Asa Norte, 70910900 Brasília, DF, Brazil
[3]Divisão de Geologia Econômica, Serviço Geológico do Brasil. Urca, Rio de Janeiro, RJ, Brazil.
[4]Fac. de Ciências e Tecnologia, Univ. Federal de Goiás, Setor Conde dos Arcos, 74968755 Aparecida de Goiânia, GO, Brazil

* Corresponding Author: toscanisilveira@gmail.com

Abstract

The Natividade Group is a Paleo-Mesoproterozoic metasedimentary sequence outcropping in the external zone of the Northern Brasília Belt, western margin of the São Francisco Craton, Brazil. The present study delimited eleven sedimentary rock types grouped into four rock assemblages: i) Sand-Silt-Carbonate; ii) Sand-Conglomerate; iii) Sand, iv) Silt-Clay. A geological map for the region was produced, and six stratigraphic columns were composed. Based on the descriptions of rock types and on lateral variation of rock assemblages, it was possible to establish four depositional environments for the Natividade Group, including mixed platform (siliciclastic-carbonate deposition), internal siliciclastic platform, open-marine siliciclastic platform, and a shallow water turbidite (mass flow slope deposition). The mixed platform was controlled by the basement paleogeography, which allowed the deposition of carbonates in warm, agitated, and clean, shallow water conditions in parallel to deposition in deeper water settings, where thin siliciclastic sediments were deposited. The siliciclastic internal platform consists mostly of quartzite, originating from sandy sediments, probably indicating deposition dominated by bedload currents under shallow water shoreface conditions. The open-marine siliciclastic platform is dominated by fine-grained sediments, indicating deepening water conditions under lower shoreface conditions below the fair-weather wave base. Shallow water turbidite occurs in the southern parts of the study area. The elevated paleorelief in the southeast of the Natividade basin is considered as the provenance area providing suitable slope environments for density flow initiation. The basin was shallower in the southern portion with a predominance of carbonate and gravitational flux deposits and deeper to the north, evidenced by the northward predominance of fine-grained sediments. Finally, the study shows that the Natividade Group was deposited in a basin controlled by thermo-flexural subsidence.

Keywords: *Natividade Group; Shallow water turbidites; Paleo-Mesoproterozoic basins; Mixed platforms.*

1. Introduction

The Natividade Group is a metasedimentary sequence that outcrops in the southeast of Tocantins state. Although it has been studied since the 1960s (Moore, 1963), most research in the region is mainly descriptive, not approaching in detail the sedimentological aspects and interpretations of depositional environments. A single age determination has been published for the sequence, which proposes a maximum deposition age of 1779 ± 6 Ma (Silva et al., 2005) calculated with the youngest detrital zircon grains via U-Pb method. This unit has been preliminarily correlated to the Paleo-Mesoproterozoic rift and sag systems in the São Francisco Craton western margin (Veadeiros Supergroup, Brasília Belt) and eastern margin (Espinhaço Supergroup, Araçuaí Belt) (Gorayeb et al., 1988; Hasui et al., 1990; Silva et al., 2005; Uhlein et al., 2013; Martins-Ferreira et al., 2018a). However, the sets of rocks present in different stratigraphic arrangements, the different depositional systems, and the lack of comprehensive geochronological data hinder this correlation.

Most modern turbidites are deposited at great depths from the continental slope into deeper waters and are usually related to thrust-and-fault regions (Põldsaar et al., 2019). However, very similar deposits, known as shallow-water turbidites, are described in the literature and can occur even in epicontinental environments (Fenton & Wilson, 1985; Mutti et al., 2007; Põldsaar et al., 2019).

It is worth mentioning that in the stratigraphic succession of the Natividade Group, there are frequent lateral and vertical interfingering of rock types (RT), containing matrix- and clast-supported conglomerates, large lenses of dolomitic and calcitic carbonates, lutites, and sandstones composing a complex and intricate stratigraphy. In this way, the understanding of depositional processes becomes difficult. Thus it is necessary to evaluate the interaction of different depositional conditions to explain the complex stratigraphy.

The depositional complexity was investigated by the different stratigraphic columns proposed by the authors who studied the Natividade Group in different locations (Costa et al., 1976; Correa Filho & Sá, 1980; Costa et al., 1984; Gorayeb et al., 1988; Saboia, 2009; Fuck et al., 2017). Thus, the present research aims to describe the sedimentary rock types, evaluate the rock assemblages in the different sectors of the basin, study the depositional processes related to each rock assemblage, and propose the depositional processes responsible for the filling of the Natividade basin. To better understand the Natividade basin, we have conducted geological mapping, stratigraphic section surveys, petrographic studies, and sedimentological analysis in detail.

The study has allowed toshed light on important aspects of the Natividade basin depositional history that were previously unknown. This paper characterizes the Natividade Group as a mixed platform (Saboia, 2009) with simultaneous deposition of shallow water turbidite in a basin controlled by thermo-flexural subsidence. The occurrence of this turbidite, related to the mass flow deposits, has never been described in other sedimentary sequences in the Brasília Belt. Our results provide the basis for future geochronological studies in the region.

2. Geological Setting

The Paleo-Mesoproterozoic Natividade Group is located in the Tocantins Structural Province (Fig. 1), (Almeida et al., 1981), which represents an extensive Neoproterozoic orogenic system in central Brazil that is part of a wide and long orogenic system extending for thousands of kilometers in central and northern Brazil, and in NW Africa, in the Hoggar-Pharusian and Dahomey belts (Pimentel, 2016). This province originated in the Brasiliano orogeny involving the Amazonian, São Francisco-Congo, and Paranapanema (Rio de La Plata) cratons, as well as smaller allochthonous blocks (Pimentel, 2016; Fuck et al., 2014).

The Tocantins Province is located in the western margin of the São Francisco Craton and is divided into three orogenic belts called the Brasília, Araguaia and Paraguay belts, which host several Proterozoic sequences separated by regional unconformities (Almeida, 1977; Alkmim & Martins Neto, 2012; Martins-Ferreira et al., 2018a). The study area is located in the extreme north of the Brasília Belt, where the sedimentary sequences of the Natividade Group are preserved (Fig. 1).

The northern segment of the Brasília Belt is characterized by a general NE/SW structural trend and verges to the east. The external zone of the Brasília Belt, where the study area is located, is comprised of a pile of sedimentary sequences deformed against the west margin of the São Francisco Craton with significant exposures of their sialic basement (Fuck et al., 2017).

According to Fuck et al. (2014), the basement of the area, Natividade-Cavalcante Crustal Block, is considered a Paleoproterozoic terrane with two main domains: Almas-Conceição do Tocantins and Cavalcante-Arraias. First, in the Almas-Dianópolis region there are granites of 2.2 Ga (Fuck et al., 2014). In the area of Natividade-Conceição do Tocantins the magmatism is 2.3-2.4 Ga. Finally, there are younger additions of 2144 ± 21 Ma (Fuck et al., 2014). In the Cavalcante-Arraias Domain, peraluminous granitoids of the Aurumina Suite are exposed and show ages from 2.11 to 2.16 Ga (Cuadros, 2017). From the geological mapping carried out in the area by the University of Brasília in 2012, 2016, and 2018, (Oliveira et al., 2012; Franco et al., 2016; Morbeck et al., 2016; Ress et al., 2016; Teixeira et al., 2016; Dantas et al., 2018) it was possible to detail the rocks of the Archean/Paleoproterozic basement, consisting of gneisses and volcano-sedimentary sequences which have historically been interpreted as Greenstone Belts. In the region, the most important units are Riachão do Ouro and Água Suja Volcano-sedimentary sequences, tonalite-trondhjemite-granodiorite rocks, small mafic-ultramafic complexes of the Gameleira Type, and several intrusive suites exemplified by the Manuel Alves, Rio do Moleque, Príncipe, Serra do Boqueirão, Xobó, and Serranópolis bodies. To more details about the basement rocks, understood to be the source areas to the Natividade Basin infilling, see Martins-Ferreira et al. (2020).

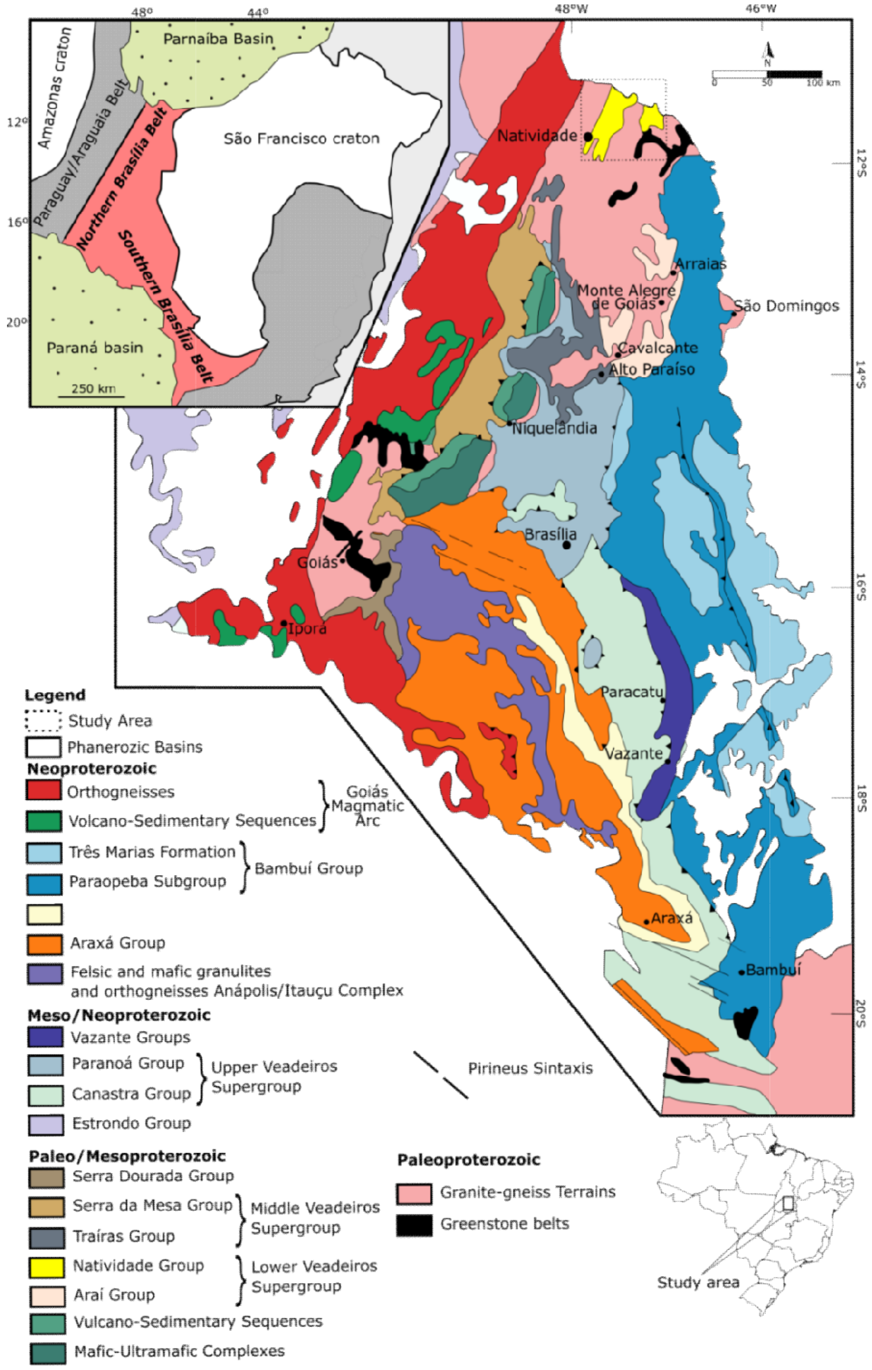


Fig. 1. Geological map of the Brasília Belt, where the Natividade Group outcrops in the extreme northeast, being covered by Phanerozoic sediments from the Parnaíba basin further to the north (adapted from Dardenne, 2000; Fuck, et al., 2017). The study area is also represented in Fig. 3f.

Over the crystalline basement, the Veadeiros Supergroup represents the Paleoproterozoic (Sthaterian) to the beginning of the Neoproterozoic (Tonian) extensional basin successions in the Northern Brasília Belt, and includes the Araí, Traíras, and Paranoá groups, besides the Quilombo Formation and may include the units with geographic and geochronological similarities Natividade, Serra da Mesa, and Canastra groups (Fig. 2), (Martins-Ferreira et al., 2018a).

The Veadeiros Supergroup is divided into three major sedimentary sequences. The first sequence of Paleoproterozoic age is comprised by the Araí Group and is known as Lower Veadeiros (Statherian age) which represents the pre-syn rift phase. The second sequence, in the Middle Veadeiros, is of Mesoproterozoic (Calymian to early Ectasian) age and consists of the Traíras Group and its probable lateral equivalent, the Serra da Mesa Group, which together represent the intracratonic sag phase of the orogeny (Martins-Ferreira et al., 2018a). The Middle Veadeiros sequence is correlated to the lower and middle Espinhaço Supergroup, which occurs in the eastern margin of the São Francisco Craton (Guadagnin & Chemale Jr, 2015). The third sequence, in the Upper Veadeiros, is interpreted as a late Mesoproterozoic (Stenian to early Tonian), represented by the Paranoá Group, which occurs in an Intra/Pericratonic sag basin type (Campos et al., 2013; Seraine et al., 2020; Martins-Ferreira et al., 2018b).

The Araí Group (Barbosa et al., 1969; Dyer, 1970) was interpreted as a rift-sag basin with a maximum depositional age of 1,771 Ga (Pimentel et al., 1991; Tanizaki et al., 2015). According to Martins-Ferreira et al. (2018a), the Araí Group consists of the Água Morna and Arraias formations. The Traíras Group with maximum deposition age at 1,543 ± 31 Ma (concordia age of youngest detrital zircons in marine sediments) is a sag-type basin deposited over the Araí Group or locally directly over the crystalline basement and might have coexisted in time with Serra da Mesa Group, possibly as part of the same sag basin system.

To the south of the study area, in the Alto Paraíso de Goiás, Monte Alegre de Goiás, and Arraias regions (Figs. 1 and 2), continental deposits are associated with a syn-rift phase deposition, comprising the Araí Group. Towards the north, there is the predominance of rocks of the Natividade Group that indicate possible transitional and post-rift stages with a more significant amount of carbonate (dolomite and limestone) (Marques, 2009; Saboia, 2009).

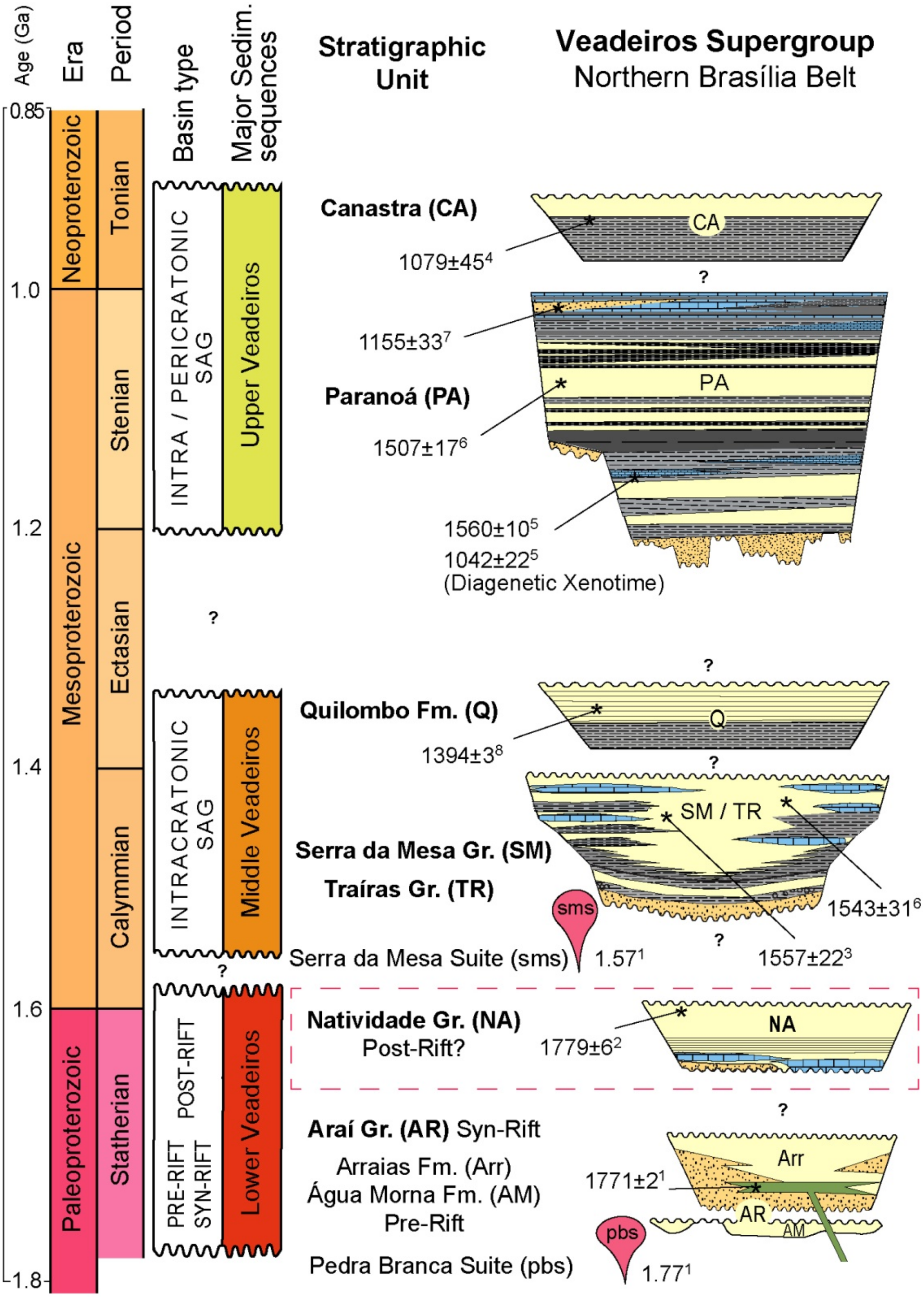


Fig. 2. Stratigraphic chart of the Veadeiros Supergroup in the Northern Brasília Belt (after Martins-Ferreira et al., 2018a). 1 - Pimentel et al. (1991); 2 - Silva et al. (2005); 3 - Marques (2009), concordia age; 4 - Rodrigues et al. (2010), youngest zircon age; 5 - Matteini et al. (2012), youngest zircon age and diagenetic xenotime age; 6 - Martins-Ferreira et al. (2018a), youngest zircon ages for Traíras and Paranoá Group; 7 - Seraine et al. (2020), youngest zircon age; 8 - Campos et al. (2020), youngest zircon age. Geologic time scale from Cohen et al. (2013).

The Serra da Mesa Group was described by Marques (2009) as a siliciclastic-carbonate marine platform, without continental facies, characterized mainly by muscovite-quartzite, shale, and marble lenses. It shows detrital zircons U-Pb ages ranging from 1.55 to 2.4 Ga and is frequently interpreted as chrono-correlated to the Traíras Group (Marques, 2009; Saboia, 2009; Martins-Ferreira et al., 2018a).

In the central portion of the Brasilia Belt, recent detailed geological mapping has allowed the identification of acid lavas interbedded to low-grade metasedimentary rocks, that were attributed to the Quilombo Formation which is an Ectasian unit (1394 Ga U-Pb zircon age), (Moura, 2018; Campos et al., 2020).

The Natividade Group is a sequence of metasedimentary rocks of Paleo-Mesoproterozoic age that was initially recognized by Moore (1963). In the 1960 and 1970 decades, studies in the region were quite descriptive without concern for sedimentary processes and environments (Moore, 1963; Dyer, 1970; Costa et al., 1976) (Fig. 3a). In the 1980 and early 1990 years, the work was more complete, with important data and interpretive ideas about the deposition environment. Correia Filho & Sá (1980) (Fig. 3b) suggested that the deposition environment is platformal with small periods of instability, giving rise to a fine-grained sandy-muddy sequence with conglomeratic and carbonatic facies, finally there is deposition in stable condition of a sandy pack. They also mention a moderate sediment input that enabled mixed sedimentation (siliciclastic-carbonatic). Costa et al. (1984) define the Natividade Group as a sandy sequence with levels of conglomerate, clay, and possible volcanic intercalation (Fig. 3c). Gorayeb et al. (1988) state that the Natividade Group developed in an ensialic basin with simple folding and low-grade metamorphism (greenschist facies). Hasui et al. (1990) believed that the Natividade Group belonged to a package deposited on the edge of an ensialic basin that opened to the east.

One of the most important studies in the region was carried out by Gorayeb et al. (1988) where the Natividade Group was divided into four formations: Santa Clara, Mato Virgem, Córrego Fundo, and Jacuba, from bottom to top, which is summarized in Fig. 3d. The Santa Clara Formation consists of a package of pure quartzite at the base, becoming micaceous with discontinuous intercalations of metaconglomerate, dolomitic marble, phyllite and quartzite with kyanite and chloritoid, where primary structures are preserved. The Mato Virgem Formation consists of dolomitic marbles with intercalations of phyllite and micaceous quartzite at the base. The Córrego Fundo Formation starts with quartzite moving to phyllite and slate, with thin beds of metalutite with graphite or hematite, and micaceous quartzite towards the top. The Jacuba Formation consists of pure or micaceous quartzite, with arkosean levels, grading laterally and vertically to quartzite with alternation of arkose, phyllite, and marble.

Another interesting description of Natividade Group is given by Hasui et al. (1990), where it was divided into three portions based on the columns of Correia Filho & Sá (1980), Costa et al. (1984), and Gorayeb et al. (1988) (Figs. 3b, 3c and 3d). The western portion overlaps the basement rocks, and the stratigraphy is summarized in: i) metaconglomerate with pebbles of quartz or quartzite; ii) pure quartzite with quartz pebbles; iii) micaceous quartzite with tremoliteactinolite schist intercalations; iv) phyllite; v) micaceous quartzite with phyllite lenses (Costa et al., 1984). In the Central Portion, from the base to the top, the rocks already described by Gorayeb et al. (1988) occur. Finally, the eastern portion has a 120 meter package of: i) phyllite with conglomeratic quartzite lenses; ii) phyllite or carbonate phyllite with marble lenses; iii) marble with intercalations of sedimentary metabreccia and phyllite; iv) locally carbonate phyllite; v) Micaceous quartzite (Correia Filho & Sá, 1980).

According to Saboia (2009), the Natividade Group is a sequence of metasedimentary rocks that were deposited in a mixed marine siliciclastic-carbonate platform typical of a marine expansion phase related to a thermal flexure after the rift phase observed in the south of the studied region. Saboia (2009) divided the group into eight lithostratigraphic units: metadolomite and metasiltstone (1); quartzite and metaconglomerate (2), metadolomite and metalimestone (3); metasiltstone and metadolomite (4); quartzite (5); metasiltstone and metadolomite (6); quartzite and metasiltstone (7); and metasiltstone (8) (Fig. 3e).

It is worth mentioning that the stratigraphic proposals are significantly different for each study site, since the vertical and lateral variations of rock types are very sensitive due to the different depositional environments, facies architecture and basement relief (Fig. 3).

3. Material and Methods

Fieldwork began on July 1st to 24th, 2016, when the authors worked and supervised the undergraduate students of the Geology Course at the University of Brasília. This undergraduate work consisted of the geological mapping near Natividade and Almas cities (Fig. 3f). This fieldwork allowed the recognition of some stratigraphic columns as well as the description of petrographic thin sections used in the study. In addition, hundreds of field measurements related to the Natividade Group were developed with the main foliation with mean plane NS/20°W (parallel to the bedding plane).

The follow fieldwork was carried out near the towns of Natividade and Almas (Fig. 3f), southern Tocantins State, Brazil, to investigate the rock types variations, assemblage and the related depositional environments, and sedimentary processes responsible for the deposition of the Natividade Group. In this way, stratigraphic sections were surveyed in detail, evaluating the stacking in different locations. Besides, samples were collected for petrographic analysis.

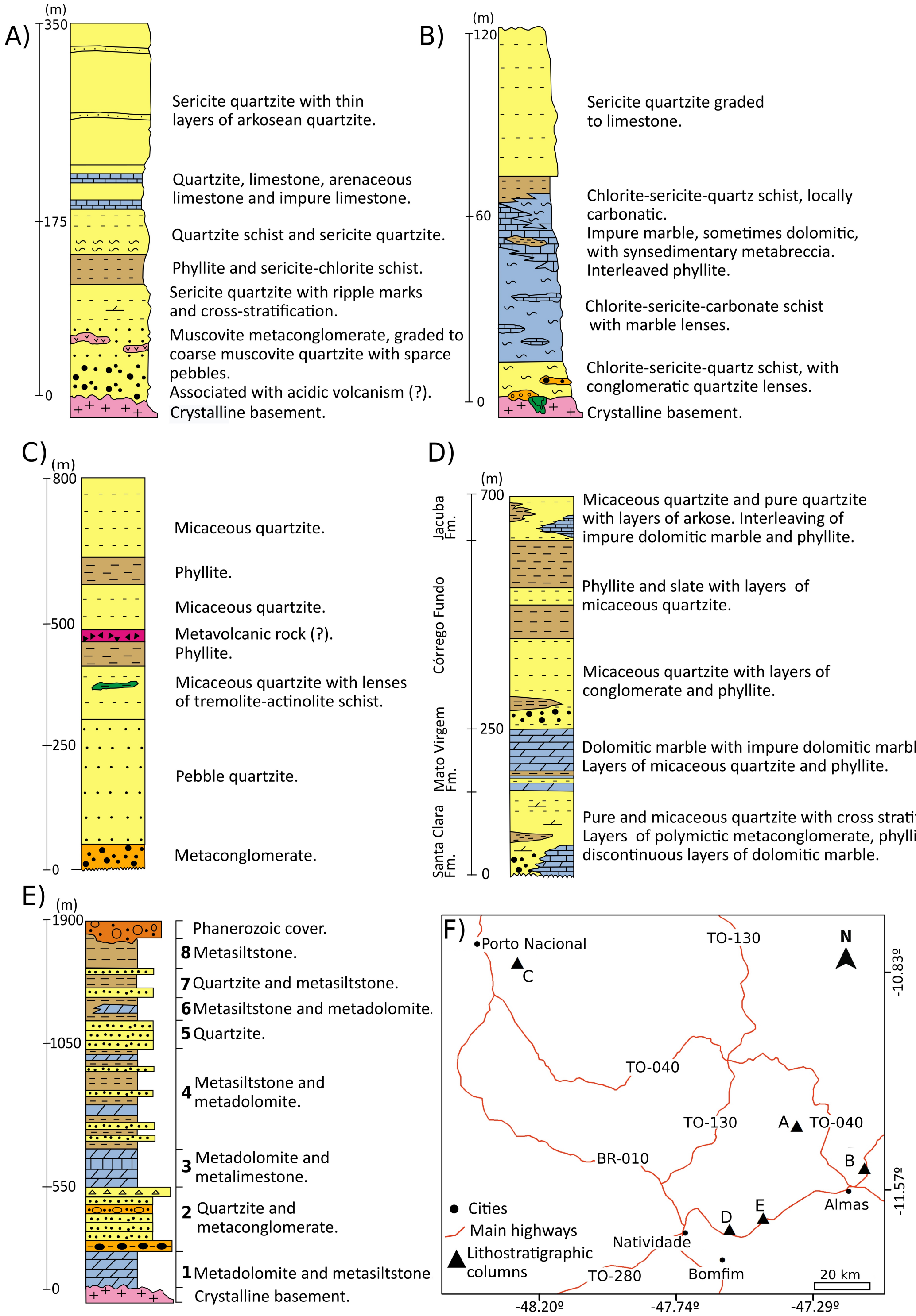


Fig. 3. Main lithostratigraphic columns of the Natividade Group and respective locations. (A) Costa et al. (1976); (B) Correa Filho & Sá (1980); (C) Costa et al. (1984); (D) Gorayeb et al. (1988); (E) Saboia (2009); (F) Location of the stratigraphic columns (black triangles) in the road map (where TO indicates regional highways and BR National highways) of the study area (map area showed in Fig. 1 by dotted square).

Subsequently, three more field works were carried out by the present research group, the first between January 6th and 8th, 2018, to recognize the area and collect samples. The second fieldwork in Natividade Group took place from February 11th to 15th, 2019, where several lithologies were identified as well as stratigraphic sections. Finally, the last fieldwork took place from February 12th to 16th, which allowed defining rock types and rock assemblages as well as defining some geological contacts. Altogether, in these three periods, 72 outcrops were described in the study area. Table 1 describes the location and dimensions of the outcrops and thin sections contained in this article. It is important to stand that besides these specific trips; much more study has been developed in previous fieldwork in the Natividade area and in the Araí and Traíras groups in Tocantins and Goiás states. The results now presented correspond to the integration of data acquired in all these field observations.

Table 1. Location and dimensions of the outcrops and thin sections contained in this article.

Samples/outcrops according to the Figs. in this paper	UTM Coordinates (WGS84)	Outcrop dimensions
4a, 4b	23L 223981 E; 8701394 S	It is a deactivated carbonate quarry. The main outcrop wall is greater than 50 meters high.
4c	23L 261566 E; 8724087 S	Outcrop with a maximum height of 2 meters and a lateral continuity of 10 meters.
4d	23L 270298 E; 8726854 S	It occurs in flat relief, with dimensions of 2 to 3 meters.
4e, 4f, 5c, 5d	23L 226945 E; 8705256 S	Active carbonate mine. Most rocks are altered blocks where sedimentary structures are evident.
5a, 5b	23L 284716 E; 8726768 S	Blocks of 1 to 2 meters close to the Manuel Alves river.
6a, 6b, 6c, 6d, 6e	23L 205581 E; 8707424 S	Outcrop on a hill in the form of flagstone, next to a stream.
7a	23L 234179 E; 8725670 S	Outcrop located on a 600 meters high hill. It consists of blocks of 1 to 2 m.
7b	23L 234097 E; 8725934 S	Outcrop situated on a rugged relief, consisting of 1 to 2 m blocks.
7c, 7d	23L 236026 E; 8713113 S	Thin section sample collected from 1 to 2 meters thick outcrop, located at the hill in contact with the basement.
8a	23L 205920 E; 8708726 S	Outcrop on a hill near the city of Natividade. It is 1.5 meters high and 2 meters wide.
8b, 8c	23l 234179 E; 8725670 S	Blocks with approximately 1 to 2 meters on a 600 meter high hill.
8d	23L 234148 E; 8725790 S	Outcrop located in rugged relief. It is formed by a wall 2 meters high and approximately 4 meters long.
9a	23L 224415 E; 8696420 S	Outcrop of 1 to 2 meters, in an intermediate portion of the hill.
9b	23L 224700 E; 8696295 S	Top of the mountain with approximately 600 m high. Outcrop 1 to 2 m high Rich in rolled blocks.
9c	23L 224415 E; 8740974 S	Hill with approximately 600 meters high. Outcrop 1 to 2 m high rich in blocks.
9d	23L 239015 E; 8721787 S	Outcrop in the form of flagstone with metric dimensions.
9e	23L 219161 E; 8750788 S	Hill with approximately 600 meters high. The outcrops are 1 to 2 meters long and have several blocks.
9f	23L 224303 E; 8741105 S	Hill with approximately 600 meters high. The outcrops are 1 to 2 meters long and have several blocks.
10a	23L 223599 E; 8701636 S	Small outcrop in the shape of a slab. It is situated beside the road.
10b	23L 265935 E; 8725422 S	Outcrop near the road, metric dimensions.
10c	23L 223795 E; 8702394 S	Outcrop at the side of the road with dimensions of tens of meters.
10d	23L 211312 E; 8726197 S	Plant outcrop, close to the road, with lateral continuity for more than ten meters.
10e, 10f	23L 283302 E; 8725378 S	Outcrop in a road cut. It is 1.5 meters high and 10 meters long.
11a, 11b, 11c	23L 235529 E; 8768192 S	Large outcrop with dozens of meters.
14	23L 215083 E; 8716425 S	Hill over a hundred meters high.
15	23L 234247 E 8725019 S	Hill over a hundred meters high.
16	23L 269808 E; 8727494 S	Hill over a hundred meters high.

A high-resolution aero magnetometric data was processed and interpreted to better understand the regional context of the Natividade Group. This aero magnetic survey was conducted in 2006 by the Brazilian Geological Survey, entitled "Aerogeophysical Survey of Tocantins". This data in nanotesla (nT) was processed in the Oasis MontajTM, version 9.6

(Geosoft, 2019).

The following procedures were carried out: i) noise level analysis using the fourth difference filter (Geosoft, 2013); ii) removal of the International Geomagnetic Reference Field (IGRF) using the Oasis Montaj 9.6 software; iii) data interpolation in a regular mesh set to 1/4 of the spacing between flight lines (Reeves, 2005). The bidirectional method yielded the best results, providing a higher definition and spatial correlation of the sampled data. This method takes into account the distribution of data-oriented online and emphasizes trends perpendicular to flight lines (Geosoft, 2019). As a result, the Anomalous Magnetic Field (AMF) was obtained, as well as the Total Gradient (TG) and first-order derivatives in the X, Y, and Z directions (Dx, Dy, and Dz) for each of the aerial surveys.

4. Results

4.1 Sedimentary Rock Types Analysis

The Natividade Group rocks are affected by low-grade metamorphism of the greenschist facies (chlorite zone) (Gorayeb et al., 1988; Saboia, 2009). Therefore, this article will describe the rock types (RT) using the metamorphic designation and not the equivalent sedimentary protolith names. For that reason, Table 2 brings the correlation of the metamorphic rock types used in this study with their original sedimentary facies.

Table 2. Rock Types designation applied in this study, the correlative terms in the sedimentary nomenclature, and the associated depositional conditions.

Rock type (RT)	Metamorphic Rock Types	Sedimentary Corresponding Rocks	Probable Depositional Conditions
1	Micritic calcitic/dolomitic marble	Carbonate mudstone	Shallow marine platform
2	Intraclastic calcitic/dolomitic marble	Grainstone and mudstone with micritic intraclasts	Shallow marine water over waves reworking
3	Stromatolitic marble	Stromatolite	Shallow to very shallow marine water.
4	Calcitic/dolomitic marbles in assemblage with lamellar metabreccia	Lamellar breccia	Very shallow marine water with occasional sub aerial exposure
5	Coarse to medium clast-supported metaconglomerate	Clast-supported conglomerate	Channelized tractive flow
6	Coarse matrix-supported metaconglomerate	Matrix-supported conglomerate	Mass flow in widespread conditions
7	Pebble quartzite	Sandstone with sparse quartz pebbles	Mass flow deposits
8	Micaceous quartzite	Fine-grained sandstone with a small amount of clay in the matrix	Inner platform (shoreface)
9	Pure fine-grained quartzite	Pure fine-grained sandstone	Inner platform in foreshore conditions under wave influence
10	Phyllite	Lutite	Outer platform in shoreface zone conditions
11	Metarhythmite	Intercalation between lutite and sandstone (rhythmite)	Outer platform in lower shoreface conditions

After field studies and analysis of petrographic data, eleven sedimentary rock types were distinguished throughout the Natividade basin occurrence area:1) micritic calcitic/dolomitic marbles; 2) intraclastic calcitic/dolomitic marbles; 3) stromatolitic marbles, 4) calcitic/dolomitic marbles in assemblage with lamellar metabreccias; 5) coarse to medium clast-supported metaconglomerate; 6) coarse matrix-supported metaconglomerate; 7) pebble quartzite; 8) micaceous quartzite; 9) pure fine-grained quartzite; 10) phyllite; 11) metarhythmite.

In general, carbonatic rocks are fine-grained (micritic) and are characterized by calcitic/dolomitic fine-grained marble. These rocks may be recrystallized, making it difficult to preserve primary sedimentary structures. However, occasionally there are structures such as bedding, teepee, lamellar metabreccia, intraclast, and stromatolite.

The **micritic calcitic/dolomitic marble (RT 1)** is represented by light gray to dark color, massive or stratified appearance with a significant amount of calcite and quartz veins (Figs. 4a, 4b, 4c, and 4d). The original sedimentary rock was possibly made up mostly of carbonate mudstone. Analysis of thin sections shows a high occurrence of carbonate recrystallization, resulting in a predominance of granoblastic texture with polygonal contacts. The mineralogy consists of calcite, dolomite, chlorite, muscovite, and tremolite, locally called tremolite marble (Fig. 4d).

The **intraclastic calcitic/dolomitic marble (RT 2)** has a crystalline matrix with intraclasts oriented parallel to the bedding (Figs. 4e and 4f). Cross-stratification is rarely observed, especially in less metamorphosed areas. The original sedimentary facies would consist of grainstone and mudstone matrix with micritic intraclasts (Table 2). The allochem components are still preserved even after the low metamorphism the rocks have been submitted. The observation of such structures is easier in the weathered face of the samples.

Stromatolitic marble (RT 3) outcrops occur in restricted areas with dimensions of approximately 10 meters and cannot be mapped. They are classified as columnar stromatolites interspersed with massive dolomites (Figs. 5a and 5b) (Saboia, 2009; Franco et al., 2016). This rock is commonly silicified.

Calcitic/dolomitic marbles in assemblage with lamellar metabreccias (RT 4) show oriented intraclasts ranging from 2 to 10 cm consisting mostly of micritic mud (Fig. 5c). Teepee structures and quartz or calcite veins can be observed (Fig. 5d). According to Saboia (2009), there are intercalations with metamorphic oolitic limestone. Sedimentary protolith would be an intrabasin lamellar breccia, due to small sedimentary slumping movements.

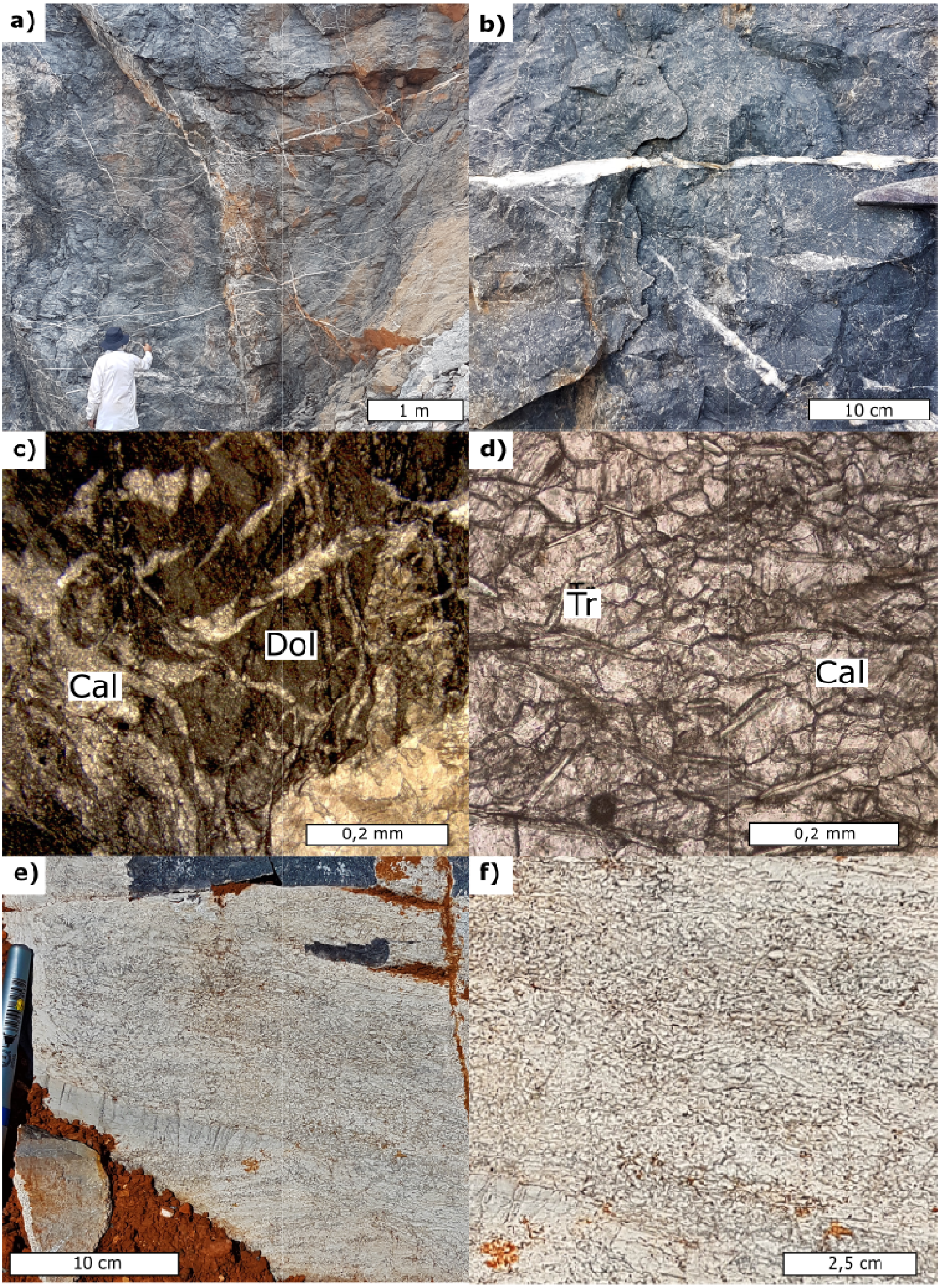


Fig. 4. Outcrops and thin-sections photographs showing: a) micritic dolomitic marble with a large quantity of calcite and quartz venules (RT 1); b) detail in micritic dolomitic marble with veins of quartz and calcite (RT 1); c) thin section photograph viewed in plane-polarized light (PPL) of dolomitic marble rich in calcite venules immersed in a dolomitic matrix (RT 1) (Teixeira et al., 2016); d) thin section photograph (PPL) of calcitic marble with tremolite (RT 1) (Gomes et al., 2016); e) light gray rudstone rich in intraclasts parallel to bedding (RT 2); f) detail in rudstone rich in intraclasts (RT 2).

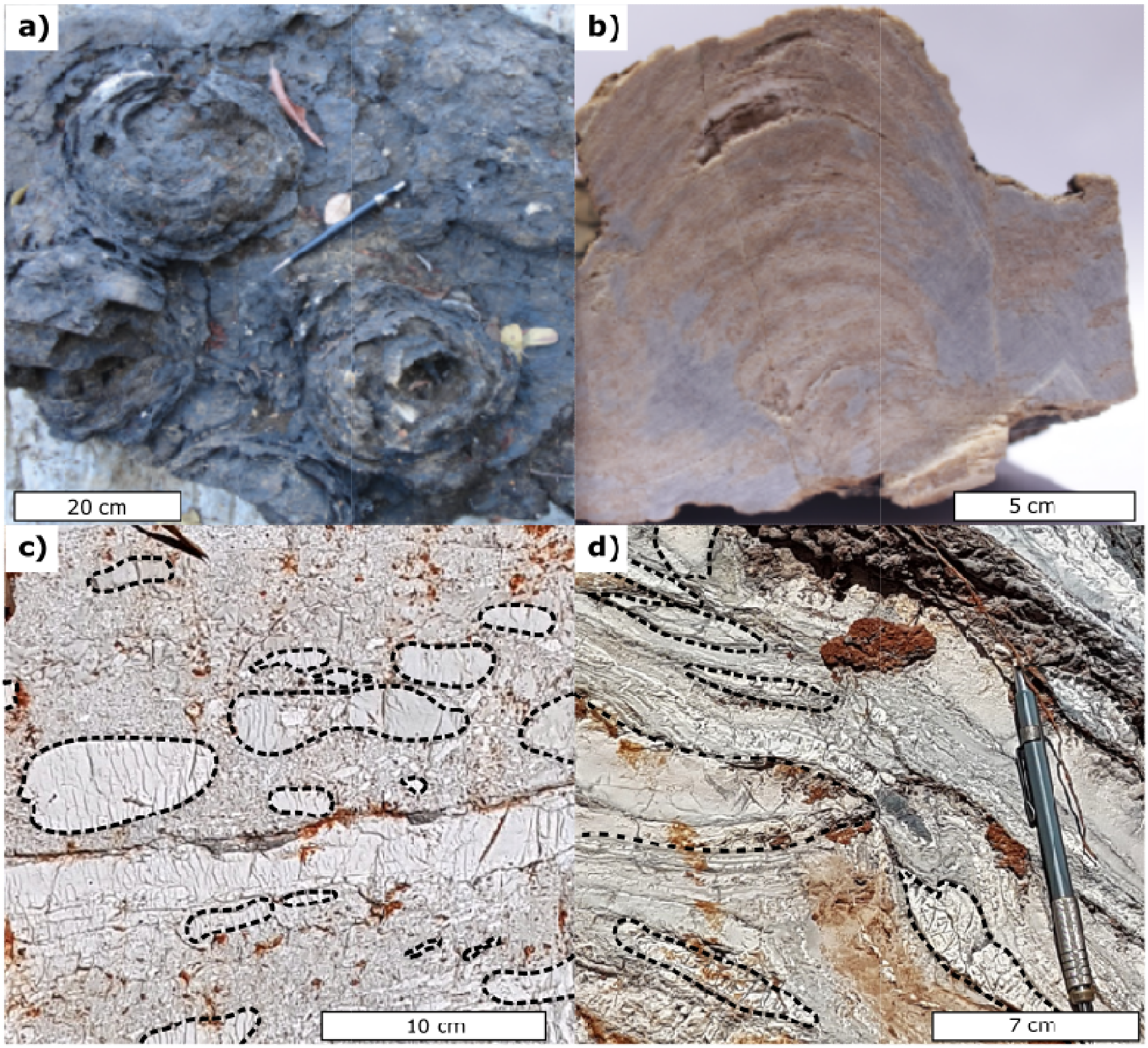


Fig. 5. Outcrops photographs showing: a) columnar stromatolites interspersed with massive dolomites (RT 3) (Franco et al., 2016); b) detail in columnar stromatolites interspersed with massive dolomites (RT 3) (Franco et al., 2016); c) lamellar carbonate metabreccia with clasts from 2 to 10 cm (RT 4); d) teepee structure in lamellar carbonate metabreccia (RT 4).

Clast-supported metaconglomerate (RT 5) is characterized by poorly sorted sediments with clasts ranging from 1 to 40 cm. There is a predominance of metaconglomerate with a sandy-clay matrix. The clasts are rounded to sub-angular, composed of quartzite and veins of quartz (Figs. 6a, 6b, 6c, and 6d).

Less frequently, clasts are composed of phyllite (Fig. 6e), smoky quartz, and banded iron formation. It is common to find these clasts stretched and deformed, generating part of the matrix. According to Saboia (2009), in this metaconglomerate, there is a rare occurrence of lithic fragments of gneiss derived from the crystalline basement rocks. Sedimentary protolith would be a clast-supported conglomerate with predominant matrix of fine to medium-grained quartz and poorly sorted quartz clasts, originated due to high slope in paleogeography.

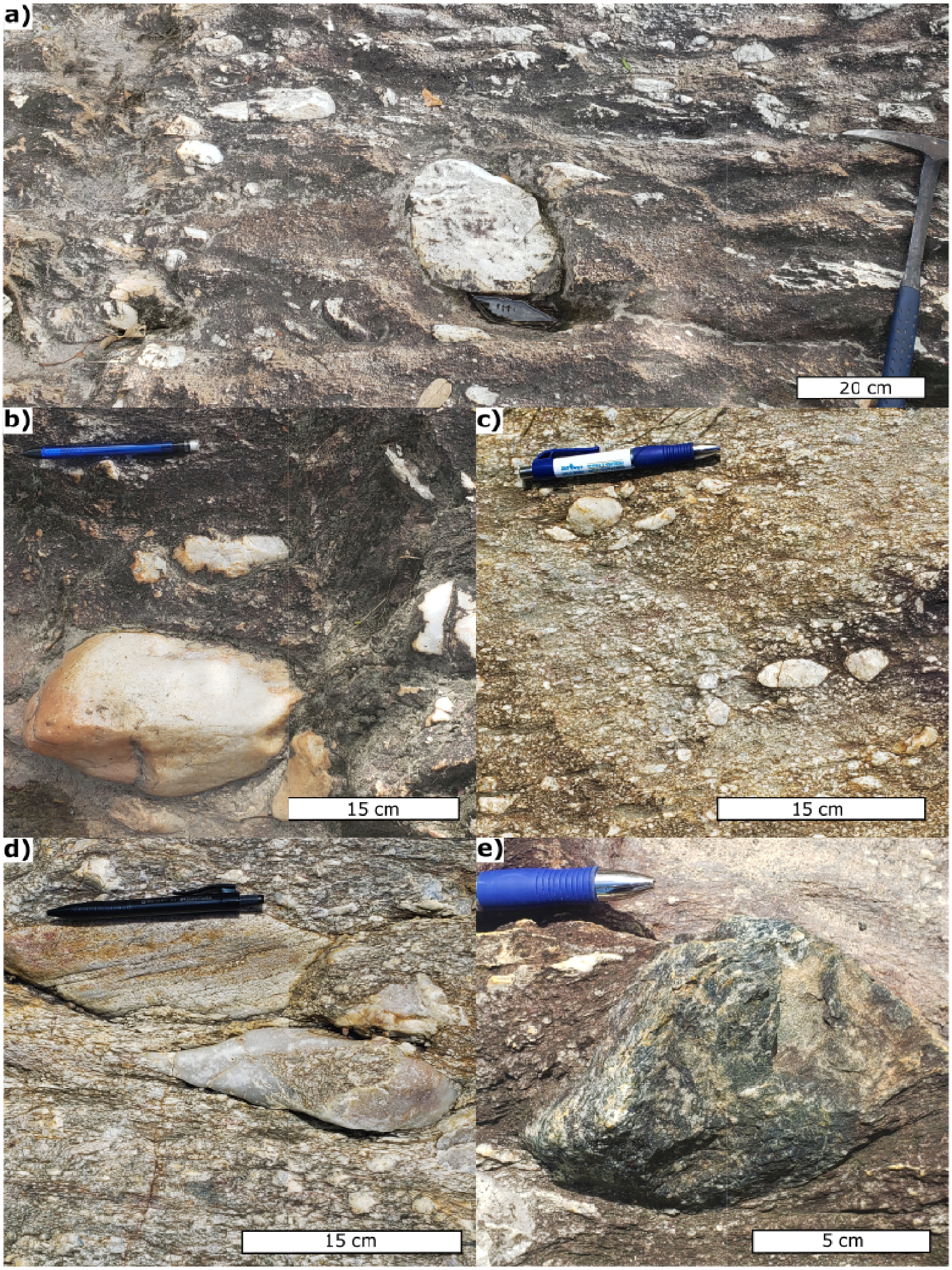


Fig. 6. Outcrops photographs showing: a) clast-supported metaconglomerate with clasts of quartz vein and quartzite, ranging from 1 to 40 cm immersed in a sandy-muddy matrix (RT 5); b) subrounded quartzite clast detail (RT 5); c) matrix-supported metaconglomerate with a predominance of oriented quartz vein clasts ranging from 1 to 3 cm (RT 5); d) quartzite clast with preserved bedding (upper-left corner) (RT 5); e) detail of phyllite clast, 10 cm in diameter (RT 5).

The **matrix-supported metaconglomerate (RT 6)** is mostly oligomictic, with sparse foliation. The matrix consists mostly of fine-grained quartz and sericite. The lithic fragments are rounded to sub-angular, formed by pebbles of quartzite and quartz vein, varying from 1 to 5 cm (Figs. 7a and 7b).

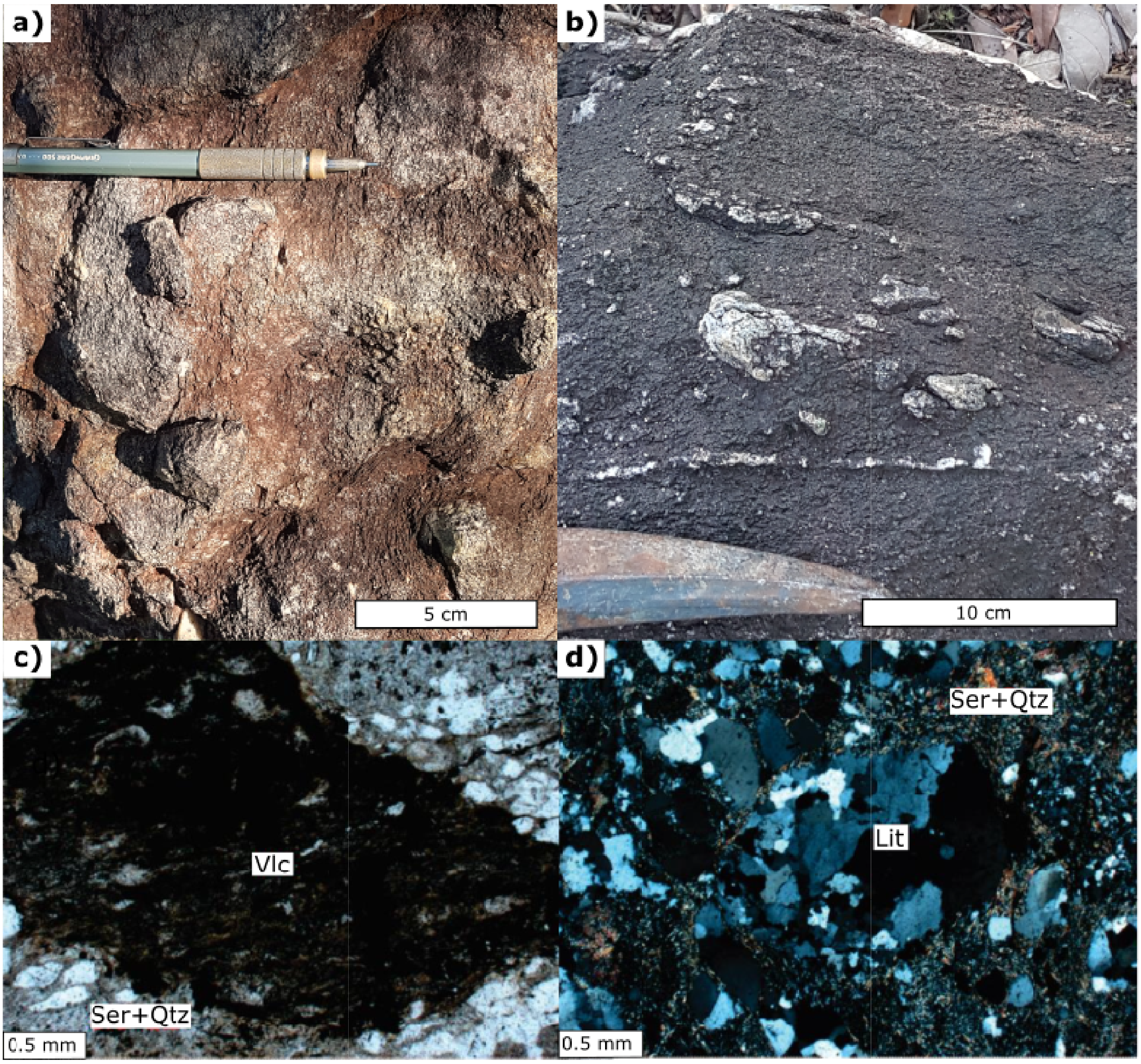


Fig. 7. Outcrops and thin-sections photographs showing: a) matrix-supported metaconglomerate with clasts of quartz vein and quartzite ranging from 1 to 5 cm in a sandy matrix (RT 6); b) detail for quartz clasts (RT 6); c) thin section (PPL) of volcanic rock clast (Vlc) immersed in a sericite and quartz matrix (Ser + Qtz) (RT 6) (Ress et al., 2016); d) the same thin section (c) viewed in cross-polarized light (XPL) with lithic fragments of quartzite (Lit) immersed in a matrix rich in sericite and quartz (Ser + Qtz) (RT 6) (Ress et al., 2016).

Less frequently, metaconglomerate with a carbonate matrix or sericite, muscovite, feldspar, or quartz matrix is observed in contact with the basement rocks. The lithic fragments in these rocks are more varied, composed of quartzite grains, volcanic or granitic rocks, indicating more immature sectors (Figs. 7c and 7d). The original sedimentary facies is interpreted as matrix-supported conglomerate with vein quartz clasts with sand-clay matrix.

The **pebble quartzite (RT 7)** shows sparse quartz vein fragments with 0,4 to 4,0 cm size (Figs. 8a and 8b). Sometimes the pebble quartzite contains muscovite and structures such as cross-stratification (Fig. 8c). It is common to observe the intercalation of these rock types with phyllite in sharp contact (Fig. 8d). The original sedimentary facies would consist of sandstone with fine to medium-grained quartz grains. The pebble quartzite rock type presents much more widely spaced pebbles and a sandy matrix compared to the matrix-supported metaconglomerate that shows a sand-clay matrix and larger quartz fragments.

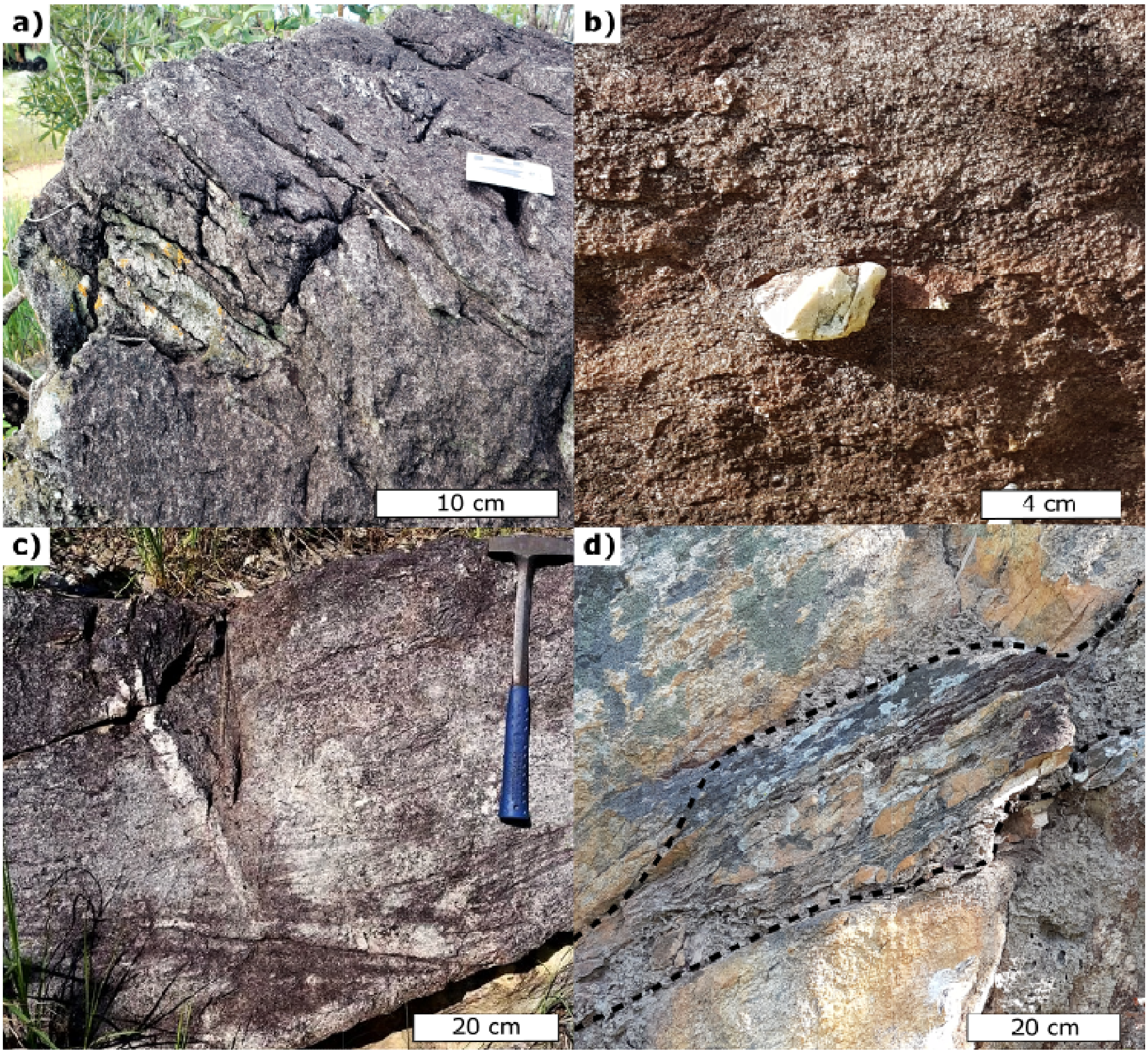


Fig. 8. Outcrops photographs showing: a) pebble quartzite with sandy matrix (RT 7); b) detail of quartz vein clast in pebble quartzite (RT 7); c) cross-stratification structure in pebble quartzite (RT 7); d) sharp contact between pebble quartzite and phyllite (RT 7).

The **micaceous quartzite (RT 8)** shows well-defined bedding (or lamination) with rounded to sub-angular grains. In its matrix, muscovite or chlorite may occur (Figs. 9a, 9b, 9c, and 9d). The original sedimentary facies would consist of fine-grained sandstone with a small amount of clay in the matrix. This bedding is probably a primary structure that has been reinforced by metamorphism in greenschist facies.

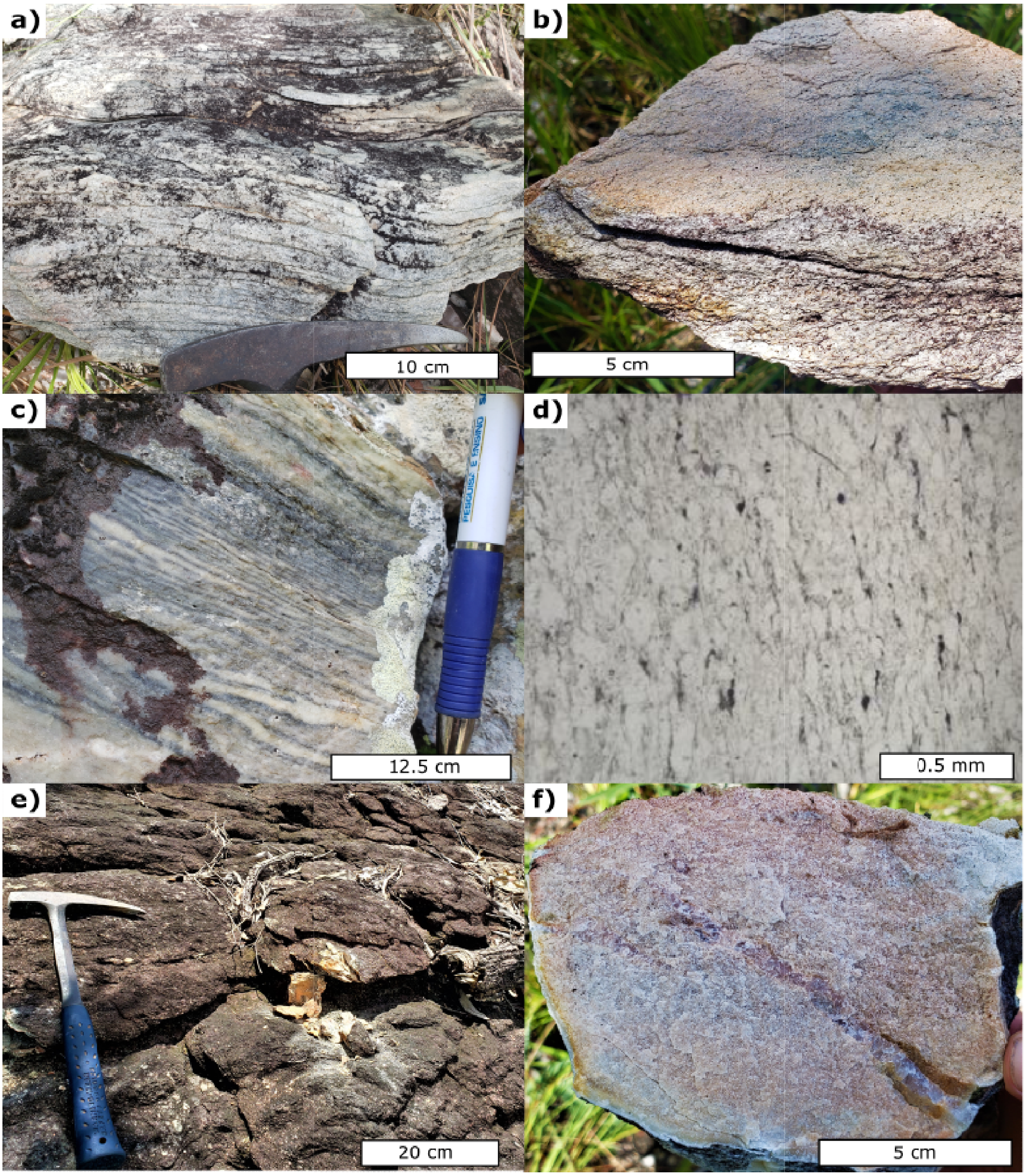


Fig. 9. Outcrops and thin-section photographs showing: a) bedding in micaceous quartzite (RT 8); b) fine-grained chlorite-quartzite (RT 8); c) detail for bedding in quartzite rich in muscovite (RT 8); d) thin section (PPL) of muscovite quartzite, where stretched quartz grains with a predominance of lepidoblastic texture are observed (RT 8) (Morbeck et al., 2016); e) outcrop of pure quartzite (RT 9); f) detail of fine-grained quartzite, recrystallized with polygonal contacts (RT 9).

It is common to observe the alternation of micaceous quartzite with **pure fine-grained quartzite (RT 9)**, which has rounded and spherical grains, with a predominance of granoblastic texture. They are often recrystallized (Figs. 9e and 9f). Cross laminations are commonly preserved. The sedimentary protolith is interpreted to be fine-grained pure sandstone

The **phyllite (RT 10)** rock type occurs in four different varieties and its sedimentary protolith is considered basically as lutite or shale. The first type of phyllite exhibits color ranging from gray to beige (Figs. 10a and 10b). It has large lateral extent of several kilometers, corresponding to the largest mapped area of the Natividade Group, according to the fieldwork descriptions and studies carried out by Gorayeb et al. (1988) and Saboia et al. (2009). The outcrops are poorly preserved, occurring in regions of low and flat relief. Sometimes the phyllite occurs interlayered with fine-grained quartzite (Fig. 10c). The second phyllite type exhibit light gray to greenish color. It is common to occur in regions close to carbonate hills, in flatter portions. Phyllites with dark layers are frequent (Fig. 10d).

The third phyllite type exhibits gray color and has as main characteristic intercalation with pebble quartzite, with sharp contact (Fig. 8d). This same relationship is verified in the micaceous quartzite and metaconglomerate.

The fourth phyllite type occurs in an area of about 350 hundred square meters, close to the Manuel Alves River dam, in the northeast portion of the area. It is deposited directly over the crystalline basement. It is characterized by the intercalation between black carbonaceous phyllite and reddish to beige phyllite (when weathered), and can be laminated (Fig. 10e) or show ripples marks (Fig. 10f) (Franco et al., 2016). The dark aspect of the fresh rock (non-weathered) could be linked with the presence of organic matter.

The **metarhythmite (RT 11)** (Figs. 11a and 11b) occurs in areas of flatter relief and is characterized by millimetric to centimetric intercalations of metasiltstone and fine-grained quartzite with evident bedding, and soft-sediment deformation structure (Fig. 11c).

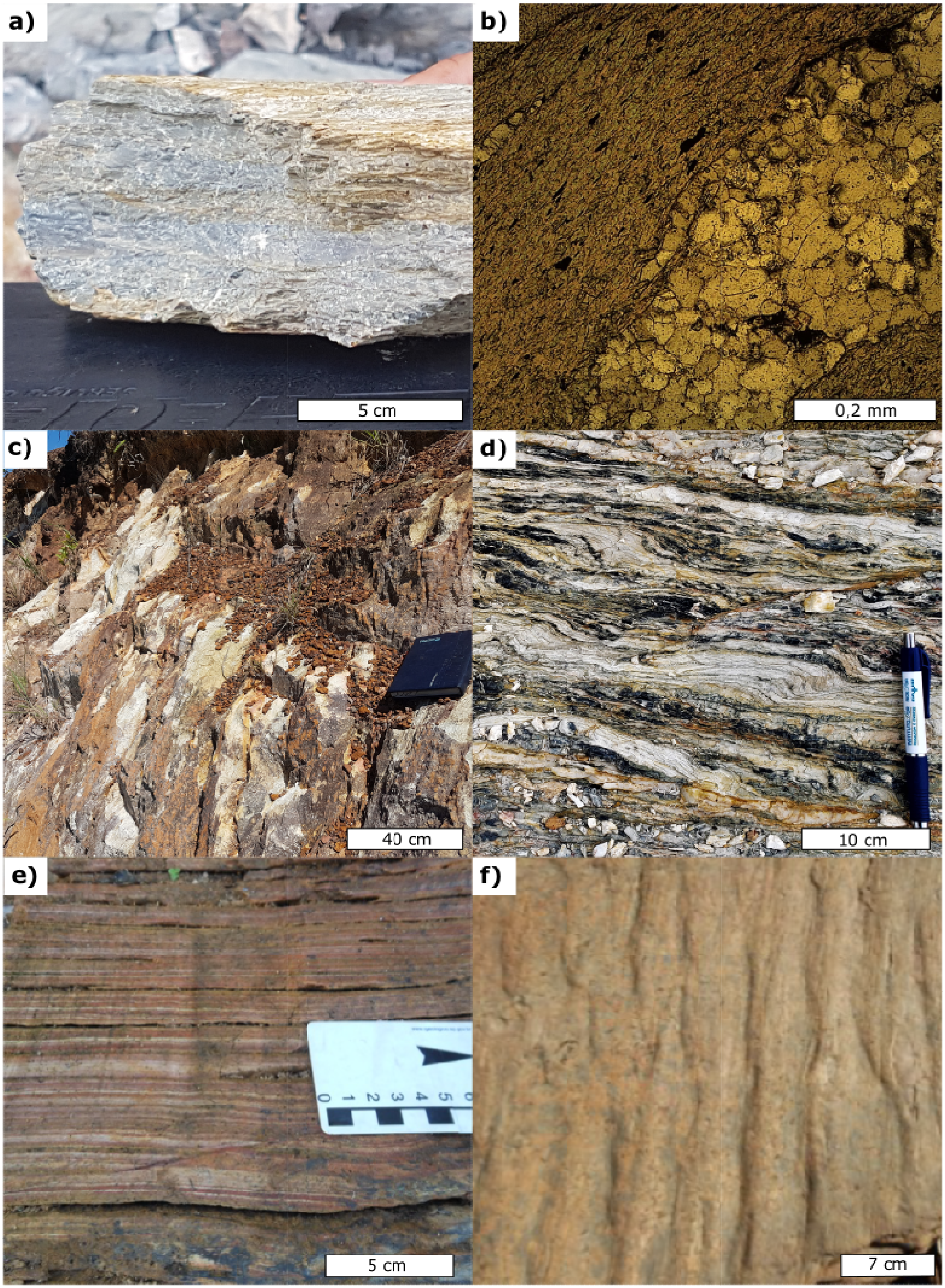


Fig. 10. Outcrops and thin-section photographs showing: a) greenish phyllite commonly observed in a flatter relief area (RT 10); b) thin section (PPL) of phyllite rich in sericite with quartz lenses (RT 10) (Teixeira et al., 2016); c) phyllite interlayered with fine-grained quartzite (RT 10); d) phyllite with intercalations of dark layers (RT 10); e) intercalation between black carbonaceous phyllite and reddish to beige phyllite (RT 10) (Franco et al., 2016); f) detail of ripples marks structures (RT 10) (Franco et al., 2016).

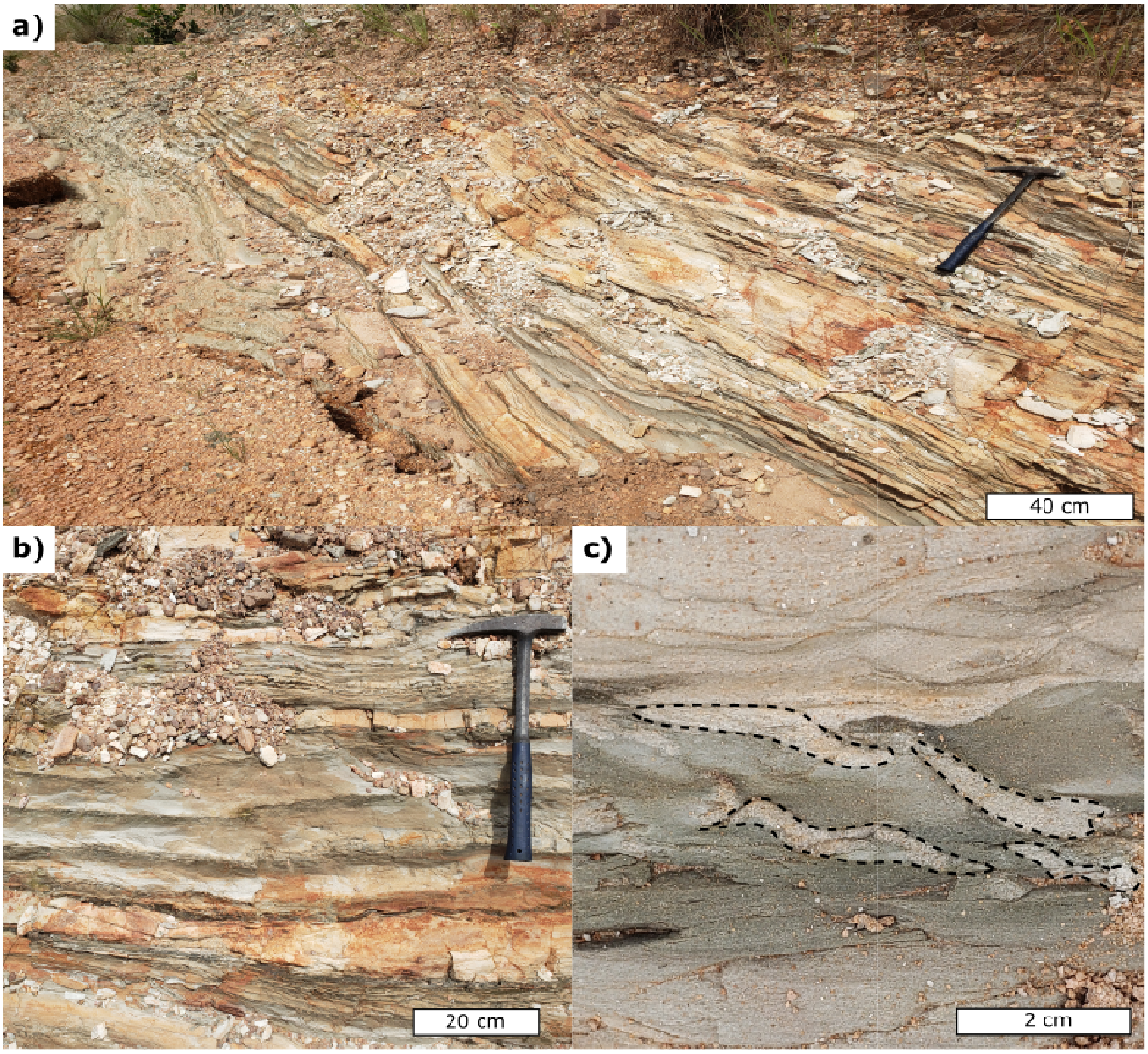


Fig. 11. Outcrops photographs showing: a) general appearance of the metarhythmite outcrop (RT 11); b) detail in a metarhythmite outcrop (RT 11); c) soft-sediment deformation structure in a metarhythmite (RT 11).

4.2 Geological Map, Lithostratigraphy, and Rock Assemblages

After analyzing the described rock types, interpreting satellite and radar images, and reviewing the geological contributions of previews studies by Gorayeb et al. (1988), Saboia (2009), and the geological mapping works of the University of Brasília in the years 2012 and 2016, it was possible to propose a more detailed geological map of the Natividade Group for the region (Fig. 12), and provide six new stratigraphic columns (Fig. 13).

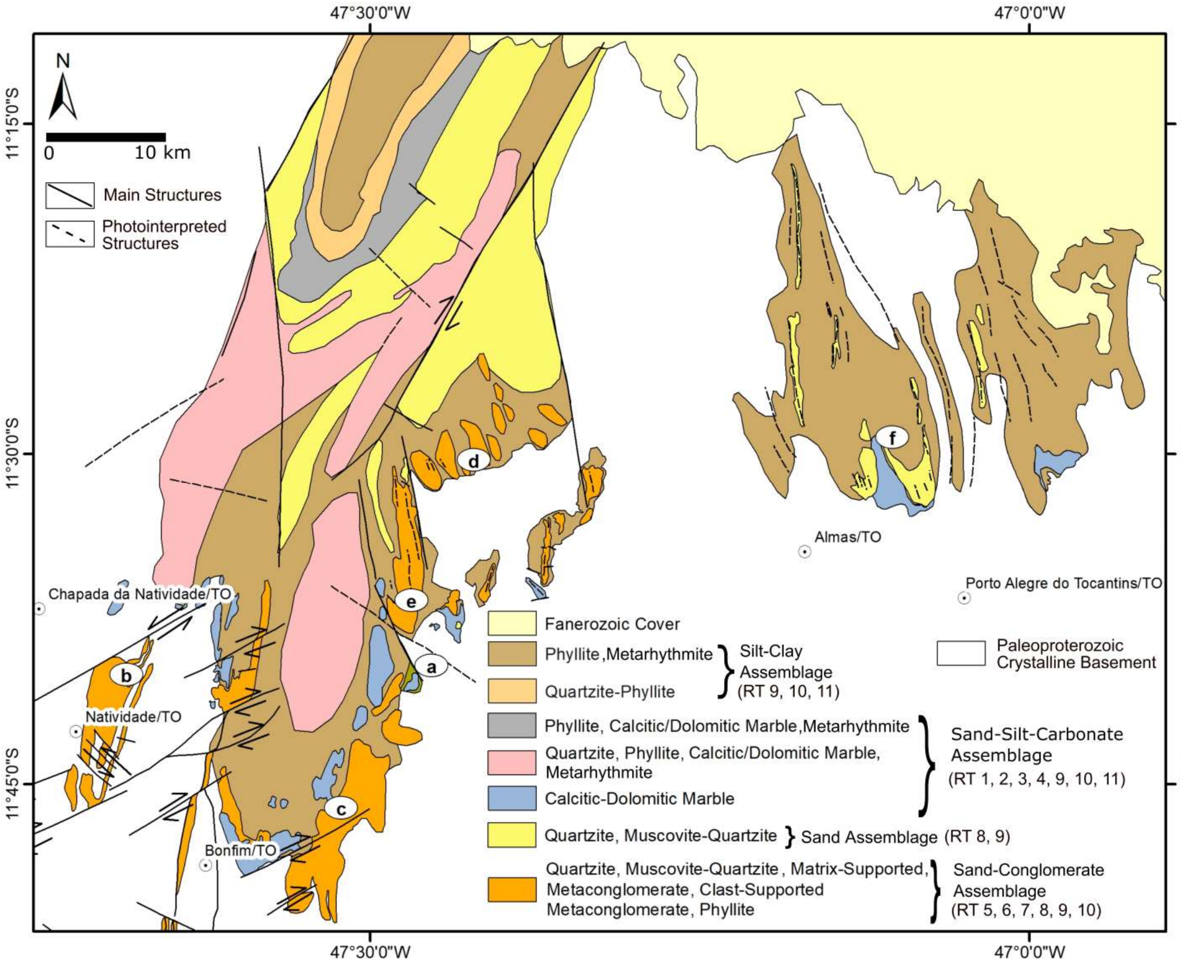


Fig. 12. Geological map of the Natividade Group. This map is the result of the compilation of field data, interpretation of SRTM images, and reviews of Grorayeb et al. (1988), Saboia (2009), and geological mapping work of the University of Brasília carried out in the 2012 and 2016 years (Oliveira et al., 2012; Franco et al., 2016; Morbeck et al., 2016; Ress et al., 2016; Teixeira et al., 2016). The letters "a" to "f" indicate the locations of the columns shown in Fig. 13.

The columns represented in Fig. 13 show a very different stratigraphic pattern, depending on the area of the survey. Locally, the marble can occur directly over the basement, as seen in Figs. 13a, 13c, 13d, and 13f, or occupy upper levels in the stratigraphy (Fig. 13a). Sedimentary packages related to clast-supported and matrix-supported metaconglomerate occur in basal to higher portions in stratigraphic columns. Generally, in the upper portions, these metaconglomerate occur in thick sedimentary packages forming hills (Figs. 13b, 13d, and 13e), while in the basal position, they usually occur in less thick sedimentary packages (Figs. 13a, 13c, 13d, and 13e).

Locally, there are polymictic metaconglomerate with tonalite, acid volcanic rocks, quartzite, and recrystallized quartz veins clasts. These are interpreted as basal metaconglomerate that is directly overlaid by dolomitic marble or phyllite (Figs. 13c, 13d, and 13e).

Phyllite crops out in several portions of the stratigraphic columns. In basal levels, they can occur directly over the basement overlaid by quartzite or marble lenses (Figs. 13b and 13e).

In the upper levels, phyllite occurs in sharp contact with pebble quartzite, micaceous quartzite, and clast-supported or matrix-supported metaconglomerate (Figs. 13a, 13b, 13c, 13d, and 13f).

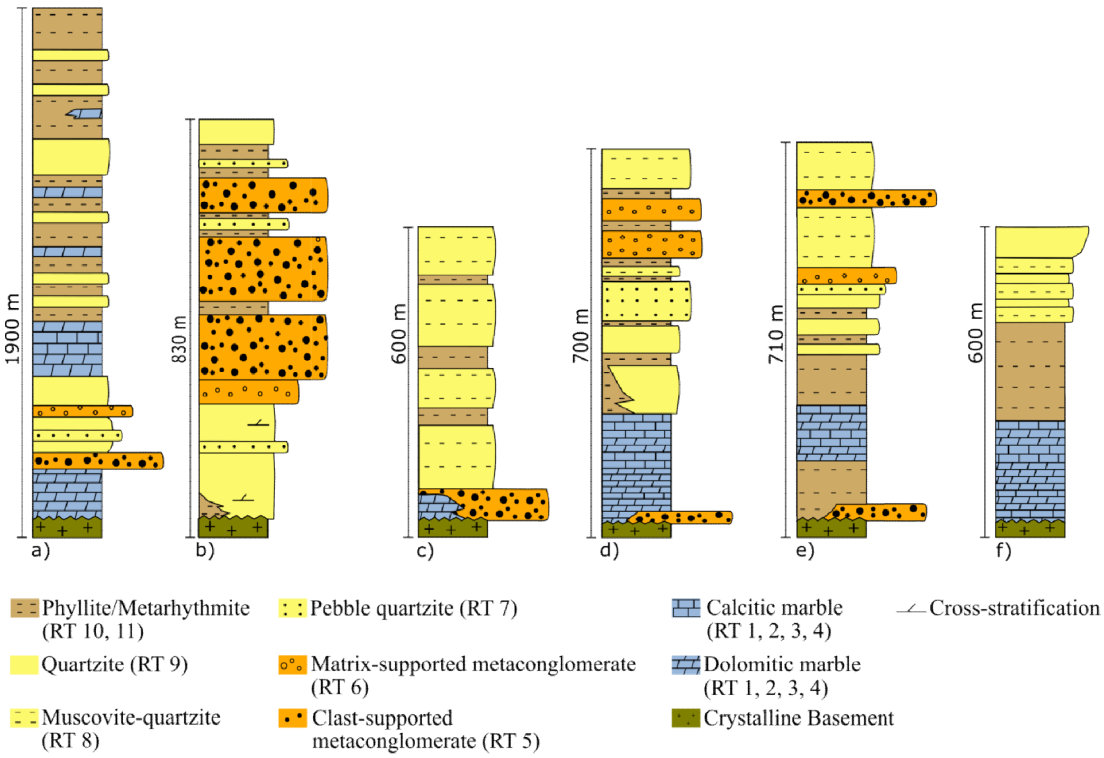


Fig. 13. Lithostratigraphic columns of different locations in the Natividade Group. The letters show the locations of the columns according to the map in Fig. 12. The lithostratigraphic column "a" is modified from Saboia (2009), and the columns "e" and "f" are modified from geological mapping work of the University of Brasília (2016) (Ress et al., 2016; Teixeira et al., 2016).

After defining eleven different rock types, the following rock assemblages were identified: i) Sand-Silt-Carbonate; ii) Sand-Conglomerate; iii) Sand; iv) Silt-Clay. Each of these rock assemblages is described as follows.

i) Sand-Silt-Carbonate Assemblage

This assemblage includes carbonate and siliciclastic rocks, containing the largest rock diversity of the Natividade Group (Fig. 12): micritic calcitic/dolomitic marbles (RT 1); intraclastic calcitic/dolomitic marbles (RT 2); stromatolitic marbles (RT 3); calcitic/dolomitic marbles in assemblage with lamellar metabreccias (RT 4); micaceous quartzite (RT 8); pure fine-grained quartzite (RT 9); phyllite (RT 10); metarhythmite (RT 11).

Marble generally occurs as large lenses immersed in the phyllite (Fig. 14) and quartzite. Less frequently, they occur interlayered in these rocks. There is a significant predominance of micritic calcitic/dolomitic marble (Figs. 4a, 4b, 4c, and 4d). The other carbonate type occurs less abundantly, with intraclasts (Figs. 4e and 4f), stromatolites (Figs. 5a and 5b), and lamellar metabreccia (Figs. 5c and 5d) being more visible in blocks that have been exposed to weathering.

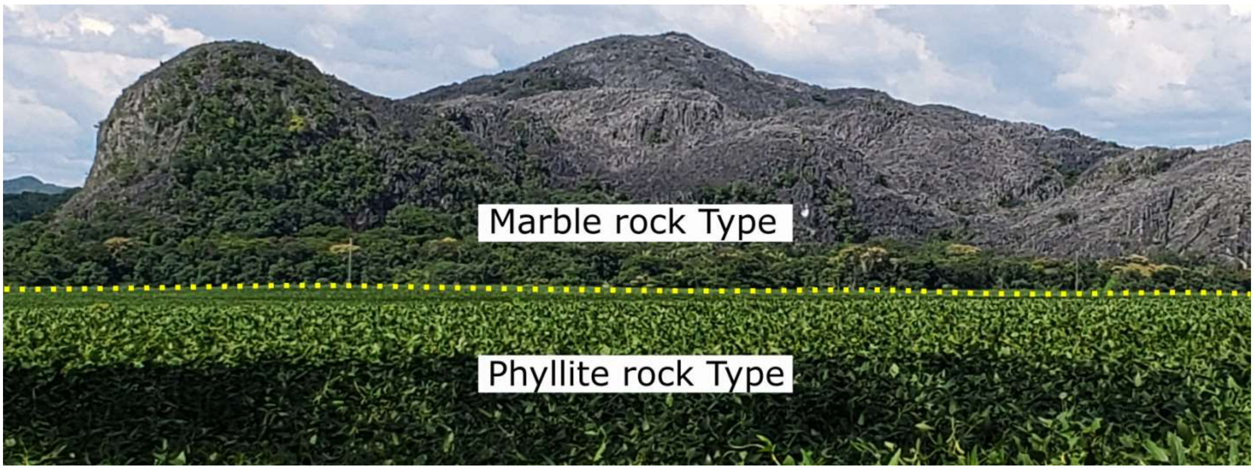


Fig. 14. Large marble lens (RT 1) inserted in phyllite (RT 10) rock type.

ii) Sand-Conglomerate Assemblage

This assemblage presents large lateral and vertical coverage (Figs. 12 and 15), is located in the rugged relief portions of the area. It consists of the following rock types: coarse to medium clast-supported metaconglomerate (RT 5); coarse matrix-supported metaconglomerate (RT 6); pebble quartzite (RT 7); micaceous quartzite (RT 8); phyllite (RT 10).

Matrix-supported and clast-supported metaconglomerate can occur in conjunction with pebble quartzite and gray phyllite, which are usually separated by sharp contacts (Figs. 8d and 15).

Although the micaceous quartzite appears to be interlayered with the other rocks of the assemblage, it is more frequent at the top of these sequences.

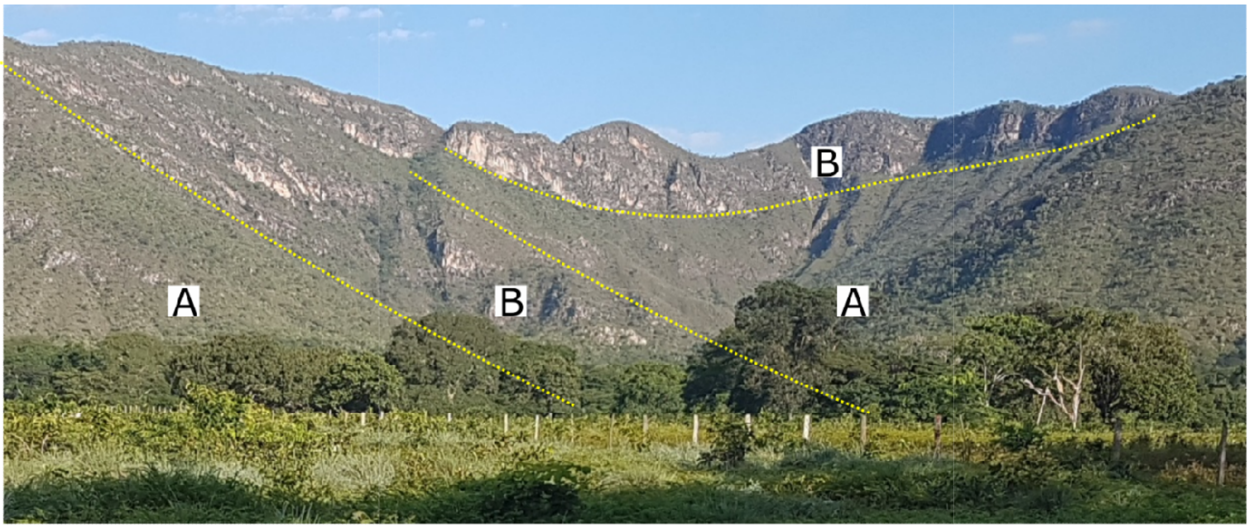


Fig. 15. Hill consisting of sand-conglomerate assemblage: A) predominance of phyllite (RT 10) with lower amounts of metaconglomerate and quartzite (RT 5, 6, 7, 8); B) predominance of clast-supported and matrix-supported metaconglomerate, and quartzite (RT 5, 6, 7, 8).

iii) Sand Assemblage

This assemblage occurs in a rugged relief portion that consists mostly of a thick package of pure fine-grained quartzite (RT 9) (Figs. 9e, 9f, 12, and 16) and more rarely of the micaceous quartzite (RT 8) (Figs. 9a, 9b, 9c and 9d).

The rocks in this assembly are commonly mature, laminated, and silicified. According to Martins-Ferreira & Campos (2017), quartzite rocks are resistant to weathering and can preserve high relief due to silicification. This is verified in the present study, with outcrops greater than 100 meters in height (Fig. 16).

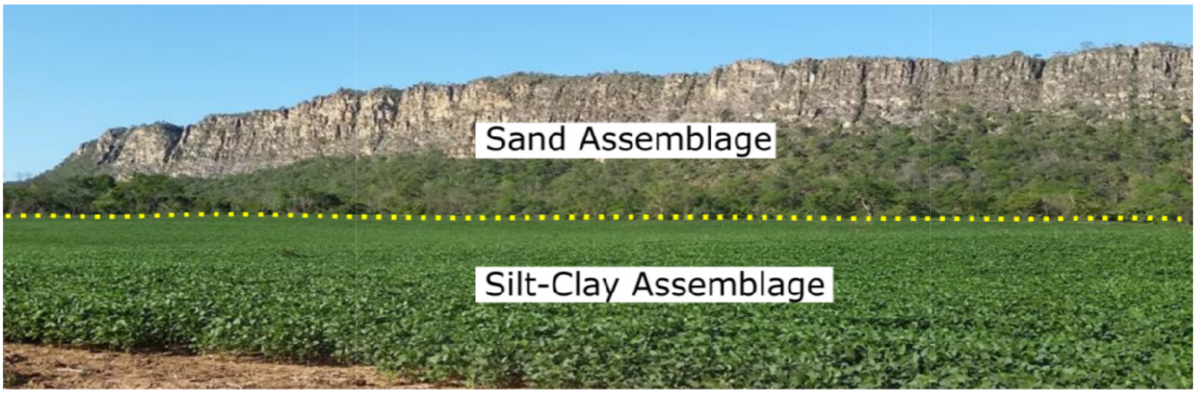


Fig. 16. Hill consisting of sand assemblage (RT 9). The flat relief shows the interfingering of silt-clay assemblage (RT 10).

iv) Silt-Clay Assemblage

It is the most abundant rock assemblage observed in the Natividade Group, located in the areas of flat relief (Fig. 16), it is comprised mainly of the phyllite rock type (RT 10) (Fig. 10) and more rarely by metarhythmite (RT 11) (Fig. 11). Commonly, gray to beige phyllite is intercalated with fine-grained quartzite of the micaceous quartzite rock type (RT 8) and pure fine-grained quartzite (RT 9).

5. Discussion

5.1 Depositional Environments

The Natividade Group is interpreted as a post-rift basin derived from the isostatic rebalance after the evolution of the Araí rift basin located to the south (Costa et al., 1976; Silva et al., 2005; Saboia, 2009; Marques, 2009). This study proposes that the sedimentation of the Natividade Group would occur in a shallow mixed siliciclastic-carbonate platform associated with mass flow currents. Based on few paleocurrent structures (observed cross-stratification structures), the presence of granite and gneiss clasts with the same petrographic signature (locally observed in basal conglomerate), the presence of smoky quartz vein pebble (commonly observed in the tonalite-trondhjemite-granodiorite and volcanic sedimentary sequences), and the largest occurrence of marbles in the south of the area, it was possible to indicate that the source of sediment for the Natividade Group platform comes from continental or transitional environments located to the south of the basin.

Four depositional environments are proposed to have co-existed, simultaneously filling the Natividade basin: i) mixed platform (siliciclastic-carbonate deposition), ii) internal siliciclastic platform, iii) shallow water turbidite (mass flow slope deposition), and iv) external siliciclastic platform (open-marine platform). These environments are proposed based on the different assemblages of rock types listed and described in detail below.

i) Mixed platform (siliciclastic-carbonate deposition)

Mixed platform deposition occurs in several tectonic contexts (Mount, 1984; Campos et al., 2012; Tagliari, 2013), ranging from stable conditions such as passive margins to environments related to rift phases in active subsidence.

The main controls for thick carbonate succession deposition include clean, shallow, and warm water with low terrigenous input (Campos et al., 2012). It is common to say that sediments are hardly formed by mixtures of carbonatic and siliciclastic material. However, there are many modern and ancient deposits formed on a platform consisting of a spectrum of "mixed" sediments (Mount, 1984; Tagliari, 2013).

In the Brasília Belt, it is common to find assemblages of siliciclastic-carbonate rocks in Proterozoic successions, including the Traíras, Paranoá, Vazante, Natividade and Bambuí groups (Monteiro, 2009; Marques, 2009; Saboia, 2009; Campos et al., 2012; Martins-Ferreira et al., 2013; Sotero et al., 2019). Due to the absence of superior organisms in most of the Proterozoic, carbonate rocks are interpreted as formed by a variety of abiotic processes and products of the metabolism of microorganisms (Grotzinger & James, 2000). According to these authors, the carbonate developed in that period can present a great diversity of sedimentary rock types such as micritic mud, rocks with carbonate intraclasts (at different sizes), and to a lesser extent, stromatolites, oncolites, ooliths, among others.

It is worth noticing that the main factors controlling the sedimentation in mixed platforms are related to i) position of the photic zone; ii) basement paleogeography; iii) protected platform regions (calm and with less terrigenous input); iv) favorable physical and chemical conditions (Khetani & Read, 2002; Mcneill, 2010; Campos et al., 2012; Tagliari, 2013).

In the Natividade paleobasin, the mixed deposition is represented by the Sand-Silt-Carbonate assemblage located in an internal position of the platform, controlled especially by the paleogeography inherited from the basement. Thus, it would be possible to form shallow, warm, agitated, and clean water environments (in the photic zone) occurring side-by-side with deeper water environments, allowing the deposition of terrigenous sediments (Fig. 17).

In areas of carbonate precipitation, the existence of shallow water is confirmed by the presence of lamellar metabreccia, intraclastic marble (Figs. 4e, 4f, 5c, and 5d), and teepee structures (Fig. 5d), which indicate occasional sub-aerial exposure. Dolomite could be originated in basin areas with more restricted water circulation, where the carbonate dolomitization would occur similarly to the Psammo-pelitic-carbonate Unit of the Paranoá Group (Campos et al., 2012). In thin sections, it is easily observed rhombohedral dolomite crystals what is interpreted as eodiagenetic origin.

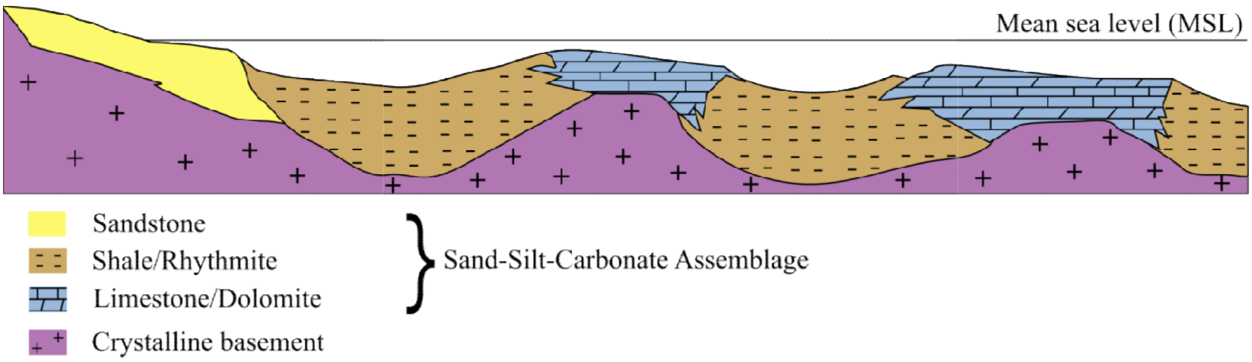


Fig. 17. Schematic cross-section showing an example of a mixed platform controlled by basement paleogeography, allowing simultaneous deposition of carbonates in shallow, calm, and warm waters and detrital sediments in relatively deeper waters (adapted from Campos et al., 2012).

In addition to the importance of paleorelief, locally, the organic control over the deposition of carbonate may favor the occurrence of columnar stromatolites, which can be found in a wide range of environments and depths (Böhm & Brachert, 1993; Grotzinger & James, 2000).

The detrital sequence composed of quartzite and phyllite is deposited in the deeper parts of the paleobasin, in the inner platform. In this case, the sedimentary contribution comes from the emerged and elevated areas of the crystalline basement, related to the early-Paleoproterozoic Almas-Conceição do Tocantins Terrane (Martins-Ferreira et al., 2020).

The significantly low amount of metarhythmite rocks could be related to rapid flooding of the shallow portions of the mixed platform (rapid marine transgressions) with a considerable elevation of the water depth (Campos et al., 2013).

In regions where Phyllite and Calcitic/Dolomitic marble occurs in nearby conditions, the intercalation between carbonate lenses and terrigenous sediments is common. Thus it was possible to infer lateral interfingering and competition during the deposition between carbonate and detrital sediments.

ii) Internal siliciclastic platform

The environment interpreted as an internal platform consists primarily of the Sand Assemblage. The original sandy sediments of the Natividade Group are mature and fine-grained, with sedimentary structures including laminated bedding and cross-laminations. These structures would possibly indicate sedimentation above the base level with the influence of tides close to the coast (Suguio, 2003; Della Favera, 2008; Campos et al., 2012). The source area for this sedimentation would also be the rocks of the Almas-Conceição do Tocantins Terrane (Silva et al., 2005).

Carbonaceous phyllite has direct contact with the basement, and small total thickness, corroborating the interpretation that these are sediments (lutites) deposited in lagoons or other protected environments (Neumann et al., 2008). The lutites would probably be formed in reducing environments typical of restricted lagoons without connection to a marine platform due to the paleogeography inherited from the basement.

iii) Open-marine siliciclastic platform

It is related to the Silt-Clay Assemblage, composed primarily of fine-grained sediments, which suggests sedimentation in calm waters under open-marine platform conditions below the occurrence of fair-weather waves (Della Favera, 2008; Campos et al., 2013). The dominant sedimentary process would be the suspension in deeper and flatter portions of the external platform.

In the field, structures indicating deposition by storms were not observed. Nevertheless, this type of condition is quite common in open-marine platforms when subjected to geostrophic currents. In this case, sand bodies with hummocky cross-stratification (HCS) and amalgamated sigmoid should be observed (Harms, 1975; Yang et al., 2006; Della Favera, 2008).

iv) Shallow water turbidite (mass flow slope deposition)

Shallow water turbidites are gravitational flows very similar to conventional turbidites. However, they can occur in epicontinental environments and at shallower depths (Fenton & Wilson, 1985; Mutti et al., 2007; Põldsaar et al., 2019) as a result of mass flow controlled by the slope of the high zones in the source areas.

Thus, based on our field evidence, stratigraphic and petrographic analysis, we propose that turbidite conditions are responsible for the deposition of the Sand-Conglomerate rock assemblage, which is interpreted to be controlled by debris flows sedimentation typical of the shallow water turbidite environment.

The rock types associated with these deposits present large lateral continuity and are influenced by cohesive or diluted turbulent flows and, secondarily, by a vertical suspension of fine-grained material (Bouma, 1962; Lowe, 1982; Pomerol et al., 2013).

The main arguments for classifying these rock types as turbidite deposits include: lateral continuity of the rock types; sharp contacts between contrasting rock types; lateral interfingering with shallow-water carbonate rock types; the presence of clast- and matrix-supported conglomerates that are poorly sorted with rounded to subangular clasts; intercalation of lutite layers in the conglomerate rock types, and the sandy-silty-clayey nature of the conglomerate matrix.

These rocks cannot be classified as classic turbidite environments, which are those deposited in deep waters after the continental slope break. This is because there is no evidence of deep waters in the paleogeography of the Natividade Group (Gorayeb et al., 1988; Saboia, 2009). In addition, the geotectonic context of the "Brasília Belt" at the study area does not indicate the occurrence of a deep basin according to the studies by Fuck et al. (2017) and Dardenne & Saboia (2007). Thus, the occurrences of mass flow deposits in the Natividade Group are probably linked to shallow water turbidite. Mutti et al. (2007) describe these deposits as almost identical and equally common, and stratigraphically important as classic turbidite environments.

The areas of high paleobasement relief, located to the south of the Natividade basin, would be responsible for the debris flows that enter the platform in a similar way to the study by Fenton & Wilson (1985), who described the occurrence of shallow water turbidites.

Based on the description of the Sand-Conglomerate Assemblage, characterized by an extensive lateral and vertical continuity of metaconclomerates (RT 5, 6) quartzites (RT 7, 8) and phyllites (RT 10) (Fig. 14), it was possible to elaborate Table 3. In this table, we elaborated a probable relationship between the rock types described in the Sand-Conglomerate Assemblage with the turbidite facies code by Mutti et al. (1999).

Table 3. Probable relationship between the rock types described in the Sand-Conglomerate Assemblage with the turbidite facies code (modified after Mutti, 1992; Mutti et al., 1999; D'Ávila et al., 2008; Costa et al., 2018).

Rock Types (RT)	Code (According *Mutti* et al., *1999*)	Description	Depositional Processes	Architectural Element
Clast-supported metaconglomerate (RT 5)	F2	Conglomerate with a sand-mud matrix. Clasts of: quartzite, quartz veins, and phyllite	It is the product of hyper-concentrated flows, resulting from the transformation of the cohesive flow through continuous mixing with the local fluid	Gravel bars and excavations in the proximal portions of the valleys
Matrix-supported meta-conglomerate (RT 6)	F3	Conglomerate with clasts of quartzite and quartz veins	Even though it belongs to the granular flow, in the upper portion of the current, extremely turbulent flow occurs, which generates traction in the deposited gravel producing bars of clast-supported conglomerate	Feeder valleys in the transfer zone
Pebble quartzite (RT 7)	F5	Coarse quartzite, poorly sorted, with sub-rounded quartz pebbles	Fast deposition by granular flow	Valleys filled in the transfer zone
Fine-grained micaceous quartzite (RT 8)	F8	The predominance of fine to medium-grained quartzite	Formed by decanting sand grains suspended in the turbulent flow	Accumulation of sand in the depositional zone (lobe)
Metasiltstones/phyllite (RT 10)	F9	Rocks with silt to clay (fine-grained material)	Fall-out process dominant	Depositional zone on distal plains

5.2 Basin Evolution Model

Based on Costa et al. (1976), Silva et al. (2005), Saboia (2009), Marques (2009), and Martins-Ferreira et al. (2018a), the Natividade basin most likely evolved via thermo-flexural subsidence as a result of isostatic rebalance after the evolution of the Araí rift basin located to the south, being thus classified as a post-rift basin. The overall sedimentary environment responsible for the deposition of the Natividade Group is associated with a mixed siliciclastic-carbonate platform (Saboia, 2009) with simultaneous deposition of turbidite sediments in shallow waters.

In this context, the basement would have a high regional relief, which would allow the rapid formation of debris flows in a shallow water platform context. This is reinforced by the presence of "basal conglomerates" composed of lithic fragments of quartzite grains, volcanic or granitic rocks, indicating more immature sectors (Figs. 7c and 7d). In Fig. 18, the high magnetic relief indicates crystalline basement rocks, which is considered the main sediment source area of the Natividade basin. This basement includes the Almas-Conceição do Tocantins Terrane, characterized by granite-gneisses associated with supracrustal volcano-sedimentary sequences (Riachão do Ouro Group and Água Suja Sequence), in assemblage with Tonalite-trondhjemite-granodiorite, and mafic-ultramafic intrusions (Fuck et al*.*, 2014; Fuck et al*.*, 2017).

It is worth mentioning that the displacement between the low magnetic relief and the geological occurrence of the Natividade Group on the surface is probably due to the dip of the Natividade Group's layers subsurface (Li, 2006; Moro, 2017).

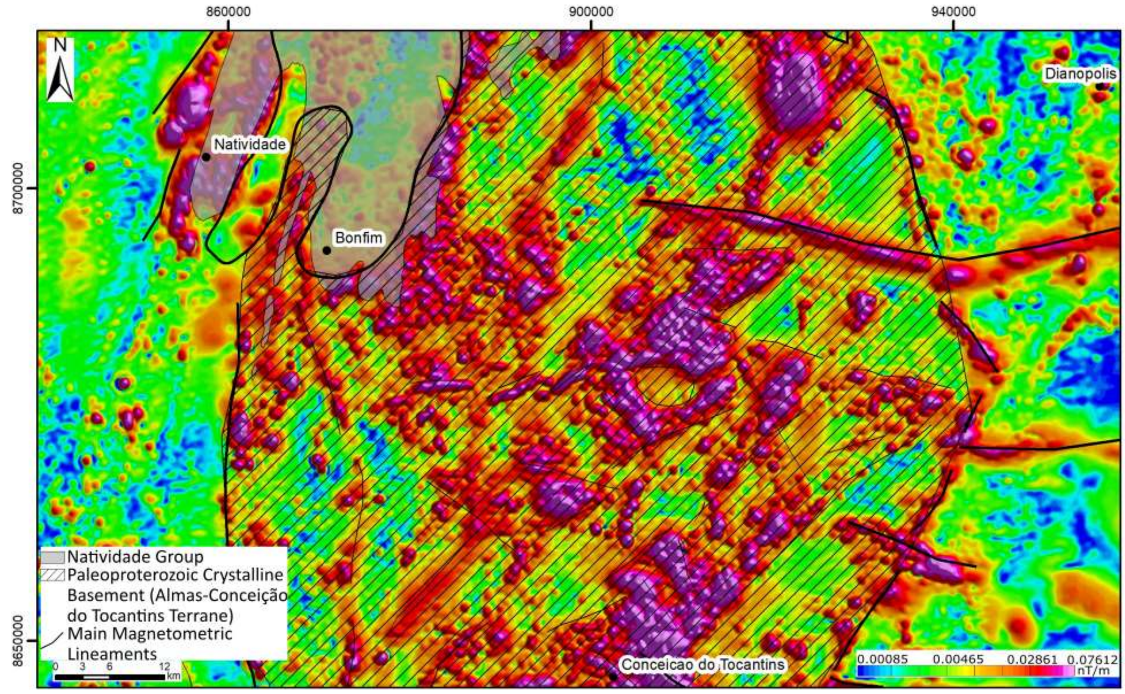


Fig. 18. Magnetometric Map of Total Gradient showing the spatial distribution of the crystalline basement (Almas-Conceição do Tocantins Terrane) and the Natividade Group.

The predominance of carbonates and mass flow deposits in the southern portion of the area (Fig. 12) suggests a lower depth of the sea to the south of the basin. Also, a significantly high basement relief is expected to the south to provide the slope necessary for the formation of the gravitational flows. Further north, the basin deepens, favoring the deposition of finer terrigenous sediments.

The depositional model for the Natividade Group (Fig. 19) suggests that the carbonate would be deposited by chemical precipitation and biological induction over basement paleohighs in the internal platform. In this mixed platform, detrital deposition composed of sandstone and lutite would also be possible in the deeper areas.

A hypothesis to explain the mixed sedimentation would be the occurrence of low to moderate sediment input (Correia Filho & Sá, 1980). In addition, the presence of a rugged relief in the basin floor, inherited from the basement paleogeography, would be responsible for deep waters side by side with shallow waters similarly to the sedimentation of the Psammo-pelitic-carbonate Unit of the Paranoá Group (Campos et al., 2012).

Shallow water turbidites occur interfingered with carbonatic rock types. They are linked to the high topography of the basement, which is capable of generating debris flows that culminate in the deposition of turbidites on the internal siliciclastic platform (Fig. 19), formed primarily of the Sand Assemblage. These turbidites would have been deposited, especially in valleys carved in the paleorelief (Fig. 19). According to Fenton & Wilson (1985) and Mutti et al. (2007), part of the shallow water turbidites can be reworked by waves and tides.

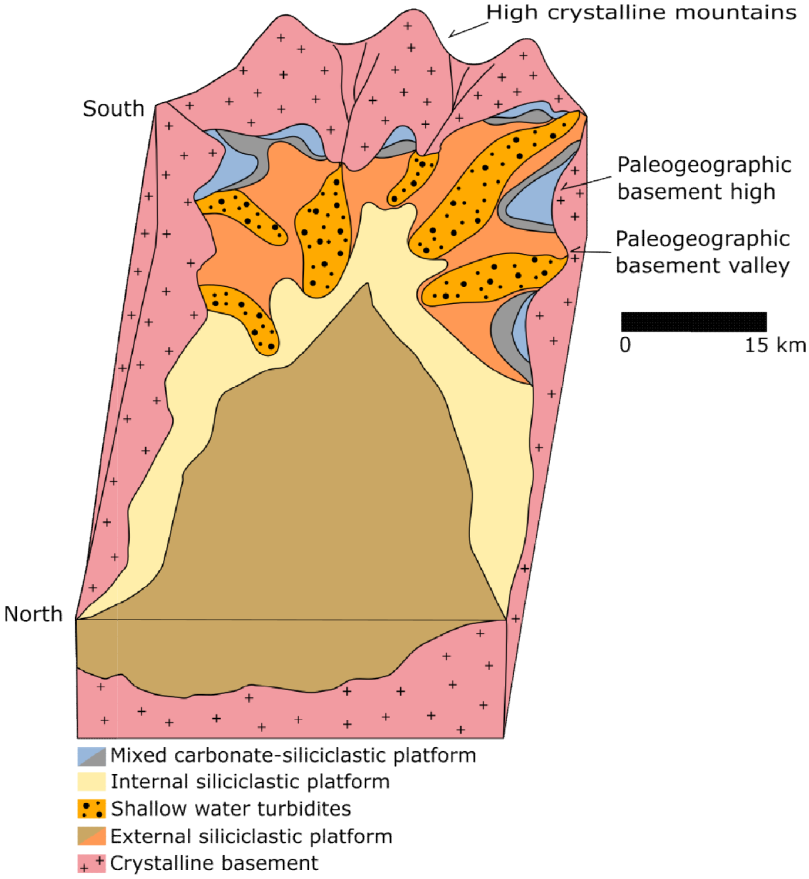


Fig. 19. Schematic depositional model for the Natividade Group basin. In the south of the area, the paleorelief would present a high topography, allowing the formation of gravitational flows. In this same portion, the sea would be shallower, favoring carbonate precipitation, especially over basement highs. To the north, the sea would deepen, and the basement would be more eroded, favoring the deposition of fine-grained sediments.

As the basin deepens to the north, the sedimentation became predominantly siliciclastic, formed mostly by lutite and fine-grained sandstone. There are still rare intercalations with clast-supported metaconglomerate and pebble quartzite. The basin deepening to the north is interpreted by the fine-grained sediments, the lower altitude of the sediments/basement contact, and the flat unconformity surface.

6. Conclusions

This study focused on the identification of distinct sedimentary rock assemblages and resulted in the interpretation of specific depositional conditions during the evolution of the Natividade basin. The reported results shed light over the dynamic evolution of this basin and allow envisaging a schematic depositional model that serves as a basis for future studies and supports the following main conclusions.

- Eleven metasedimentary rock types are reported from the Natividade basin, representing four major sedimentary environments.
- Rock assemblages correspond to specific deposition conditions:
  - Sand-Silt-Carbonate Assemblage - mixed platform environment with simultaneous

siliciclastic and carbonate deposition;
    - Sand-Conglomerate Assemblage - shallow turbidite environment, related to mass flow controlled by the paleorelief of the source area;
    - Sand Assemblage - internal platform in backshore and foreshore conditions;
    - Silt-Clay Assemblage - external siliciclastic in an open-marine platform with primarily fine-grained deposition.
- The Natividade Group is interpreted as deposited in a basin controlled by thermo-flexural subsidence associated with a mixed siliciclastic-carbonatic marine platform in which shallow-water turbidite deposits co-occurred. In the mass flow deposits, the sharp contact of metaconglomerate and quartzite with phyllite and marble is frequent.
- The Natividade Group is interpreted as a post-rift basin related to the isostatic rebalance that occurred after the filling of the Araí rift.
- The geological map indicates that the basin is shallower in the southern portion with a predominance of carbonate precipitation and occasional gravitational flux.
- The basin deepens to the north, which explains the predominance of fine-grained sediments.
- The basement would have an important role in the control of this deposition since its paleorelief allowed the deposition of a lateral assemblage of depositional environments of mixed platform, internal and external siliciclastic platform, and turbidite deposits of shallow waters.
- Finally, due to the constant rock types interfingering and lateral variations in sedimentation conditions, it is not possible to propose a representative stratigraphic column for the Natividade Group. In this case, it is necessary to develop a local vertical stratigraphy for each segment of the basin.

7. Acknowledgments:

We would like to thank the journal reviewers whose contribution resulted in a significant improvement in the final manuscript. The support of Brazilian National Council for Scientific and Technological Development (CNPq) for funding the fieldwork and the University of Brasilia (Geosciences Institute) for equipments and laboratories.

8. References

Aerogeophysica Latinoamerica - AGP-LA. 2006. Levantamento Aerogeofísico do Estado do Tocantins. Programa Geologia do Brasil - CPRM. Relatório Final do Levantamento e Processamento dos Dados Magnetométricos e Gamaespectrométricos. Vol. 1. 478p.

Alkmim, F.F. & Martins Neto, M.A. 2012. Proterozoic first order sedimentary sequences of the São Francisco Craton, eastern Brazil. Marine and Petroleum Geology, 33(1):127-139. https://doi.org/10.1016/j.marpetgeo.2011.08.011.

Almeida, F.F.M. 1977. O Cráton do São Francisco. Revista Brasileira de Geociências, 7(4):349-364.

Almeida, F.F.M., Hasui, Y., Brito Neves, B.B., Fuck, R.A. 1981. Brazilian structural provinces: an introduction. Earth-Science Reviews, 17(1):1-29.

Barbosa, O., Baptista, M.B., Braun, O.P., Dyer, R.G., Cotta, J.C. 1969. Geologia e inventário dos recursos minerais do Projeto Brasília. Rio de Janeiro, PROSPEC/DNPM, 225p.

Böhm, F. & Brachert, T.C. 1993. Deepwater stromatolites and Frutexites Maslov from the early and Middle Jurassic of S-Germany and Austria. Facies, 28(1), 145–168. DOI:10.1007/bf02539734

Bouma, A.H. 1962. Sedimentology of some Flysch Deposits. A Graphic Approach to Facies Interprettion. Elsevier, Amsterdam, 168p.

Campos, J.E.G., Bogossian, J., Carvalho, R.M. 2012. Sedimentology of the Psammo-pelitic-carbonate Unit, Paranoá Group, and Sete Lagoas Formation, Bambuí Group: examples of mixed carbonate-siliciclastic sedimentation in the Proterozoic of the Brasília Fold Belt. Revista Brasileira de Geociências, 42(3):513-522. http://dx.doi.org/10.5327/Z0375-75362012000300006.

Campos, J.E.G., Dardenne, M.A., Freitas-Silva, F.H., Martins Ferreira, M.A.C. 2013. Geologia do Grupo Paranoá na porção externa da Faixa Brasília. Revista Brasileira de Geociências 43:461-476. DOI: 10.5327/Z2317-48892013000300004.

Campos, J.E.G., Martins Ferreira, M.A.C., Moura, F.G., Chemale Jr, F. 2020. Discovery of Precambrian deep-water turbidites and submarine volcanism in the Brasilia Belt, central Brazil: The Quilombo Formation. Journal of South American Earth Sciences. Submitted.

Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X. 2013. Updated. The ICS International Chronostratigraphic Chart. Episodes 36:199-204.

Correa Filho, F.C.L. & Sá, A.M. 1980. Projeto Natividade. Goiânia, DNPM/CPRM (inédito).

Costa, A.F.O., Danderfer, A., Bersan, S.M. 2018. Record of a Statherian rift-sag basin in the Central Espinhaço Range: Facies characterization and geochronology. Journal of South American Earth Sciences, 82:311-328.

Costa, J.B.S., Lemos, R.L., Martins, J.P.A., Beltrão, J.F., Goes, A.M., Hasui, Y. 1984. Geologia da região de Porto Nacional. Rev. Bras. Geoc., 14 (1):3-11.

Costa, L.A.M., Portela, A.C., Nilson, A.A., Vale, C.R.O., Marchetto, C.L.M., Santos, E.L., Meneghesso, G., Inda, H.A.V., Sterna, R., Marchetto, P., Baptista, M.B., Fratin, O., Mosmann, R., Oliveira, T.F.D., Silva, W.E. 1976. Projeto Natividade Área VI. Projeto Leste do Tocantins, Oeste do Rio São Francisco. Conv. DNPM/CPRM/PROPESC. (relatório final), Rio de Janeiro. 151p.

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017. The peraluminous Aurumina Granite Suite in central Brazil: An example of mantle-continental crust interaction in a Paleoproterozoic cordilleran hinterland setting? Precambrian Research, 299:75-100.

D'Ávila, R.S.F., Arienti, L.M., Aragão, M.A.N.F., Vesely, F.F., Santos, S.F., Voelcker, H.E., Viana, A.R., Kowsmann, R.O., Moreira, J.L.P., Coura, A.P.P., Paim, P.S.G., Matos, R.S., Machado, L.C.R. 2008. Ambientes de Águas Profundas (Cap 10) In: da Silva, A.J.C.L.P., Aragão, M.A.N.F., Magalhães, A.J.C. Ambientes de Sedimentação Siliciclástica do Brasil. São Paulo: Beca-Ball, 244-300p.

Dantas, E.L., Horbe, A., Yokoyama, E., Peixoto, E.N., Jiménez, F.A.C., Garnier, J., Viegas, L.G.F., Hauser, N., Botelho, N.F., Rodrigues, S.W.P. 2018. Projeto Monte do Carmo - Tocantins. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Dardenne, M.A. 2000. The Brasília Fold Belt. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 31st International Geological Congress, 231-263.

Dardenne, M.A. & Saboia, A.M. 2007. Litoestratigrafia do Grupo Natividade na região de Natividade-Pindorama, Tocantins. In: Horbe, A.M.C., Souza, V.S. (Org.). Contribuições à Geologia da Amazônia. Belém: Sociedade Brasileira de Geologia, 5: 29-38.

Della Favera, J.C. 2008. Ambientes Marinhos Rasos (Cap. 9). In: da Silva, A.J.C.L.P., Aragão, M.A.N.F., Magalhães, A.J.C. Ambientes de Sedimentação Siliciclástica do Brasil. São Paulo, Beca-Ball, 224-243p.

Dyer, R.C. 1970. Grupo Araí - Um Grupo de Metamorfitos do Centro-Leste de Goiás. Revista da Escola de Minas. Ouro Preto, 28(2):55-63.

Fenton, M.W. & Wilson, C.J.L. 1985. Shallow-water turbidites: an example from the Mallacoota Beds, Australia. Sedimentary Geology, 45:31-260.

Franco, C.G.T., Almeida, M.A.R., Reis, S.T., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins – Subárea IV. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Fuck, R.A., Dantas, E.L., Pimentel, M.M., Botelho, N.F., Armstrong, R., Laux, J.H., Junges, S.L., Soares, J.E., Praxedes, I.F. 2014. Paleoproterozoic crust-formation and reworking events in the Tocantins Province, central Brazil: A contribution for Atlantica supercontinent reconstruction. Precambrian Research, 244:53-74.

Fuck, R.A., Pimentel, M.M., Alvarenga, C.J.S., Dantas, E.L. 2017. The Northern Brasília Belt. In: São Francisco Craton, Eastern Brazil. Tectonic Genealogy of a Miniature Continent. Editors: Heilbron, M., Cordani, U.G., Alkmim, F.F. Regional Geology Reviews. Springer, 1ed, 205-220p. DOI:10.1007/978-3-319-01715-0.

Geosoft. 2013. Oasis Montaj 7.5 - Mapping and Processing System. In: Quick Start Tutorials. Geosoft Incorporated, 258p.

Geosoft. 2019. Oasis MontajTM 9.6 Geosoft Inc. Toronto, Canadá.

Gomes, A.W., Godoy, H.V., Altoé, I.L., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea XVI. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Gorayeb, P.S.S., Costa, J.B.S., Lemos, R.L., Gama, J.R.T., Bemerguy, R.L., Hasui, Y. 1988. O Pré-Cambriano da Região de Natividade, GO. Revista Brasileira de Geociências, 18:391-397.

Grotzinger, J.P. & James, N.P. 2000. Precambrian carbonates evolution of understanding. Carbonate Sedimentation and Diagenesis in the Evolving Precambrian. Society for Sedimentary Geology Special Publication, 67. ISBN 1-56576-072-7.

Guadagnin, F., Chemale Jr, F., Magalhães, A.J., Santana, A., Dussin, I., Takehara, L. 2015. Age constraints on crystal-tuff from the Espinhaço Supergroup - Insight into the Paleoproterozoic to Mesoproterozoic intracratonic basin cycles of the Congo–São Francisco Craton. Gondwana Research, 27(1): 363-376.

Harms, J.C., Southard, J.B., Spearing, D.R., Walker, R.G. 1975. Depositional environments as interpreted from primary sedimentary structures and stratification sequences: SEPM, Short Course Notes 2, 161p.

Hasui, Y., Costa, J.B.S., Saad, A.R., Campanha, V.A. 1990. O Grupo Natividade e sua correlação com o Grupo Bambuí. Geociências (UNESP. Impresso), São Paulo, v. Esp., n. Especial, 299-316p.

Khetani, B. & Read, J.F. 2002. Sequence development of a mixed carbonate-siliciclastic high-relief ramp, Mississippian, Kentucky, USA. Sedimentary Geology, 72(5):657-672. https://doi.org/10.1306/022102720657.

Li, X. 2006. Understanding 3D analytic signal amplitude. Geophysics, 71:13-16.

Lowe, D.R. 1982. Sediment gravity flows; II, depositional models with special reference to the deposits of high-density turbidity currents. Journal of Sedimentary Research, 52: 279-297.

Marques, G.C. 2009. Geologia dos grupos Araí e Serra da Mesa e seu embasamento no sul do Tocantins. Dissertação de Mestrado, Universidade de Brasília, 116p.

Martins, F.A.L. 1999. Análise faciológica e estratigráfica do Paleo-Mesoproterozóico: Sequência Araí no Parque Nacional Chapada dos Veadeiros, Goiás. Dissertação de Mestrado. IG-UnB, 137p.

Martins-Ferreira, M.A.C.&Campos, J.E.G. 2017. Compartimentação geomorfológica como suporte para estudos de evolução geotectônica: aplicação na região da Chapada dos Veadeiros, GO. Revista Brasileira de Geomorfologia, 18:501-519.

Martins-Ferreira, M.A.C., Campos, J.E.G., Alvarenga, C.J.S. 2013. A Formação Jequitaí na região de Vila Boa, GO: exemplo de sedimentação por geleiras terminais no Neoproterozóico. Brazilian Journal of Geology, 43(2):373-384.

Martins-Ferreira, M.A.C., Chemale Jr, F., Coelho Dias, A.N., Campos, J.E.G. 2018a. Proterozoic intracontinental basin succession in the western margin of the São Francisco Craton: Constraints from detrital zircon geochronology. Journal of South American Earth Sciences, 81:165-176. DOI: 10.1016/j.jsames.2017.11.018.

Martins-Ferreira, M.A.C., Campos, J.E.G., Von Huelsen, M.G. 2018b. Tectonic evolution of the Paranoá basin: New evidence from gravimetric and stratigraphic data. Tectonophysics, 734:44-58.

Martins-Ferreira, M.C., Dias, A.N.C., Chemale Jr, F., Campos, J.E.G., Seraine, M., Rodrigues, E.N. 2020. Multi-stage crustal accretion by magmatic flare-up and quiescence intervals in the western margin of the São Francisco Craton: U-Pb-Hf and geochemical constraints from the Almas Terrane. Gondwana Research, 85:32-54.

Matteini, M., Dantas, E.L., Pimentel, M.M., Alvarenga, C.J.S. and Dardenne, M.A. 2012. U-Pb and Hf isotope study on detrital zircons from the Paranoá Group, Brasília Belt Brazil: Constraints on depositional age at Mesoproterozoic–Neoproterozoic transition and tectono-magmatic events in the São Francisco craton. Precambrian Research, 206:168-181.

McNeill, D.F., Janson, X., Bergman, K.L., Eberli, G.P. 2010. Belize: a modern example of a mixed carbonate-siliciclastic shelf. In: Westphal, H. (Ed.), Carbonate Depositional Systems: Assessing Dimensions and Controlling Parameters, 81-143p. https://doi.org/10.1007/978-90-481-9364-6_3.

Monteiro, C.F. 2009. Fosforitos do Grupo Bambuí na região de Campos Belos (GO) / Arraias (TO), na borda oeste do Cráton São Francisco. Dissertação (Mestrado em Geociências) - Universidade de Brasília, Brasília, 135p.

Moore, B. 1963. Geological reconnaissance of the southwest corner of the Maranhão Basin. Relatório nº 1854, PETROBRÁS/DEPEX, RJ.

Morbeck, E., Kuberek, N., Barreto, R., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins – Subárea V. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Mount, J.F. 1984. Mixing of siliciclastic and carbonate sediments in shallow shelf environments. Geology, 12(7), 432. DOI:10.1130/0091-7613(1984)12<432:mosacs>2.0.co;2

Moro, P.S. 2017. O Rifte Araí: novas perspectivas com base em dados gravimétricos, magnéticos e geológicos. Dissertação de Mestrado, Universidade de Brasília, 116p.

Moura, F.G. 2018. Geologia do Grupo Quilombo e seu embasamento cristalino na região de Unaí-MG. Dissertação de Mestrado, Universidade de Brasília, 79p.

Mutti, E. 1992. Turbidite sandstones. AGIP Italy in E. Mutti, (ed.), 275p.

Mutti, E., Tinterri, R., Remacha, E., Mavilla, N., Angella, S., Fava, L. 1999. An Introduction to the Analysis of Ancient Turbidite Basins from an Outcrop Perspective. AAPG Continuing Education Course Note, 39, 74 p.

Mutti, E., Tinterri, R., Magalhaes, P.M., Bastam, G. 2007. Deep-Water Turbidites and Their Equally Important Shallower Water Cousins. Adapted from Extended Abstract prepared for presentation at AAPG Annual Convention, Long Beach, California, April 1-4.

Neumann, V.H., Aragão, M.A.F., Valença, L.M.M., Leal, J.P. 2008. Ambientes Lacustres Cap. 5). In: da Silva, A.J.C.L.P., Aragão, M.A.N.F. e Magalhães, A.J.C. Ambientes de Sedimentação Siliciclástica do Brasil. São Paulo, Beca-Ball, 132-168p.

Oliveira, C.G., Dantas, E.L., Roig, H.L., Chemale Jr, F., Della Giustina, M.E.S., Meneses, P.R., Vidotti, R.M., Souza, V.S. 2012. Projeto Natividade. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Pimentel, M.M. 2016. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. Brazilian Journal of Geology, 46(1):67-82. DOI: 10.1590/2317-4889201620150004.

Pimentel, M.M., Heaman, L., Fuck, R.A., Marini, O.J. 1991. U-Pb zircon chronology of Precambrian tin-bearing continental-type acid magmatism in central Brazil. Precambrian Research, 52(3-4):321-335.

Põldsaar, K., Ainsaar, L., Nemliher, R., Tinn, O., Stinkulis, G. 2019. A siliciclastic shallow-marine turbidite on the carbonate shelf of the Ordovician Baltoscandian palaeobasin. Estonian Journal of Earth Sciences, 68(1):1-14. https://doi.org/10.3176/earth.2019.01.

Pomerol, C., Lagbrielle, Y., Renard, M., Guillot, S. 2013. Princípios de geologia. Técnicas, modelos e teorias. Editora bookman, 27:654-671.

Reeves, C. 2005. Aeromagnetic surveys: principles, practice and interpretation. Delft: Geosoft, 155p.

Ress, C.B., Oliveira, L.M.C., Ribeiro, T.G.R., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea IX. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Rodrigues, J.B., Pimentel, M.M., Dardenne, M.A., Armstrong, R.A. 2010. Age, provenance and tectonic setting of the Canastra and Ibiá Groups (Brasília Belt, Brazil): Implications for the age of a Neoproterozoic glacial event in central Brazil. Journal of South American Earth Sciences, 29(2):512-521.

Saboia, A.M. 2009. O Vulcanismo em Monte do Carmo e Litoestratigrafia do Grupo Natividade, Estado de Tocantins. Dissertação (Mestrado em Geociências) - Universidade de Brasília, Brasília, 96p.

Seraine, M., Campos, J.E.G., Martins-Ferreira, M.A.C., Giorgioni, M., Angelo, T.V. 2020. Tectonic significance of abrupt immature sedimentation in a shallow cratonic margin basin: The Arkose Level, Mesoproterozoic Paranoá Group. Journal of South American Earth Sciences, 97:102397.

Silva, W.L., Kotschoubey, B., Lafon, J.M., Gallarza, M.A. 2005. Grupo Natividade e Grupo Araí: correlatos, mas diacrônicos. In: X Congresso Brasileiro de Geoquímica e II Simpósio de Geoquímica dos Países do Mercosul. Estratigrafia do Grupo Araí: registro de rifteamento paleoproterozoico no Brasil Central de Galinhas, Pernambuco, Brasil, 2:1-4.

Sotero, M.P., Caxito, F.A., Dias., P.H.A., Sotero, B.A. 2019. Análise de fácies e ambientes deposicionais do Grupo Vazante na região da Mina de Morro Agudo, Paracatu, noroeste do estado de Minas Gerais. Geol. USP, Sér. cient., São Paulo, 19(2):199-214. DOI: 10.11606/issn.2316-9095.v19-144761

Suguio, K. 2003. Geologia Sedimentar. Edgard Blücher ltda./EDUSP, São Paulo, SP, 400p.

Tagliari, C.V. 2013. Ambientes de sedimentação mista (siliciclástica e carbonática), cicloestratigrafia e halocinese durante o Albiano, Plataforma de Regência, Bacia do Espírito Santo. Tese de Doutorado. Unisinos, São Leopoldo (RS), 207p.

Tanizaki, M.L.N., Campos, J.E.G., Dardenne, M.A. 2015. Stratigraphy of the Araí Group: record of Paleoproterozoic rifting in Central Brazil. Brazilian Journal of Geology, 45(1):95-108. DOI: 10.1590/23174889201500010007.

Teixeira, A.L.S., Lemos, I.G.S., Corrêa, R.M., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea III. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Uhlein, A., Paim, P.S.G., Tassinari, C.C.G., Pedreira, A.J. 2015. Análise estratigráfica de bacias rifte Paleo-Mesoproterozoicas dos crátons Amazônico e São Francisco, Brasil. Geonomos, 23(2):1-13.

Yang, B.C., Dalrymple, R.W., Chun, S.S. 2006. The significance of hummocky cross-stratification (HCS) wavelengths: Evidence from an open-coast tidal flat, south Korea. Journal of Sedimentary Research, 76(1):2-8. https://doi.org/10.2110/jsr.2006.01.

CAPÍTULO 4

ARTIGO 2

Published in Journal of South American Earth Sciences: https://doi.org/10.1016/j.jsames.2020.102939

Journal of South American Earth Sciences 112 (2021) 103618

ELSEVIER

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

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

The Statherian Natividade Basin evolution constrained by U–Pb geochronology, sedimentology, and paleogeography, central Brazil

Toscani, R.[1]*; Campos, J.E.G.[2]; Martins-Ferreira, M.A.C.[3]; Matos, D.R.[4]; Borges, C.C.A[2]; Dias, A.N.C.[5]; Chemale Jr, F.[6]

[1] Centro de Hidrografia da Marinha, Diretoria de Hidrografia e Navegação, Marinha do Brasil, Niterói, Rio de Janeiro, RJ, Brazil.
[2] Instituto de Geociências, Universidade de Brasília, Campus Univ. Darcy Ribeiro, Asa Norte, 70910900 Brasília, DF, Brazil
[3] Fac. de Ciências e Tecnologia, Univ. Federal de Goiás, Setor Conde dos Arcos, 74968755 Aparecida de Goiânia, GO, Brazil
[4] Divisão de Geologia Econômica, Serviço Geológico do Brasil. Urca, Rio de Janeiro, RJ, Brazil
[5] Departamento de Física, Química e Matemática, UFSCar - Campus Sorocaba, 18052780 Sorocaba, SP, Brazil
[6] Programa de Pós-Graduação em Geologia.Universidade do Vale do Rio dos Sinos, 93022000 São Leopoldo, RS, Brazil

* Corresponding Author: toscanisilveira@gmail.com

Abstract

The tectonostratigraphic evolution of the intracontinental Natividade Basin is evaluated by zircon U/Pb analysis of one sample of acidic metavolcanic rock observed at the bottom of the depositional succession and three samples of metasedimentary rocks collected at different stratigraphic levels. The metavolcanic sample yielded an 1824 Ma zircon U–Pb age, and the youngest detrital zircon grains from the metasedimentary sequence resulted in a maximum depositional age of 1776 Ma for the paleobasin. The isotopic data associated with the analysis of stratigraphy, paleogeography, and sedimentary environments converge to the interpretation that the Natividade Group evolved from the late Paleoproterozoic (Statherian), possibly entering the early Mesoproterozoic. The sedimentation is interpreted to have occurred between the deposition of the Araí and the Traíras/Serra da Mesa groups. This understanding is due to the absence of continental sediments in the Natividade Basin (which could corroborate the correlation with the Araí Basin) and the absence of detrital zircon grains younger than 1.5 Ga (which would support the correlation with the Traíras/Serra da Mesa groups). The metavolcanic rocks are observed only locally and are interpreted as the result of melting by crustal rifting that was greatest in the south, related to the Araí Group, and decreased northwards of the study region. The mechanical subsidence responsible for the deposition of the Araí Group continental sediments was not observed in the Natividade Basin. The thermo-flexural subsidence responsible for the Natividade Basin evolution allowed the deposition of complex sedimentary environments related to mixed siliciclastic platforms and shallow water turbidite facies. Based on bibliographic studies and fieldwork data, our geological model suggests that the Almas Block was possibly a high paleorelief area, separating the Araí Basin to the south and the Natividade Basin to the north. This assertion is based on the following facts for the study area: i) there is no occurrence of the Veadeiros Supergroup sediments; ii) Nowadays in the region, there are many high relief areas related to quartzite layers and several granitic units that are resistant to denudation processes; iii) deposition of the shallow water turbidite present at the Natividade Group needed elevated source areas to control the sedimentation; iv) The predominance of carbonates and mass flow deposits in the southern portion of Natividade Group, near to Almas Block, suggests a lower depth of the sea to the south of the basin. Further north, the predominance of fine-grained terrigenous deposits suggests a deeper basin; v) it is common in rift-sag environments the preservation of elevated blocks as an isostatic compensation mechanism. The integrated analysis conducted allowed the following conclusions: the Natividade Basin evolution is not coeval with the Araí or the Traíras/Serra da Mesa basins and is classified as a sag-type basin in which the sedimentary environments resulted in massive carbonate accumulation in a complex platform controlled by the basement paleorelief.

Keywords: *Natividade Group, geochronology, paleorelief, mixed siliciclastic platform, shallow water turbidite.*

1. Introduction

The Natividade Group is a Paleo-Mesoproterozoic metasedimentary sequence outcropping in the southeast of the Tocantins State, central Brazil, and in the geological context of the northern external zone of the Neoproterozoic Brasília Belt (Dardenne, 2000; Valeriano et al., 2008), western margin of the São Francisco Craton. The overall sedimentary environment responsible for the Natividade Group deposition is associated with a mixed platform (Saboia, 2009) with simultaneous deposition of shallow water turbidites in a basin controlled by thermo-flexural subsidence (Toscani et al., 2021).

The lack of geochronological data about the Natividade Group is notable, leading to uncertainties regarding its age, distribution area, and complex metasedimentary rock set. This is reinforced by the presence of only a single dating in detrital zircon that proposes a maximum deposition age of 1779 ± 6 Ma (Silva et al., 2005).

This lack of data hinders a more complete study of the source areas and the relationship with other basins in the region. Nevertheless, several authors have correlated the Traíras, Natividade, and Serra da Mesa groups, indicating that they belong to the same tectonic unit formed from the evolution of the Araí rift basin (Marini et al., 1981; Martins, 1999; Silva et al., 2005; Marques, 2009; Saboia, 2009; Martins-Ferreira, 2017). It is worth mentioning that these correlations did not focus on the Natividade Group, being carried out more with the intent to insert the Natividade Group in a regional context than to properly characterize or correlate this unit.

This study, based on field data, U–Pb zircon ages, and petrographic analysis, aims to understand the source material of the Natividade Basin; investigate its tectonic evolution in the context of "West Gondwana Geology"; and more accurately correlate the Natividade Group with other Proterozoic units in central Brazil.

2. Geological setting

The present study focuses on the evolution of the Natividade Group, a sedimentary sequence belonging to the Veadeiros Supergroup (Martins-Ferreira et al., 2018a; Toscani et al., 2021), a Proterozoic supersequence of the rift-sag type located in central Brazil (Fig. 1).

The region is located in the domains of the Tocantins Structural Province (Fig. 2a) (Almeida et al., 1981), which is comprised of three orogenetic belts: Brasília, Araguaia, and Paraguay (Almeida, 1977; Pimentel, 2016).

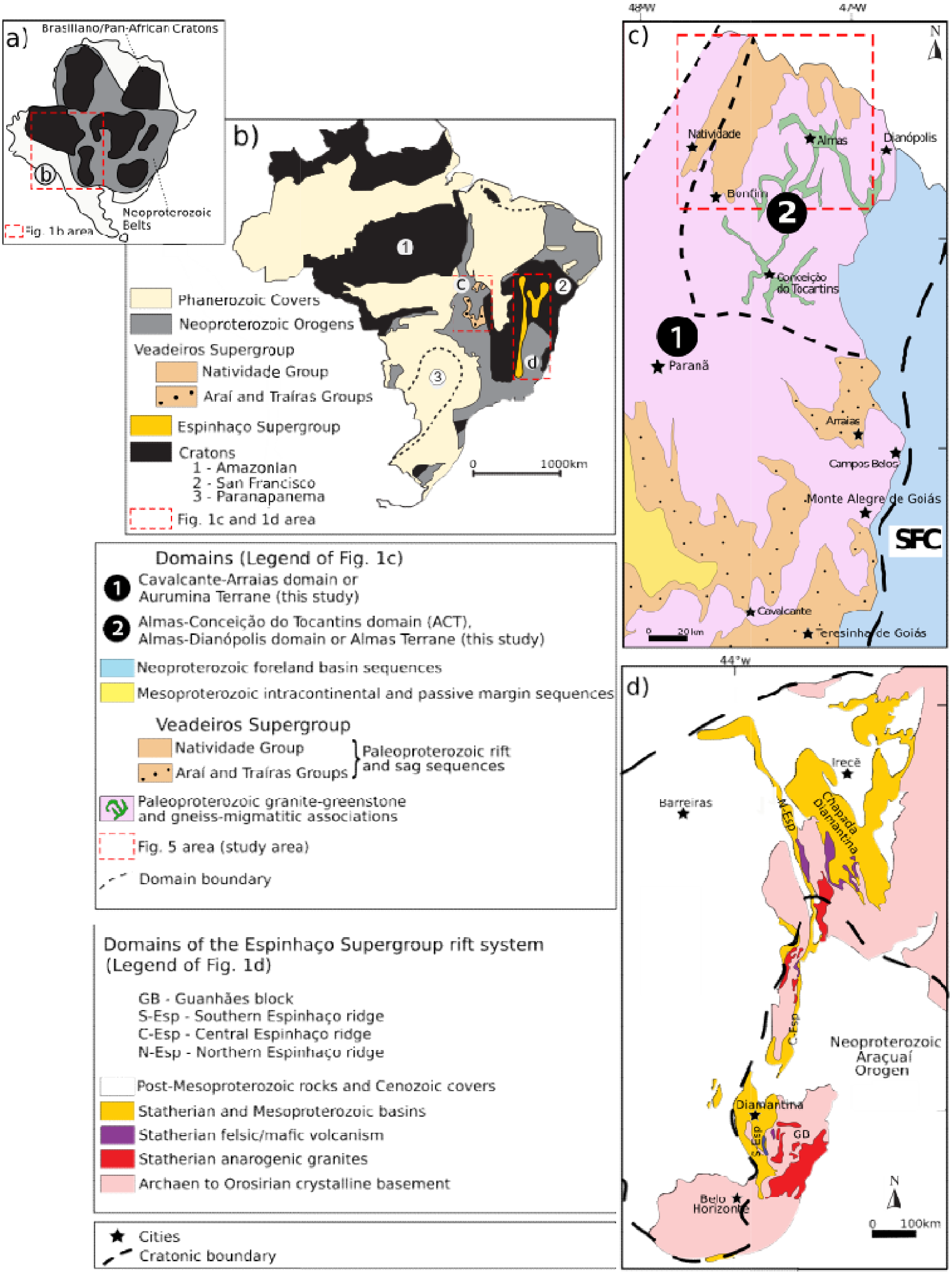


Fig. 1. Geological context maps showing: a) location of Archean/Paleoproterozoic cratons and Neoproterozoic belts and Fig. 1b area (red rectangle), b) map of the main cratons and basins in Brazil and Fig. 1c and d locations (red rectangles), c) geological map of the northern segment of the Brasília Belt showing two tectonic domains (modified from Martins-Ferreira et al., 2020; Fuck et al., 2014; Cordeiro and Oliveira, 2017), d) simplified geological map of the Espinhaço Supergroup rift system (modified from Alkmim, 2004; Pinto and Silva, 2014; Magalhães et al., 2018).

2.1 Tectonic Evolution

In Brazil, the Amazonian and São Francisco cratons are partially covered by rift, sag, and rift-sag type volcano-sedimentary units deposited during the Paleoproterozoic and Mesoproterozoic. In general, these basins are located at the margin or the interior of these cratonic landmasses and are commonly surrounded by Neoproterozoic fold belts (Fig. 1a and b).

The northern segment of the Brasília Belt is characterized by a general NE-SW structural trend and an overall east to southeast vergence (Fig. 2). The external zone of the Brasília Belt, where our study area is located, comprises a pile of sedimentary sequences deformed against the western margin of the São Francisco Craton, including significant exposures of their sialic basement (Fuck et al., 2017; Saboia et al., 2020a; Saboia et al., 2020b).

During the evolution of the Brasília Belt basement, an accretionary orogeny developed with the amalgamation of micro-blocks in the São Francisco Craton western margin from 2.5 to 2.2 Ga (Fuck et al., 2014; Sousa et al., 2016; Martins-Ferreira et al., 2020). According to Cordeiro and Oliveira, (2017), all rocks from the pre-Neoproterozoic in the central-northern part of the Brasília Belt are grouped in the Goiás Massif, which can be divided into four distinct tectonic domains: The Archean-Paleoproterozoic Crixás-Goiás Domain and the Paleoproterozoic Almas-Conceição do Tocantins (ACT), Cavalcante-Arraias and Campinorte domains.

In the present study, we used the terminology of Martins-Ferreira et al. (2020), who defined the terms: Almas Terrane for the ACT and Aurumina Terrane for the Cavalcante-Arraias domain.

The rocks of this study are located in Almas Terrane, which consists of an amphibolite facies greenstone-TTG (tonalite-trondhjemite-granodiorite) association (Cruz, 2001; Martins-Ferreira et al., 2020; Borges et al., 2021). Bordering Almas Terrane, the Aurumina Terrane is characterized by peraluminous granites and tonalites/granodiorites emplaced on the western border of the SFC at 2.11–2.16 Ga (Cuadros et al., 2017).

Recently, Martins-Ferreira et al. (2020) detailed four main episodes of accretion: (1) early Siderian - episode S1 (2.52–2.46 Ga - Novo Jardim Terrane), (2) late Siderian - episode S2 (2.43–2.37 Ga - Novo Jardim Terrane), (3) early Rhyacian - episode R1 (2.32–2.26 Ga - Pre-collisional Boqueirão Magmatic Arc) and (4) mid-Rhyacian - episode R2 (2.24–2.20 Ga - Almas Terrane and Syn-collisional Boqueirão Magmatic Arc).

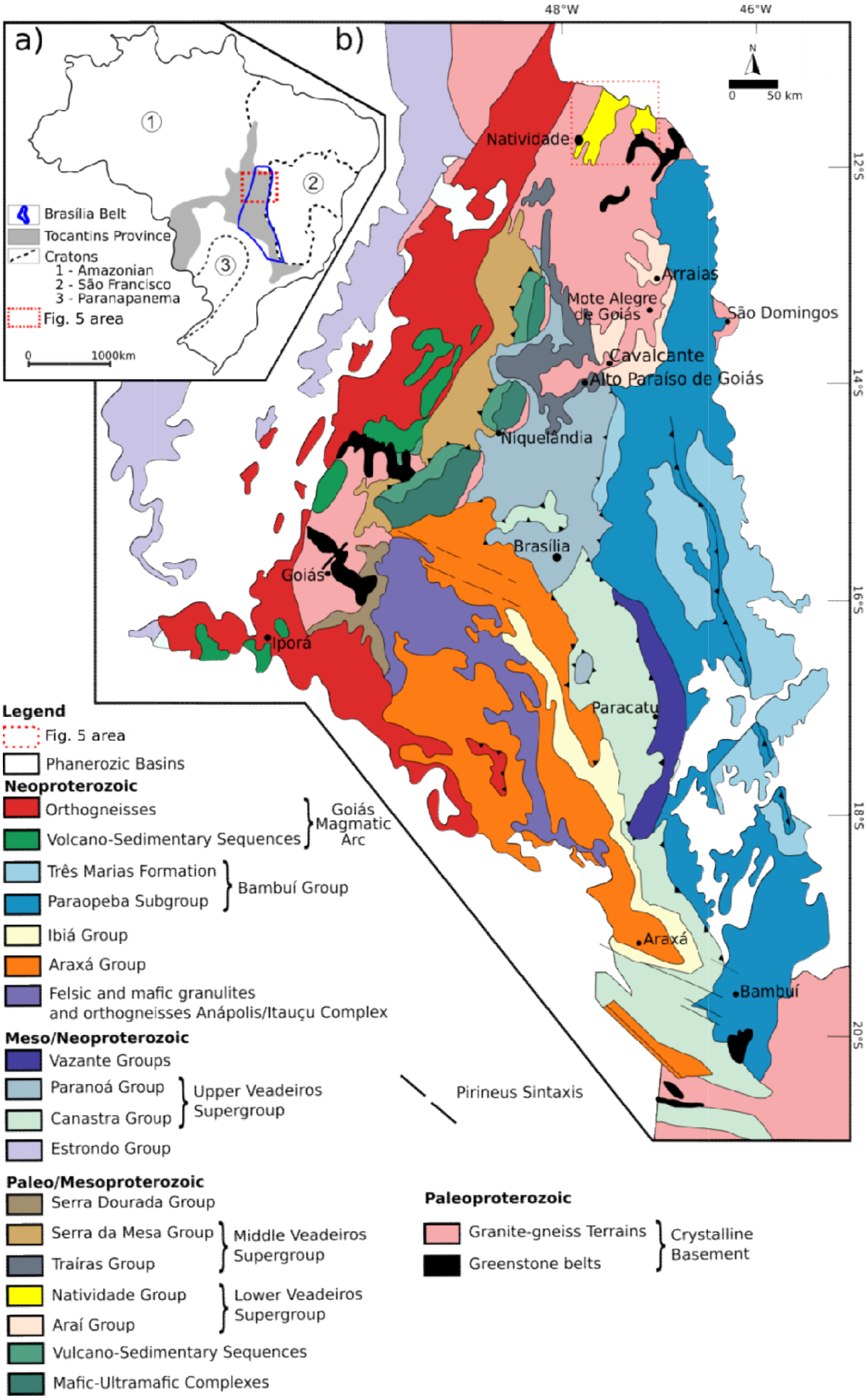


Fig. 2. Geological context maps showing: a) the location of the Brasilia Belt, Tocantins Province, and Amazonian, São Francisco, and Paranapanema cratons (adapted from Sousa et al., 2016), b) geological map of the Brasília Belt, where the Natividade Group outcrops in the northeastern, most part, covered by Phanerozoic sediments from the Parnaíba basin northwards (adapted from Dardenne, 2000; Fuck et al., 2017).

The Almas Greenstone Belt occurs in the Almas Terrane (Fig. 1c). It is preserved as narrow belts along the margins of the TTG batholiths and is represented by the Riachão do Ouro Group (RO) (Costa, 1984; Cruz, 2001; Martins-Ferreira et al., 2020). The regularly cited U–Pb zircon age of 2206 ± 13 Ma (Dardenne et al., 2009) for the Almas Greenstone Belt is not really consistent since the authors did not present the geochronological data and the location of the analyzed samples. The maximum depositional age of the Morro do Carneiro volcano-sedimentary sequence is 2234 ± 18 Ma, and its minimum depositional age is 2211 ± 9 Ma, thus representing an orogenic basin formed during the Almas Terrane accretion (Martins-Ferreira et al., 2020).

2.2 Veadeiros and Espinhaço Supergroups

The Veadeiros Supergroup represents a succession of extensional basins in the Northern Brasília Belt spanning from the Paleoproterozoic (Statherian) to the early Neoproterozoic (Tonian), and includes the Araí, Traíras, and Paranoá groups, besides the Quilombo Formation and may include the units with geographic and geochronological similarities such as the Natividade, Serra da Mesa, and Canastra groups (Fig. 3) (Martins-Ferreira et al., 2018a).

The Veadeiros Supergroup is divided into three major sedimentary sequences (Fig. 3). The first sequence of Paleoproterozoic age comprises the Araí Group and is known as Lower Veadeiros (Statherian age), representing the pre-and syn-rift phases. The second sequence is the Middle Veadeiros, considered to be of Mesoproterozoic age (Calymmian to early Ectasian) and consists of the Traíras Group and its probable lateral equivalent, the Serra da Mesa Group, which together represent the intracratonic sag phase of the basin (Martins-Ferreira et al., 2018a). The Middle Veadeiros sequence is correlated to the lower and middle Espinhaço Supergroup, which occurs in the eastern margin of the São Francisco Craton (Guadagnin and Chemale, 2015; Guadagnin et al., 2015). The third sequence, in the Upper Veadeiros, interpreted to be of late Mesoproterozoic age (Stenian to early Tonian), is represented by the Paranoá Group, which occurs in an Intra/Pericratonic sag basin type (Campos et al., 2013; Seraine et al., 2020; Martins-Ferreira et al., 2018b).

The Araí Group (Barbosa et al., 1969; Dyer, 1970), which previously included the Traíras sequence, was interpreted as a rift-sag basin with a maximum depositional age of 1771 Ma (Pimentel et al., 1991; Tanizaki et al., 2015). According to geochronological and stratigraphic data presented by Martins-Ferreira et al. (2018a), the Statherian Araí Group consists only of the Água Morna and Arraias formations, whereas the Traíras Group, with maximum deposition age at 1543 ± 31 Ma, represents a Calymmian sag-type basin deposited over the Araí Group or locally directly over the crystalline basement and might have coexisted in time with the Serra da Mesa Group, possibly as part of the same sag basin system. These two distinct basins, Araí and Traíras, are also related to different pulses of anorogenic magmatism, respectively the Pedra Branca Suite (1.77 Ga, Pimentel et al., 1991) and the Serra da Mesa Suite (1.57 Ga, Pimentel et al., 1991) (Fig. 3).

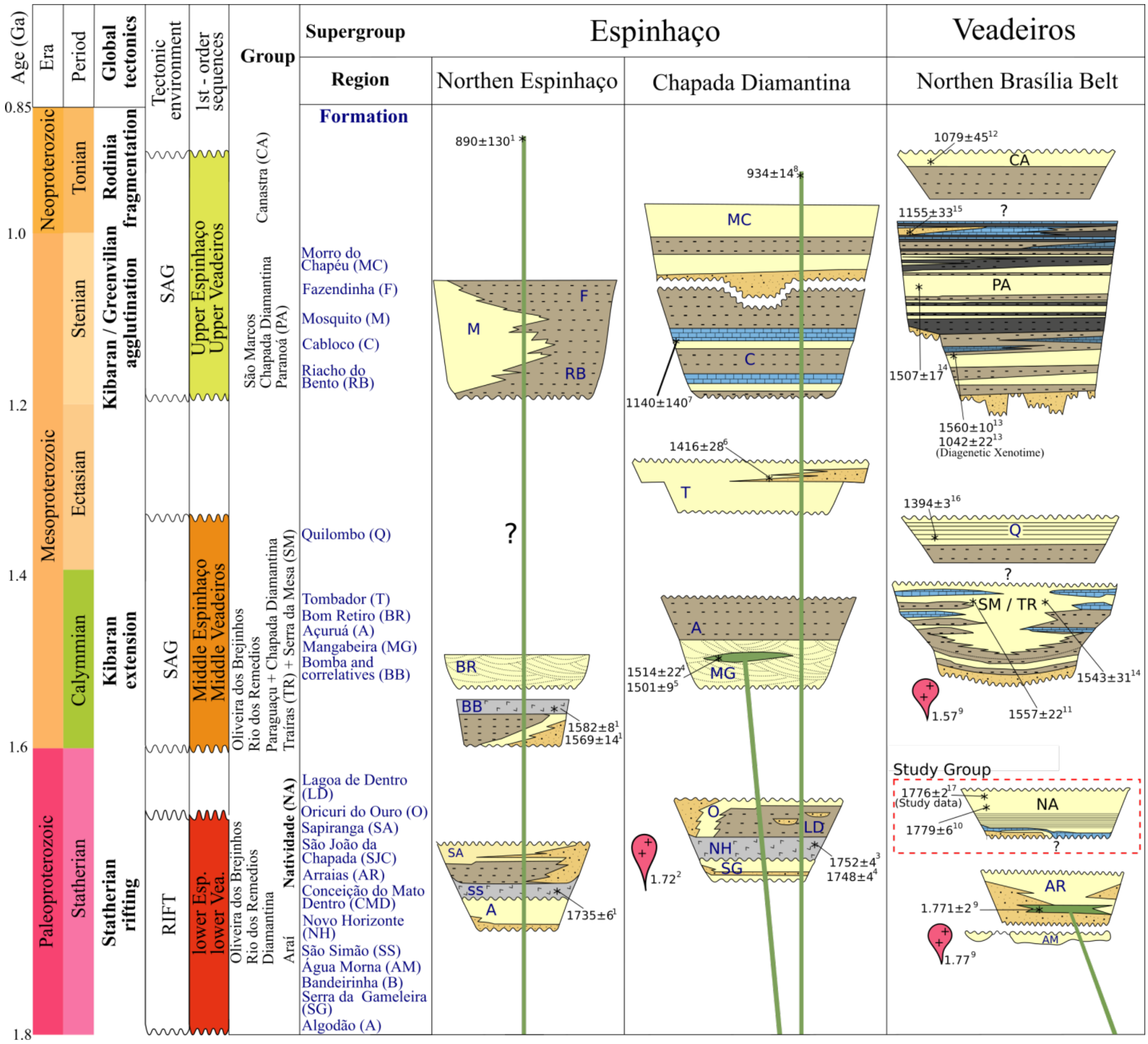


Fig. 3. Stratigraphic chart comparing the Veadeiros Supergroup sequences with its correlatives from the Espinhaço Supergroup (after Guadagnin and Chemale, 2015; Martins-Ferreira et al., 2018a; Toscani et al., 2021). The geologic time scale is from Cohen et al. (2013). 1. Danderfer et al. (2009); 2. Turpin et al. (1988); 3. Schobbenhaus et al. (1994); 4. Babinski et al. (1999); 5. Silveira et al. (2013); 6. Guadagnin et al. (2015); 7. Babinski et al. (1993); 8. Loureiro et al. (2008); 9. Pimentel et al. (1991); 10. Silva et al. (2005); 11. Marques (2009); 12. Rodrigues et al. (2010); 13. Matteini et al. (2012); 14. Martins-Ferreira et al. (2018a); 15. Seraine et al. (2020); 16. Campos et al. (2021); 17. Toscani et al. (2021).

To the south of the study area, in the Alto Paraíso de Goiás, Monte Alegre de Goiás, and Arraias regions (Fig. 1, Fig. 2), continental deposits are associated with a syn-rift phase deposition, comprising the Araí Group. Towards the north, near to Natividade city (Fig. 1, Fig. 2), there is a predominance of rocks of the Natividade Group, indicating possible transitional and post-rift stages with a more significant number of carbonates (dolomite and limestone) (Marques, 2009; Saboia, 2009).

The Serra da Mesa Group was described by Marques (2009) as a siliciclastic-carbonate marine platform, without continental facies, characterized mainly by muscovite-quartzite, shale, and marble lenses. It shows detrital zircons U–Pb ages ranging from 2.4 to 1.55 Ga and is frequently interpreted as chrono-correlated to the Traíras Group (Marques, 2009; Saboia, 2009; Martins-Ferreira et al., 2018a).

In the Espinhaço Supergroup, two rifting processes related to the Statherian and Calymmian periods have been identified and are known as Tuxás and Tupinaés events, both associated with intracontinental extension (Danderfer et al., 2015; Costa et al., 2018). The Espinhaço Basin outcrops in three geographic regions known as Serra do Espinhaço Meridional (Southern Espinhaço range), Serra do Espinhaço Setentrional (Northern Espinhaço range), and Chapada Diamantina (Diamantina Plateau) (Schobbenhaus and Brito Neves, 2003; Guadagnin et al., 2015; Uhlein et al., 2015) (Figs. 1 and 3).

In this context, the Paleo/Mesoproterozoic Espinhaço and Veadeiros Supergroups have been postulated to be chrono-correlated, and their main evolutionary stages are linked to equivalent regional or global tectonic processes (Fig. 3) (Guadagnin and Chemale, 2015 and references therein).

2.3 Natividade Group

The Natividade Group is a sequence of metasedimentary rocks of the Paleo-Mesoproterozoic age that was initially recognized by Moore (1963), with later contributions of Dyer (1970) and Costa et al. (1976). From the 1980s onwards, the studies became more detailed, with interpretations about the depositional environment. Correia Filho and Sá (1980) suggested that the depositional environment was a platform with short periods of instability. They also mentioned a moderate sediment input that enabled mixed sedimentation (siliciclastic-carbonatic). Costa (1984) defined the Natividade Group as a sandy sequence with conglomerate, clay, and possible volcanic intercalation levels. Hasui et al. (1990) believed that the Natividade Group was deposited on the edge of an ensialic basin that opened to the east.

Gorayeb et al. (1988) divided the Natividade Group into four formations: Santa Clara, Mato Virgem, Córrego Fundo, and Jacuba, from bottom to top. The Santa Clara Formation consists of pure quartzite at the base, transitioning to micaceous quartzite with levels of metaconglomerate, dolomitic marble, and phyllite. The Mato Virgem Formation consists of dolomitic marbles with intercalations of phyllite and micaceous quartzite. The Córrego Fundo Formation has quartzite at the base, moving to phyllite and slate, with thin beds of metalutite with graphite or hematite, and micaceous quartzite towards the top. The Jacuba Formation consists of pure quartzite and micaceous quartzite with levels of arkose which are interdigitated with phyllite and marble.

According to Saboia (2009), the Natividade Group is a sequence of metasedimentary rocks that were deposited in a mixed marine siliciclastic-carbonate platform typical of a marine expansion phase related to a thermal flexure after the rift phase observed in the south of the studied region. Saboia (2009) divided the group into eight lithostratigraphic units: metadolomite and metasiltstone (1); quartzite and metaconglomerate (2), metadolomite and metalimestone (3); metasiltstone and metadolomite (4); quartzite (5); metasiltstone and metadolomite (6); quartzite and metasiltstone (7); and metasiltstone (8).

In general, the Natividade Group is interpreted as a post-rift basin, derived from the isostatic rebalance after the evolution of the Araí rift basin located to the south (Costa et al., 1976; Gorayeb et al., 1988; Silva et al., 2005; Saboia, 2009; Marques, 2009; Toscani et al. 2021).

Recently, after analyzing the described rock types, interpreting satellite and radar images, and reviewing the geological contributions of preview studies by Gorayeb et al. (1988), Saboia (2009), and the geological mapping works of the University of Brasília in 2012 and 2016, Toscani et al. (2021) proposed six stratigraphic columns (Fig. 4) and a detailed geological map of the Natividade Group for the region (Fig. 5).

In this study, we used the terminology proposed by Toscani et al. (2021), which characterized the Natividade Group by a mixed platform with simultaneous deposition of shallow water turbidite in a basin controlled by thermo-flexural subsidence. Toscani et al. (2021) described eleven sedimentary rock types (Table 1) grouped into four rock assemblages corresponding to specific depositional conditions (Fig. 5): i) Sand-Silt-Carbonate Assemblage - mixed platform environment with simultaneous siliciclastic and carbonate deposition; ii) Sand-Conglomerate Assemblage - shallow turbidite environment, related to mass flow controlled by the paleorelief of the source area; iii) Sand Assemblage - internal platform in backshore and foreshore conditions; iv) Silt-Clay Assemblage - external siliciclastic in an open-marine platform with primarily fine-grained deposition.

The Natividade Group reached lower greenschist facies. Locally, chloritoid and kyanite in quartzite indicate a higher metamorphic grade (Gorayeb et al., 1988; Saboia, 2009; Toscani et al., 2021).

According to Gorayeb et al. (1988), the folds in the Natividade Group are isoclinals with sub-vertical axial plans striking at NS-20NE. Near to Natividade City, the folds are asymmetrical, closed, or isoclinal, with axial plans with a dip angle of 60NW. There are two groups of faults, the first dextral transcurrent with direction from 50 to 60NE and sinistral ranging from 60NW to 35SW, related to E-W compression, and the second with N/S, NNE, and NNW normal faults related to later reactivation.

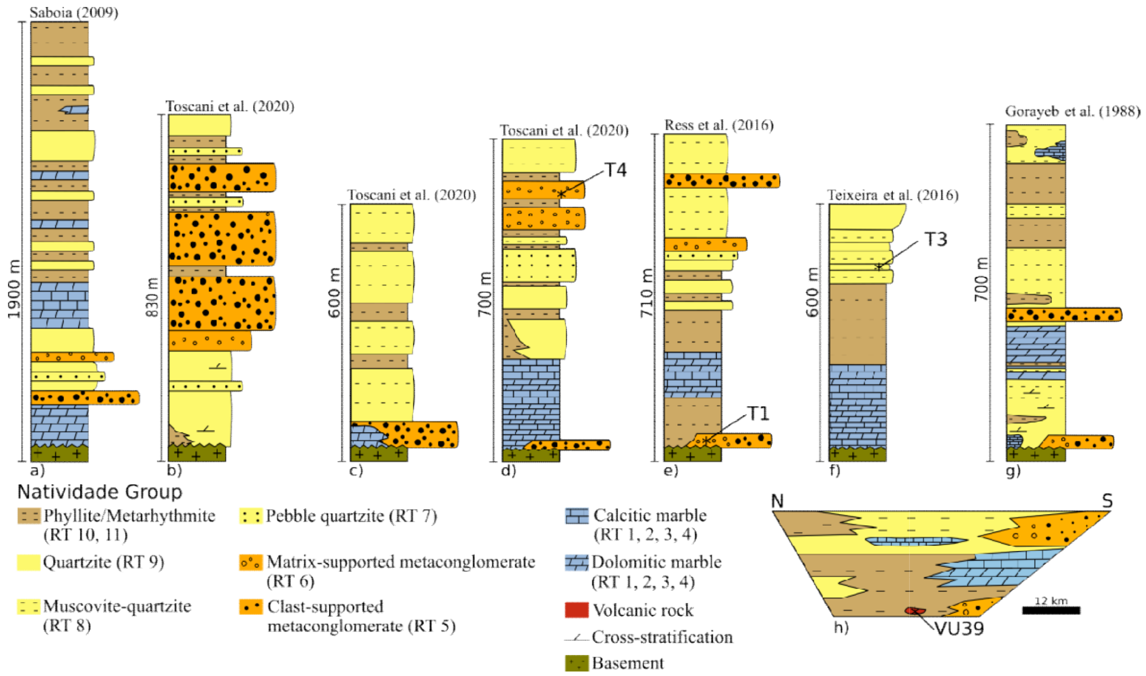


Fig. 4. Lithostratigraphic columns of different locations in the Natividade Group (modified from Saboia, 2009; Ress et al., 2016; Teixeira et al., 2016; Toscani et al., 2021). The letters "a" to "g" show the locations of the columns according to the map in Fig. 5. The letter "h" is the simplified stratigraphic chart of the Natividade Group in the area (Fig. 5). T1, T3, T4, and VU39 are samples for U/Pb analyses of the Natividade Group located in Fig. 6.

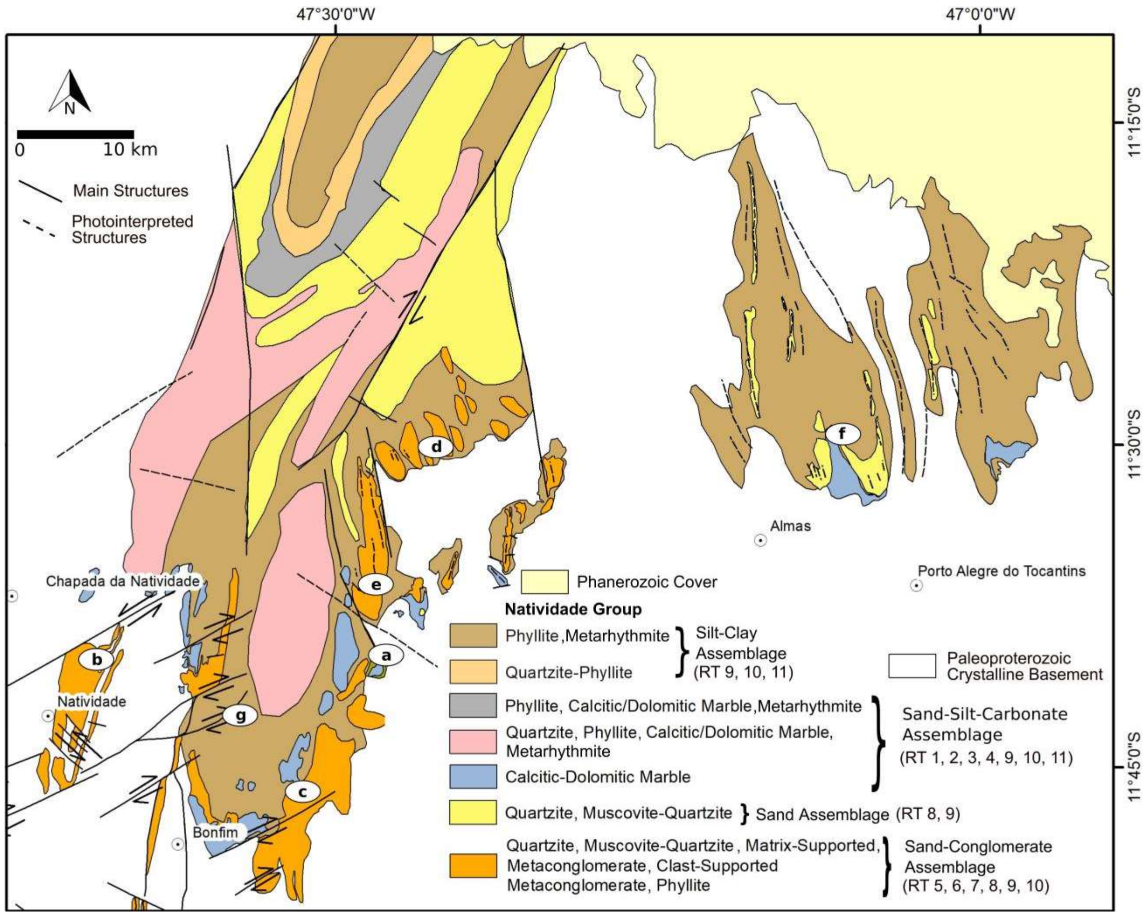


Fig. 5. Geological map of the Natividade Group (Toscani et al., 2021). This map is a result of compilation of field data, interpretation of SRTM images, and reviews of Gorayeb et al. (1988), Saboia (2009), and geological mapping work of the University of Brasília carried out in 2012 and 2016 (Oliveira et al., 2012; Franco et al., 2016; Morbeck et al., 2016; Ress et al., 2016; Teixeira et al., 2016). The letters "a" to "g" indicate the locations of the columns shown in Fig. 4.

Table 1. Rock types designation, correlative terms in the sedimentary nomenclature, and the associated depositional conditions (Toscani et al., 2021).

Rock type (RT)	Samples for U/Pb detrital zircon	Metamorphic Rock Types	Sedimentary Corresponding Rocks	Probable Depositional Conditions
1		Micritic calcitic/dolomitic marble	Carbonate mudstone	Shallow marine platform
2		Intraclastic calcitic/dolomitic marble	Grainstone and mudstone with micritic intraclasts	Shallow marine water over waves reworking
3		Stromatolitic marble	Stromatolite	Shallow to very shallow marine water
4		Calcitic/dolomitic marbles in assemblage with lamellar metabreccia	Lamellar breccia	Very shallow marine water with occasional subaerial exposure
5		Coarse to medium clast-supported metaconglomerate	Clast-supported conglomerate	Channelized tractive flow
6	T1, T4	Coarse matrix-supported metaconglomerate	Matrix-supported conglomerate	Mass flow in widespread conditions
7		Pebble quartzite	Sandstone with sparse quartz pebbles	Mass flow deposits
8		Micaceous quartzite	Fine-grained sandstone with a small amount of clay in the matrix	Inner platform (shoreface)
9	T3	Pure fine-grained quartzite	Pure fine-grained sandstone	Inner platform in foreshore conditions under wave influence
10		Phyllite	Lutite	Outer platform in shoreface zone conditions
11		Metarhythmite	Intercalation between lutite and sandstone (rhythmite)	Outer platform in lower shoreface conditions

Locally, in quartzite and marbles lenses, fractures and fan cleavage occur. In metaconglomerates, the orientation of pebbles is parallel to the fold axes. Finally, structures such as schistosity and slate cleavage are common in phyllites and metarhythmites (Gorayeb et al., 1988).

It is worth mentioning that the stratigraphic proposals are significantly different for each study site since the vertical and lateral variations of rock types are very sensitive due to the different depositional environments, facies architecture, and basement relief (Toscani et al., 2021). Some authors (Costa, 1984; Palermo, 1989; Gorayeb, 1996) report the occurrence of the Natividade Group further north, near the cities of Porto Nacional and Monte do Carmo. However, according to Saboia (2009) and Toscani et al. (2021), there are disputed interpretations and uncertainties regarding the presence of this group in that region. Thus, based on field data and the most recent literature, the present study does not consider those rocks belonging to the Natividade Group.

3. Material and methods

Fieldwork in the studied region started in July 2016, when the authors supervised the undergraduate Geology students from the University of Brasília. This work consisted of detailed geological mapping near Natividade and Almas cities. Subsequently, the present research group carried out three additional field surveys to collect samples for petrographic examination and U-Pb zircon geochronology.

Samples used for U–Pb geochronological analysis were firstly crushed, milled, and sieved. Non-magnetic heavy concentrates were separated using gravimetric procedures and a Frantz magnetic separator. Individual zircon grains were handpicked and mounted in epoxy resin for further polishing. Cathodoluminescence images were obtained with an FEI Quanta™ 450 Field Emission Scanning Electron Microscope (SEM). The procedures for dating the zircon grains were conducted at the geochronological laboratories of the University of Brasília (Samples T1, T3, T4) and the Federal University of Ouro Preto (Sample VU39) (Fig. 6) (Supplementary Material 1).

At the University of Brasília, the analyses were performed using an MC-ICP-MS Finnigan Neptune coupled to a New Wave 213 µm Nd-YAG laser. The U, Th, Pb isotopic ratios were normalized using a blank sample and the GJ-1 zircon primary standard (608.5 ± 1.5 Ma; Jackson et al., 2004). Laser ablation was performed in 25 µm spots (simple spot mode) with a 10 Hz frequency and a 2.71–3.99 J/cm2 intensity. Pulverized material was carried with a He (~0.40 L/min) and Ar (~1.00 L/min) flux. As a secondary standard, 91,500 zircon was used. For more details on methodology and equipment used, see Bühn et al. (2009).

At the Federal University of Ouro Preto, zircon grains were analyzed using a laser ablation sector field inductively coupled plasma-mass spectrometry (LA-SFICP-MS) system consisting of a CETAC 213 laser and Thermofinnigan Element 2 sector field ICP-MS. The laser spot size was set for 20 µm, and data were acquired in peak jumping mode during 20 s background measurement followed by 20 s sample ablation. Raw data were corrected for background signal and laser-induced elemental fractional. The GJ-1 and Plešovice zircon standards (337 ± 1 Ma; Sláma et al., 2008) were used to evaluate the accuracy and precision of the laser-ablation results. For more information, Santos et al. (2017) described the analytical methods and data treatment.

The decay constant of Jaffey et al. (1971) was adopted. Finally, the Chronus 1.4.3 (Oliveira, 2015) and Isoplot-Ex (Ludwig, 2003) softwares were used for data correction, age calculation, and preparation of histograms (Supplementary Material 1). The common-Pb correction was not necessary, and only grains with at least 90% concordant were used in T1, T3, and T4 samples. Common Pb was accounted by measured 204 Pb. Grains with high 204 Pb values (>1000 cps) were discarded. It is important to note that only five grains remained with more significant amounts of 204 Pb ranging from 364 to 860 cps (T1, T3, and T4 samples).

Bulk-rock geochemistry was performed in sample VU39. Major trace and rare-earth (REE) elements were analyzed at Actlabs-Canada, using the 4 Litho Actlabs package, and are listed in Supplementary Material 2. The GCDkit software was used for data handling and diagram plotting (Janousek et al., 2006).

High-resolution aero magnetometric data were processed and interpreted to better constraint the spatial relation between the crystalline basement and the deposition and source areas of the Natividade Group. The aeromagnetic survey used was conducted in 2006 by the Brazilian Geological Survey, entitled "Aerogeophysical Survey of Tocantins" (Aerogeophysica Latinoamerica - AGP-LA, 2006).

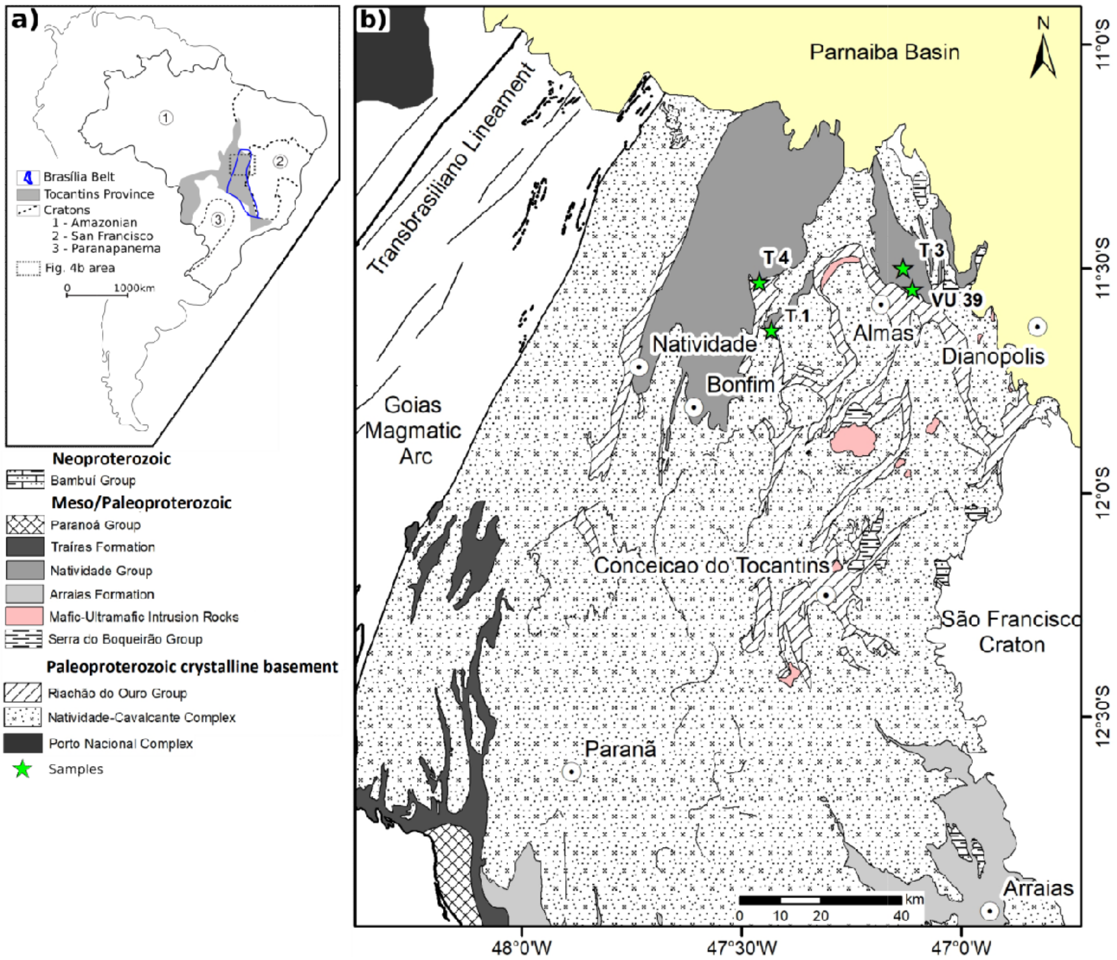


Fig. 6. Geological context maps showing: a) location of the study area in the South American regional context, b) location of sampling sites located in the geological map T1 (11°37′51.93″S; 47°25′15.62″W); T3 (11°29′45.35″S; 47°07′17.84″W); T4 (11°31′27.04″S; 47°26′51.99″W), VU39 (11°32′32.82″S; 47°05′48.92″W) (Schobbenhaus and Bellizzia, 2001; Assis et al., 2021).

The magnetometric data in nanotesla (nT) were processed in the Oasis MontajTM, version 9.6 (Geosoft, 2019). The following procedures were carried out: i) noise level analysis using the fourth difference filter (Geosoft, 2013); ii) removal of the International Geomagnetic Reference Field (IGRF) using the Oasis Montaj 9.6 software; iii) data interpolation in a regular mesh set to 1/4 of the spacing between flight lines (Reeves, 2005). The bidirectional method yielded the best results, providing a higher definition and spatial correlation of the sampled data. As a result, the Anomalous Magnetic Field (AMF) was obtained, as well as the Analytic Signal Amplitude (ASA) and first-order derivatives in the X, Y, and Z directions (Dx, Dy, and Dz).

4. Results

4.1 Samples for U/Pb detrital zircon geochronology of the Natividade Group

The first analyzed sample (T1) is a basal, polymictic, poorly sorted metaconglomerate, with angular clasts deposited in direct contact with the crystalline basement (Fig. 7a and b). According to Toscani et al. (2021), this rock is classified as rock type 6 (RT6), characterized as matrix-supported metaconglomerate with a matrix composed mainly of sericite, muscovite, and quartz (Fig. 7c and d). The nature of the lithic fragments in these rocks is varied, composed of quartzite, quartz veins, gneisses, volcanic and granitic rocks, indicating a mineralogically and texturally immature rock.

The second analyzed sample (T3) is a quartzite (Fig. 8) classified as fine-grained pure quartzite (RT9). According to Toscani et al. (2021), this rock is related to sand assemblage in the context of an internal platform in backshore and foreshore conditions.

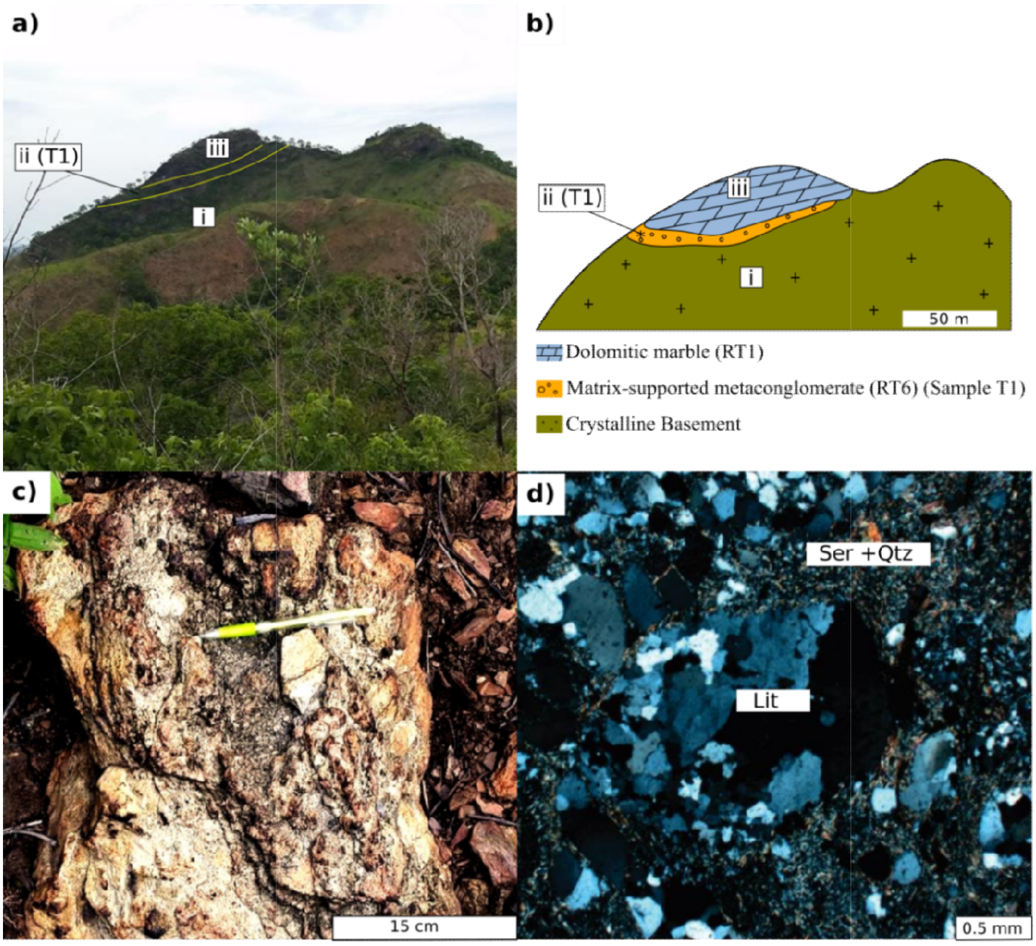


Fig. 7. Images showing: a) outcrop from bottom to top: (i) basement formed by tonalite and amphibolite, (ii) matrix-supported metaconglomerate (T1 sample), (iii) Dolomitic marble, b) schematic drawing showing the stratigraphic level where sample T1 was collected, c) detail of the matrix-supported metaconglomerate highlighting the clasts of quartzite and quartz veins in a matrix of quartz and sericite (T1 sample), d) thin section in cross-polarized light with lithic fragments of quartzite (Lit) immersed in a matrix rich in sericite and quartz (Ser + Qtz) (T1 sample) (Ress et al., 2016).

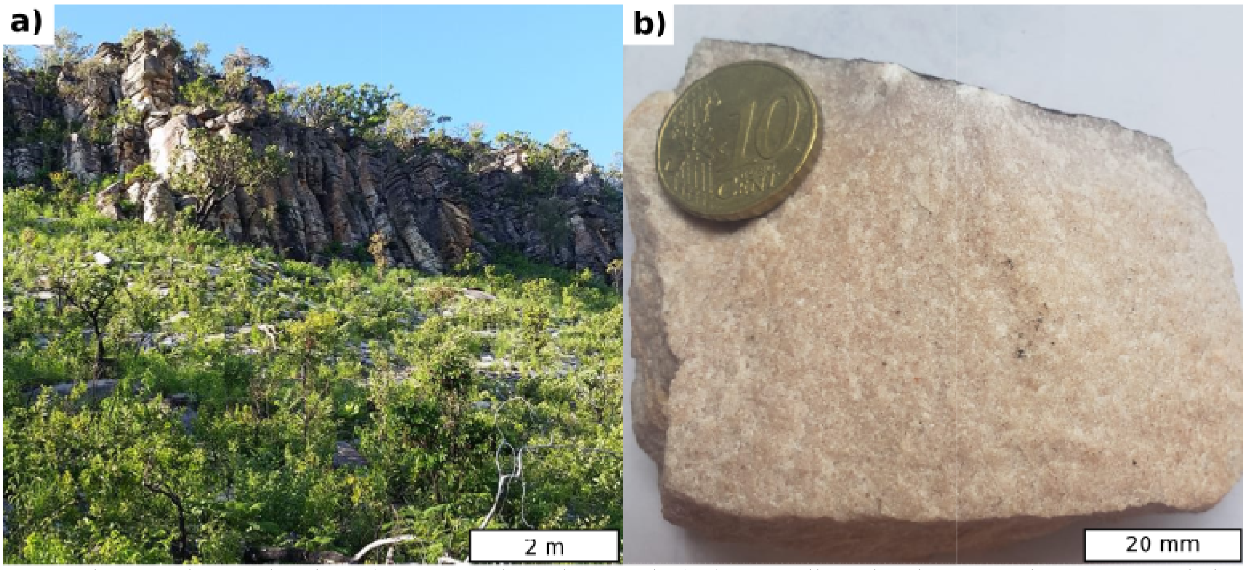


Fig. 8. Photographs are showing: a) outcrop where the sample (T3) was collected. It has more than 50 m consisting mainly of fine-grained quartzite, b) hand sample of the fine-grained quartzite (T3).

The T4 sample is a matrix-supported metaconglomerate (RT6) (Fig. 9). The lithic fragments are rounded to sub-angular, formed by pebbles of quartzite and quartz veins, varying from 1 to 10 cm. This rock is related to the typical shallow water turbidite section (mass flow slope deposition) of the Natividade Group (Sand-Conglomerate Assemblage) (Toscani et al., 2021).

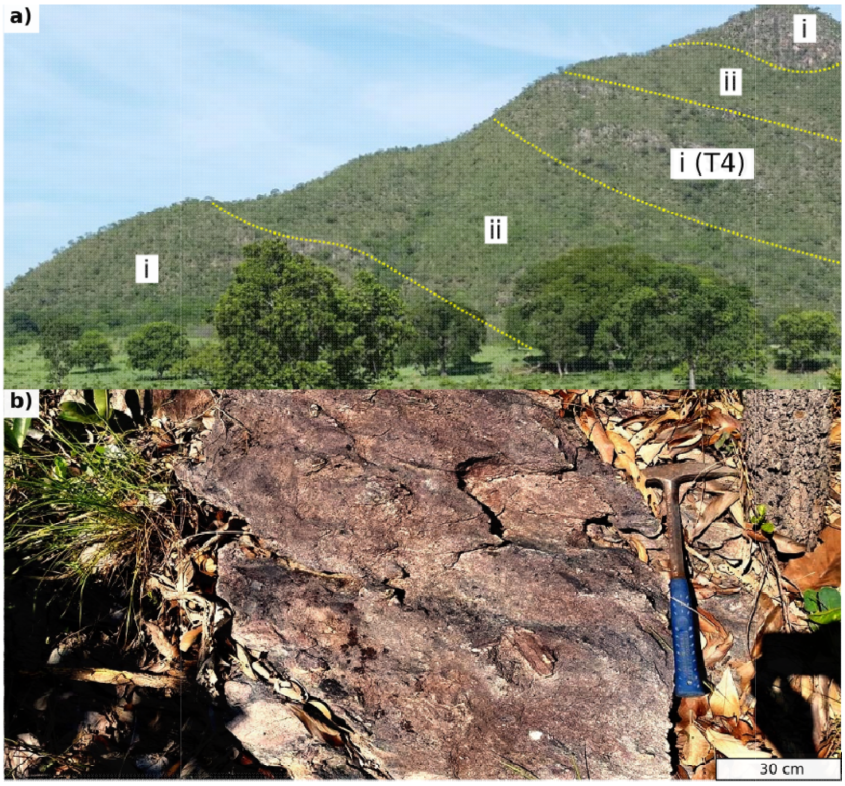


Fig. 9. Photographs showing: a) typical shallow water turbidite section where T4 sample was collected, i) predominance of metaconglomerate and quartzite, ii) predominance of phyllite (RT10) with minor metaconglomerate and quartzite; b) sample (T4) of matrix-supported metaconglomerate (RT6).

4.2 Sample for U/Pb magmatic zircon geochronology in the basal metavolcanic unit of the Natividade Group

The metavolcanic rocks at the base of the Natividade Group occur in moderately weathered outcrops located in a flat relief area near basement rocks (Fig. 10a and b). These metavolcanic rocks underwent low-grade metamorphism, deformation, and variable degree of alteration (Gorayeb et al., 1988). These processes thus make it difficult to determine its original composition.

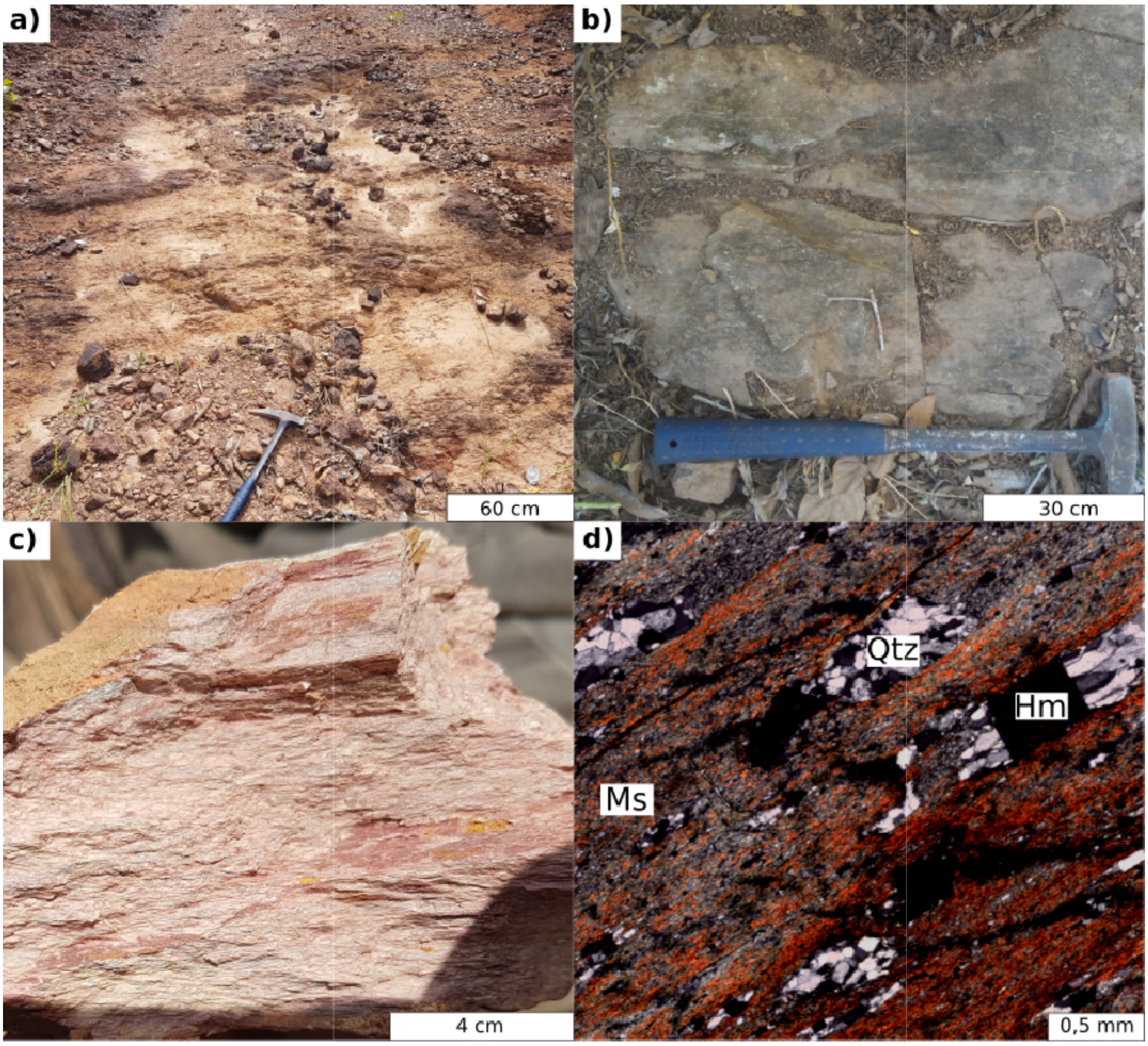


Fig. 10. Photographs showing: a) weathered outcrop of metavolcanic rock located in a flat relief area, b) detail of the metavolcanic rock outcrop, c) hand sample (VU39) rich in muscovite and quartz, d) thin section (XPL) (VU39) formed mainly by muscovite, quartz, chlorite, opaques (magnetite and hematite), and epidote.

The VU39 sample consists of a fine-grained with a prominent mylonitic foliation (S–C pairs), which protolith is interpreted as an acidic volcanic rock (Fig. 10c). In thin section, the rock has a mineralogical composition of muscovite (50%), quartz (30%), chlorite (10%), opaque minerals (magnetite and hematite; 5%), and epidote (5%). Muscovite and chlorite are preferentially oriented along the foliation in a lepidoblastic texture. In minor amounts, granoblastic lens-shaped quartz-rich domains and late magnetite porphyroblasts occur, indicating chlorite-quartz-muscovite schist. The geochemical data indicate an acidic composition. Another characteristic that corroborates with a volcanic origin is the presence of dominantly euhedral/subhedral shapes of the zircon crystals recovered from sample VU39 (Fig. 13).

4.3 Data analysis of detrital zircon (U/Pb) of the Natividade Group

Sample T1 presented a single Paleoarchean zircon of 3353 ± 19 Ma (Fig. 11a, A1). It has shown a considerable influence of sources from the limit between the Neoarchean and the early Siderian (2552 ± 40 to 2461 ± 29 Ma) (Fig. 11a, S1). There is a small concentration between 2450 ± 16 and 2443 ± 29 Ma of the late Siderian (Fig. 11a, S2) and some grains from the mid-Rhyacian (2211 ± 13 to 2179 ± 13 Ma) (Fig. 11a, R2). Finally, there is one single zircon of the late Rhyacian (Fig. 11a, R3) and one zircon of the early Statherian (1810 ± 25 Ma) (Fig. 11a, ST1).

Sample T3 yielded a small peak in the early Siderian, around 2479 ± 26 to 2466 ± 20 Ma (Fig. 11b, S1), and another small concentration of 2449 ± 19 to 2338 ± 27 Ma grains, relative to the late Siderian (Fig. 11b, S2). Also, it exhibited a large number of grains with mid-Rhyacian ages between 2256 ± 25 and 2191 ± 17 Ma (Fig. 11b, R2), and a small concentration of late Rhyacian grains of 2183 ± 18 to 2180 ± 55 Ma (Fig. 11b, R3). Finally, another major source of sediments is linked to the early Statherian, with zircon grains from 1816 ± 36 to 1743 ± 42 Ma (Fig. 11b, ST1).

Sample T4 shows small peaks in the early Siderian (Fig. 11c, S1) from 2505 ± 7 to 2488 ± 15 Ma; late Siderian (Fig. 11c, S2) at 2371 ± 12 Ma; and early Rhyacian (Fig. 11c, R1) from 2318 ± 29 to 2275 ± 16 Ma. There is a significant influence of mid-Rhyacian grains (Fig. 11c, R2) from 2225 ± 9 to 2187 ± 37 Ma and the presence of two late Rhyacian zircon grains (Fig. 11c, R3) of 2090 ± 66 to 2067 ± 9 Ma. Finally, there is a significant presence of sources from the early Statherian (Fig. 11c, ST1) from 1793 ± 13 to 1756 ± 17 Ma.

The GN sample data (Pb-evaporation method in detrital zircon) from Silva et al. (2005) presents similar ages as those obtained in the present study (Fig. 11d). It is a quartzite from the Natividade Group (RT9) with small to medium peaks in the early Siderian (Fig. 11d, S1) from 2476 ± 8 to 2457 ± 7 Ma and late Siderian (Fig. 11d, S2) from 2408 ± 5 to 2354 ± 15 Ma. It has a strong influence of sources from the Rhyacian: 2333 ± 89 to 2260 ± 98 Ma (Fig. 11d, R1); 2246 ± 144 to 2116 ± 28 Ma (Fig. 11d, R2); and 2079 ± 4 to 2069 ± 13 Ma (R3). Finally, early Statherian from 1781 ± 43 to 1779 ± 63 Ma (Fig. 11d, ST1) has a minor contribution.

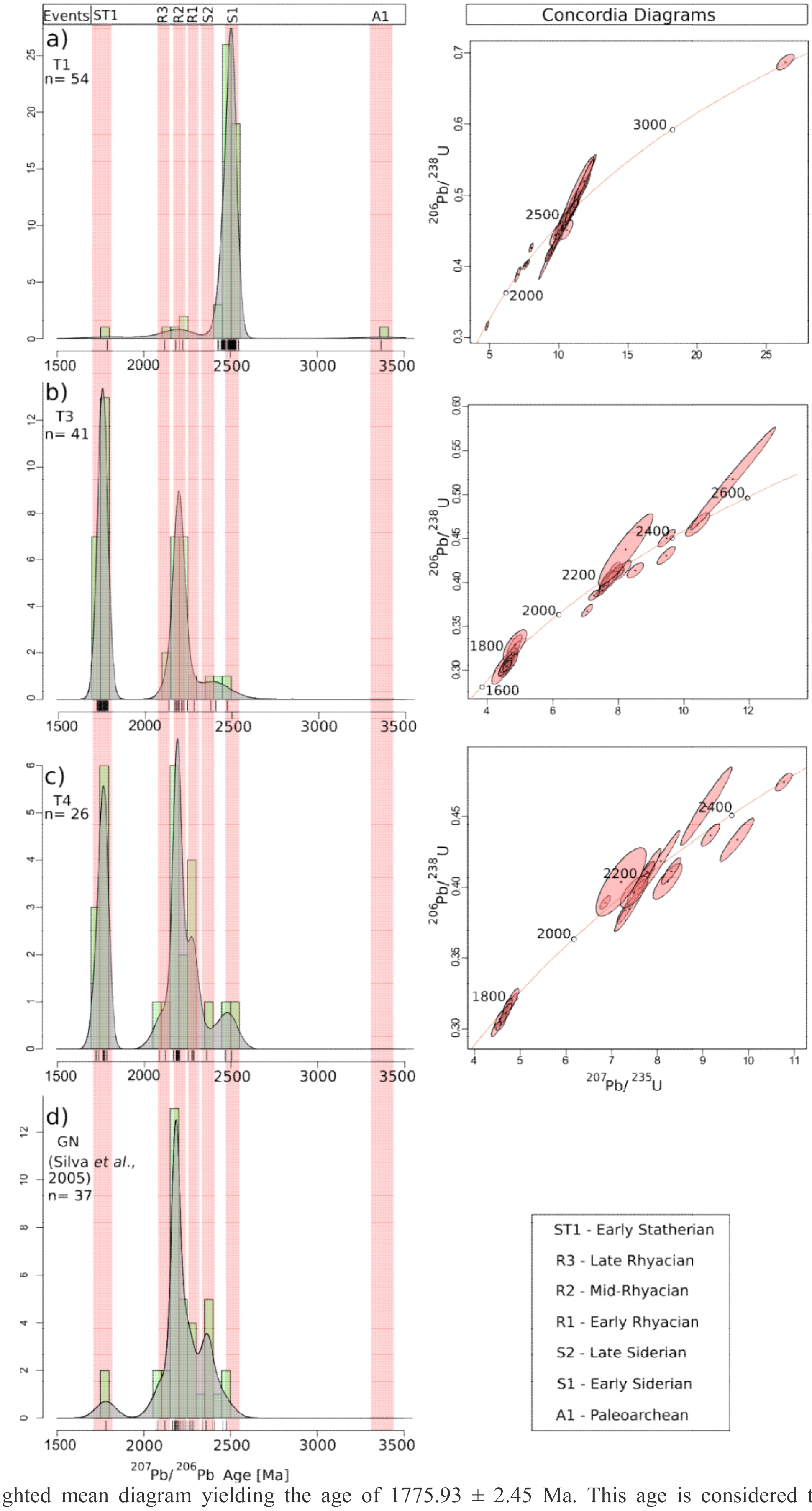


Fig. 11. Weighted mean diagram yielding the age of 1775.93 ± 2.45 Ma. This age is considered the maximum depositional age of the Natividade Group and was calculated from the thirty youngest zircon grains of samples T1, T3, and T4, in the Staherian interval.

Some authors consider the youngest single grain (YSG) to calculate the maximum depositional age (MDA) (Dickinson and Gehrels, 2009). In our study, it would provide the 1743 ± 42 Ma age (Sample T3). However, for calculating maximum depositional age (MDA), we opted to adopt the method of the youngest statistical population (Fig. 12). According to Coutts et al. (2019) and Sharman and Malkowski (2020), this conservative method can produce accurate MDAs and is less susceptible to contamination and Pb-loss issues, thus yielding ages that are less likely to be younger than the true depositional age.

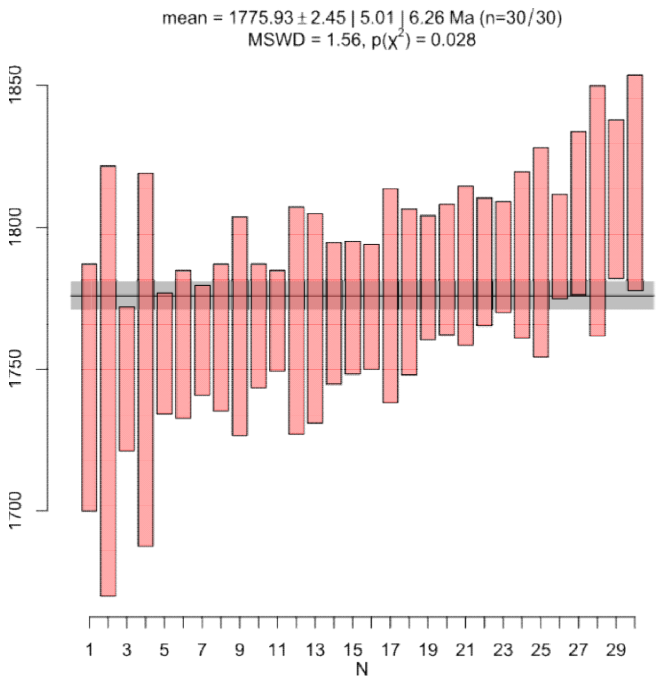


Fig. 12. Weighted mean diagram yielding the age of 1775.93 ± 2.45 Ma. This age is considered the maximum depositional age of the Natividade Group and was calculated from the thirty youngest zircon grains of samples T1, T3, and T4, in the Staherian interval.

Thus, to estimate the MDA of the Natividade Group, we selected the youngest clusters of detrital zircon grains from samples T1, T3, and T4 in the Staherian interval, ranging from 1743 ± 42 Ma to 1816 ± 36 Ma (Supplementary Material 1). The MDA was calculated from the weighted mean of the youngest population of these grains (at least 90% concordant) and yielded the 1775.93 ± 2.45 Ma age (30 grains; MSWD = 1.56; p (χ2) = 0.028) (Fig. 12).

4.4 Data Analysis of U/Pb zircon in the metavolcanic unit (Concordia diagram age)

In general, the analyzed zircon grains present euhedral to subhedral shapes, small size, and internal growth zoning, typical features of zircon found in volcanic rocks. In this sample (VU39), 12 grains were selected with 13 spot measurements analyzed (Fig. 13). The upper intercept of the Concordia diagram resulted in an early Statherian (ST1) age of 1824 ± 25 Ma (Fig. 14).

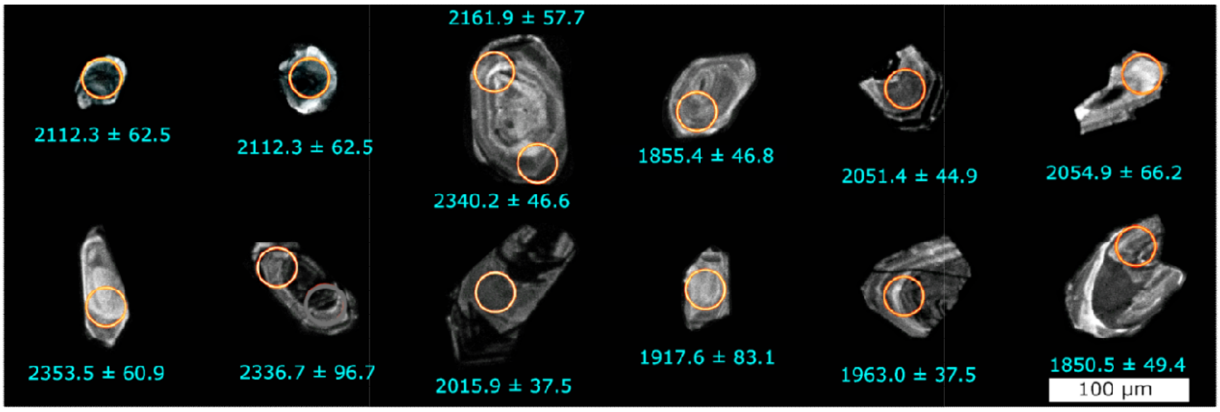


Fig. 13. Cathodoluminescence images (SEM) of representative zircon crystals from the VU39 sample.

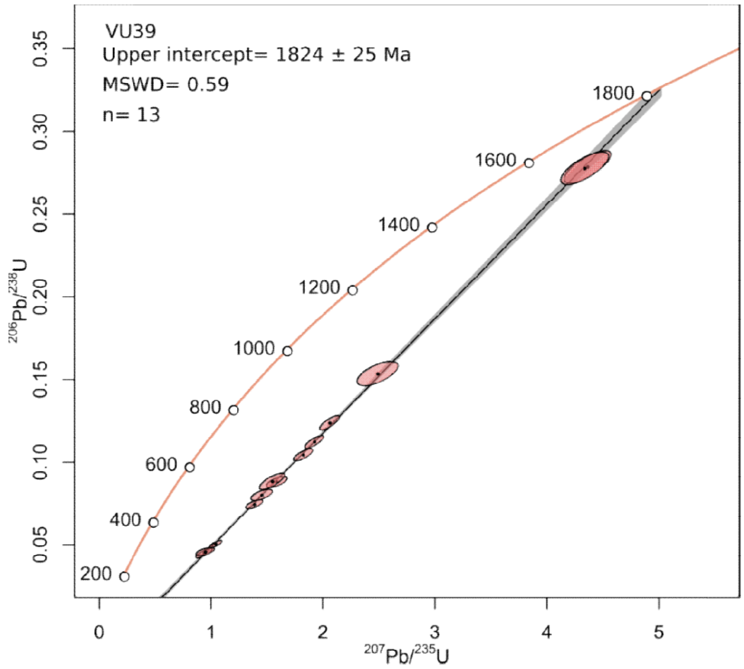


Fig. 14. Concordia diagram of VU39 sample, yielding an upper intercept age of 1824 ± 25 Ma, interpreted as the crystallization age of the acidic volcanic protolith.

4.5 Whole-rock geochemistry of the metavolcanic unit

In the study area, there is only a single outcrop of metavolcanic rock related to the Natividade Group (VU39 sample), and the whole-rock geochemical data of this sample is presented. The authors are aware that the geochemical data is statistically valuable when several samples are analyzed; thus, the results from the VU39 sample were used for comparison with 49 samples comprising acidic volcanic rocks from the Araí Intracontinental Rift analyzed by Silva (2020) (Supplementary Material 2).

Sample VU39 was classified as dacite on the Total Alkali-Silica (TAS) diagram (Le Bas et al., 1986), being possible to correlate it to the acidic rocks analyzed by Silva (2020), that plot mainly in the rhyolite field, but also with some samples plotting in the dacite field (Fig. 15).

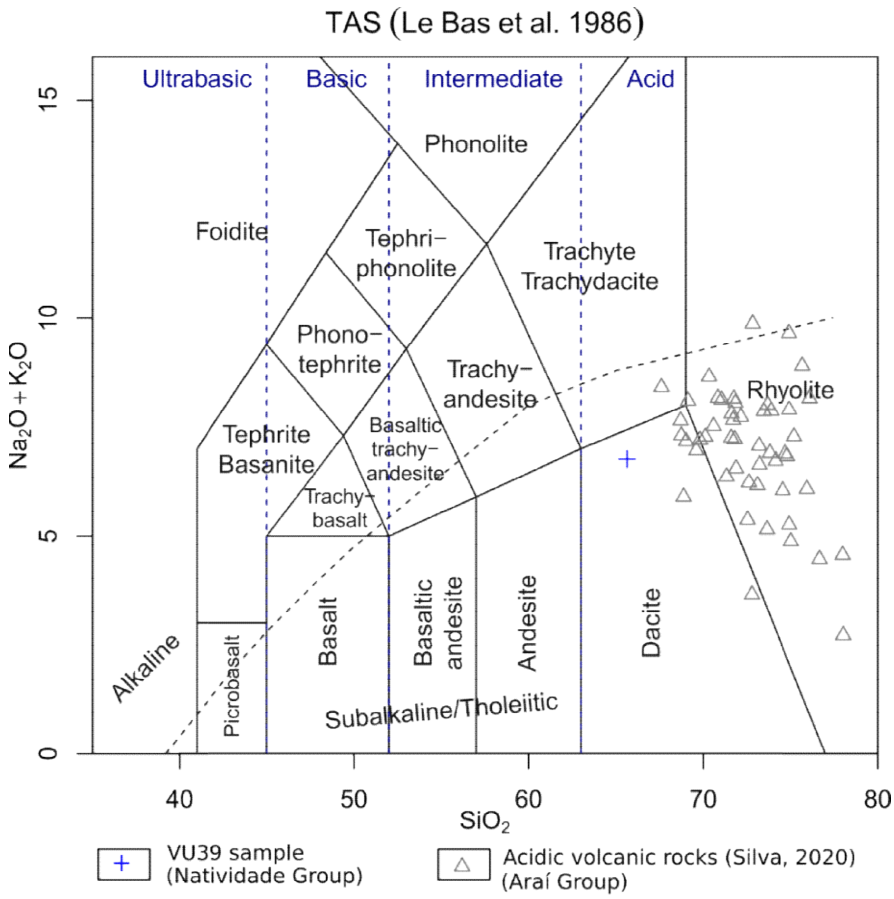


Fig. 15. Total Alkali-Silica (TAS) diagram (Le Bas et al., 1986) classifying the VU39 sample from the Natividade Group (this study) as dacite and other acidic rocks of the Araí Group (Silva, 2020) mostly as rhyolite, but also with some samples classified as dacite and trachydacite.

A chondrite-normalized REE diagram was built using the VU39 sample and the rocks analyzed by Silva (2020) (Fig. 16). In general, samples show enriched patterns of LREE and near-flat patterns of HREE. Most samples show moderate to strong negative anomalies of Eu, likely related to significant fractionation of plagioclase (Rollinson, 1993). The Eu/Eu* value of sample VU39 is 0.56, which can be correlated with most acidic samples described by Silva (2020), which present Eu/Eu* between 0.26 and 0.85. Two samples from Silva (2020) yielded a positive Eu anomaly with an Eu/Eu * ratio of 1.27 and 2.51.

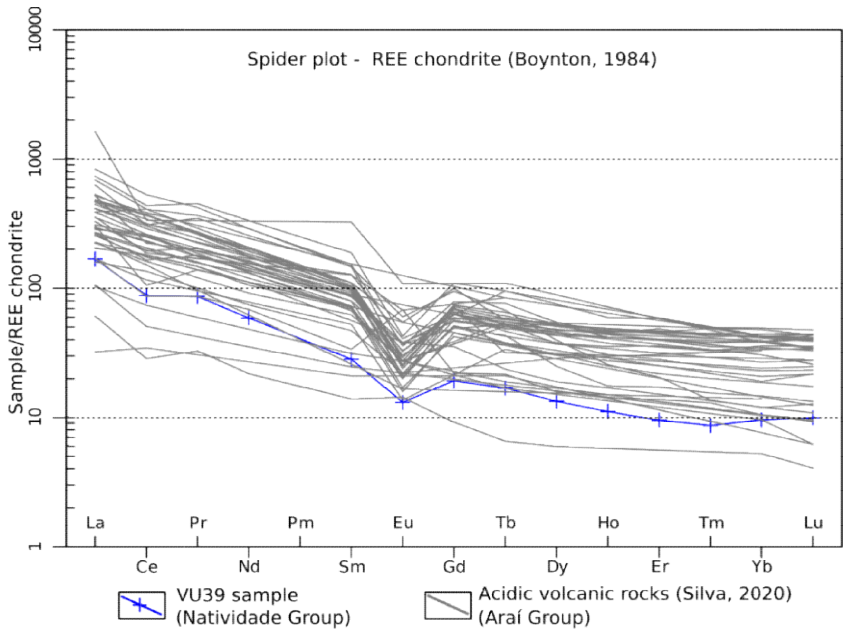


Fig. 16. Chondrite-normalized REE diagram (Boynton, 1984) with metavolcanic sample VU39 from the Natividade Group (this study) and acidic volcanic rocks of the Araí Group (Silva, 2020).

5. Discussions

Based on the presented data (Samples T1, T3, T4, and GN), the Natividade Group presents three primary sources of sediments (Fig. 11, Fig. 17). The age of the first source range from 2.55 to 2.34 Ga (S1 + S2) and can be related to the Almas Block (2.46 Ga), constituted mainly by the Ribeirão das Areias batholith. In addition, during this period, the Novo Jardim Terrane (S1 + S2) (2.52–2.37 Ga) might have contributed to this provenance (Martins-Ferreira et al., 2020).

Another significant contribution of zircon grains of 2.33 and 2.07 Ga (R1, R2, R3) is noted, which is probably mainly correlated with the Riachão do Ouro Group (2.24–2.20 Ga) (Almas Granite-Greenstone Terrane) (Martins-Ferreira et al., 2020). The Aurumina Terrane rocks (2.16–2.11 Ga; Cuadros et al., 2017) and Boqueirão Magmatic Arc (2.32–2.2 Ga; Martins-Ferreira et al., 2020) could also represent important source areas. According to Guadagnin and Chemale (2015), the Rhyacian age distribution is the most frequent age found in the provenance of the Paleoproterozoic to Mesoproterozoic basins in the São Francisco Craton.

Finally, there is an important zircon contribution ranging from 1.82 to 1.74 Ga, related to the Statherian magmatic event (ST1). This source can be compared to the Lower Espinhaço and Veadeiros supergroups basins that have their origin linked to magmatic activity that was coeval with the basin evolution or recycled from older stratigraphic units (Guadagnin and Chemale, 2015). In the context of the Natividade Basin, the primary sources related to this age must be the rift-related volcanic rocks at the base of the Arraias Formation, Araí Group, as well as the recycling of the acidic volcanic rocks observed at the bottom of the Natividade Group.

Fig. 17 shows a comparison between the ages of the Natividade, Traíras, and Serra da Mesa groups (Silva et al., 2005; Marques, 2009; Martins-Ferreira et al., 2018a). In this graph, it is possible to infer that the Natividade Group sources areas are more restricted and older than the Traíras and Serra da Mesa groups, once its source areas ages range mainly from 2.5 to 1.77 Ga and the other two units show ages from 3.3 to 1.5 Ga.

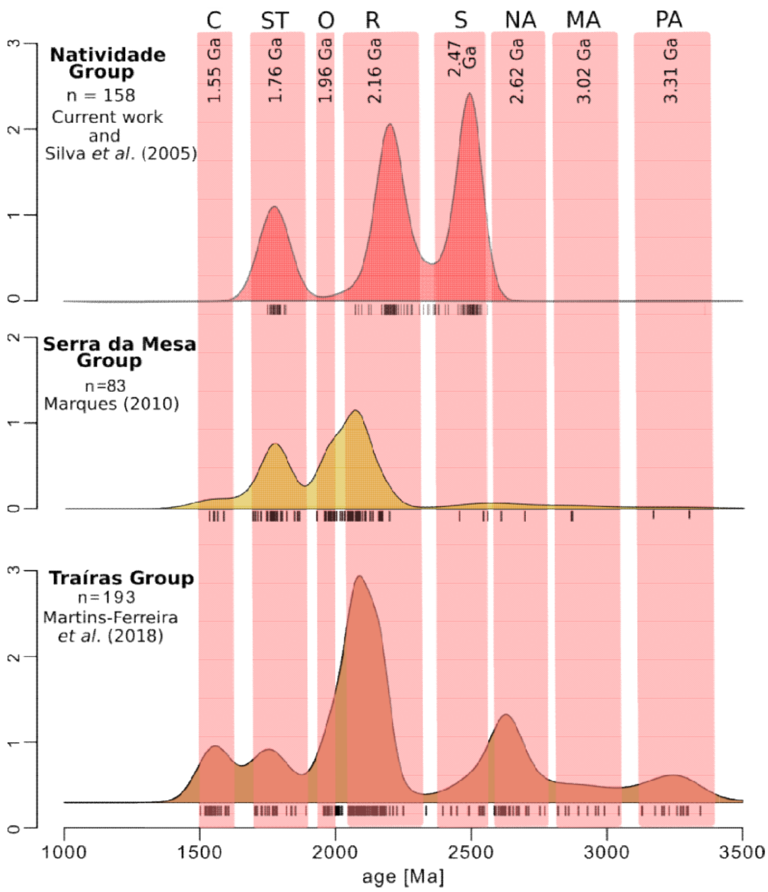


Fig. 17. Normalized age probability plot for detrital zircon U-Pb data comparing the Natividade Group (data from current work and Silva et al., 2005), and the Serra da Mesa and Traíras groups (data respectively from Marques, 2009 and Martins-Ferreira et al., 2018a). C: Calymmian; ST: Statherian; O: Orosirian; R: Rhyacian; S: Siderian; NA: Neoarchean; MA: Mesoarchean; PA: Paleoarchean.

It is known that the maximum deposition age for the Natividade Group of 1775.93 ± 2.45 Ma is not sufficient to robustly define the period of deposition. However, this data, in conjunction with the age of the metavolcanic rock of 1824 ± 25 Ma presented in this work, could corroborate the interpretation of a late deposition compared to the Araí Group, which is interpreted as a rift-sag basin of 1771 Ma (Pimentel et al., 1991; Silva, 2020).

Unlike the Natividade Group, the Araí Group is comprised of deposits with continental characteristics, including the Água Morna and Arraias Formations. The Água Morna Formation was deposited in continental conditions by braided rivers dominated by sands (pre-rift phase) (Tanizaki et al., 2015). On the other hand, the Arraias Formation represents depositional systems controlled by normal faults, including alluvial fans, fluvial, eolian, and lake environments, accumulated during the syn-rift phase of the Araí Basin. This formation was interspersed with acidic and basic volcanic rocks, marking the typical bimodal volcanism of rift-type basins (Pimentel et al., 1991; Tanizaki et al., 2015). A precise age yielded by the U/Pb method in zircon crystals of the acidic volcanic samples (rhyolite) indicates deposition of the Arraias Formation at 1.78 Ga (Pimentel et al., 1991).

In the Natividade Group, continental environment sedimentation has not been observed. This unit is characterized as a basin controlled by thermo-flexural subsidence associated with a mixed siliciclastic-carbonatic marine platform in which shallow-water turbidite deposits co-occur (Toscani et al., 2021 and references therein). Also, there was just one preserved metavolcanic rock outcrop at the base of the succession. This data can lead to two, not mutually exclusive, interpretations: i) small volcanism activity due to crustal stretching conditions, and ii) high erosion level of the previous volcanic rocks deposited directly over the Paleoproterozoic basement.

The Araí rift was classified as a passive rift by Martins-Ferreira et al. (2018b). Tensional stresses caused by passive rifting in the continental lithosphere tend to collapse it, allowing hot mantle rocks to penetrate the lithosphere. Volcanic activity is only a secondary process (Allen and Allen, 2005; McKenzie, 1978). Compared to other examples of paleorifts, volcanic activity is scarce in the Araí, with maximum thicknesses of 100 m for acidic volcanism and a rare occurrence of basalts (Alvarenga et al., 2007; Martins-Ferreira et al., 2018b).

The regional observations show strong evidence that the main volcanic centers were located in the southern region (Goiás State), more specifically in the Cavalcante, Teresina de Goiás, and Monte Alegre de Goiás regions (Fig. 2). Northward, for example, in the Arraias region (southeast Tocantins State), the volcanic activity decreases. The bimodal volcanic occurrences (Pimentel et al., 1991) are directly associated with the crustal thinning due to the plate stretching and asthenosphere uplifting so that the volcanic rock volume can be interpreted to be directly related to the intensity of tectonic activity.

Since the volcanic layer's thickness and frequency decrease from south to north, it is reasonable to interpret that crustal stretching also diminishes northwards. Plate stretching is the primary process responsible for mechanic subsidence, which will control the continental depositional environments, mainly the alluvial fan sedimentation (Tanizaki et al., 2015; Martins-Ferreira et al., 2018b).

Geochemical data of the metavolcanic rock sample (VU39) from the Natividade Group share similar patterns of major elements and REE when compared to the acidic rocks of the Araí Group (Silva, 2020). These data corroborate the suggestion that the volcanism of the Natividade

Group may have a similar origin with that of the Araí Group, which is characterized by an extensional environment.

In this way, the Natividade Group is interpreted as a sag-type basin, derived from the isostatic rebalance after the evolution of the Araí rift basin, located to the south (Costa et al., 1976; Silva et al., 2005; Saboia, 2009; Marques, 2009; Toscani et al., 2021).

Although the Araí rift influenced the filling of the Natividade Group basin; another major factor for sedimentary control was the crystalline basement paleogeography, which allowed the sedimentation of a lateral assemblage of depositional environments of the mixed platform, internal and external siliciclastic platform, and shallow water turbidite deposits (Toscani et al., 2021).

According to Toscani et al. (2021), in the southern, most area of occurrence of the Natividade Group, the paleorelief would most likely present a higher topography, allowing the formation of gravitational flows towards the north. In this same region, the seawater depth would be shallower, favoring carbonate precipitation, especially directly over crystalline basement highs, as observed in the fieldwork. To the north, the sea would deepen, and the basement would be more eroded, favoring the deposition of fine-grained sediments. Besides the paleorelief indication, it is reasonable to state that most of the sedimentary sources filing the Natividade Basin came from the south since the detrital zircon archive shows ages very similar to igneous units outcropping in the south, namely the Almas Block (2.46 Ga) (Ribeirão das Areias batholith), the Almas Granite-Greenstone Terrane (2.24–2.20 Ga), and the volcanic rocks of the Araí Group (1771 Ga) (Pimentel et al., 1991).

This is reinforced by the presence of high magnetic response (Fig. 16) near the city of Conceição do Tocantins, which separates the Natividade Group from the Araí and Traíras Groups. This high magnetic response corresponds to a high paleorelief of the crystalline basement (Almas Block) that was the most important source area for the Natividade Basin.

According to Guadagnin and Chemale (2015), who studied the Paleo-Mesoproterozoic cratonic basins in the São Francisco Craton, the Natividade Group fits into the Lower Megasequence (Statherian interval), which has mainly Statherian and Rhyacian ages. Statherian sources indicate that they are derived from the Transamazonian/Eburnean orogenic units (Congo-São Francisco paleoplate) and that their magmatic activity is coeval with basin deposition. The Rhyacian age distribution is related to the erosion of the Transamazonian/Eburnean sources or recycled terranes (Guadagnin and Chemale, 2015).

The analysis of source ages in the Veadeiros Supergroup shows that the Araí Group presents the youngest ages related to the Rhyacian (Marques, 2009; Guadagnin and Chemale,

2015) and that the Traíras (1.54 Ga) and Serra da Mesa (1.55 Ga) groups contain younger ages related to the Calymmian period (Martins-Ferreira et al., 2018a; Marques, 2009).

The joint analysis of the previous data demonstrates that the Natividade Group, with basal metavolcanic rocks of 1.82 Ga, maximum deposition detrital zircon age of 1.78 Ga, and absence of younger Calymmian detrital zircons, must be stratigraphically positioned over the Araí Group and below the Traíras and Serra da Mesa Groups.

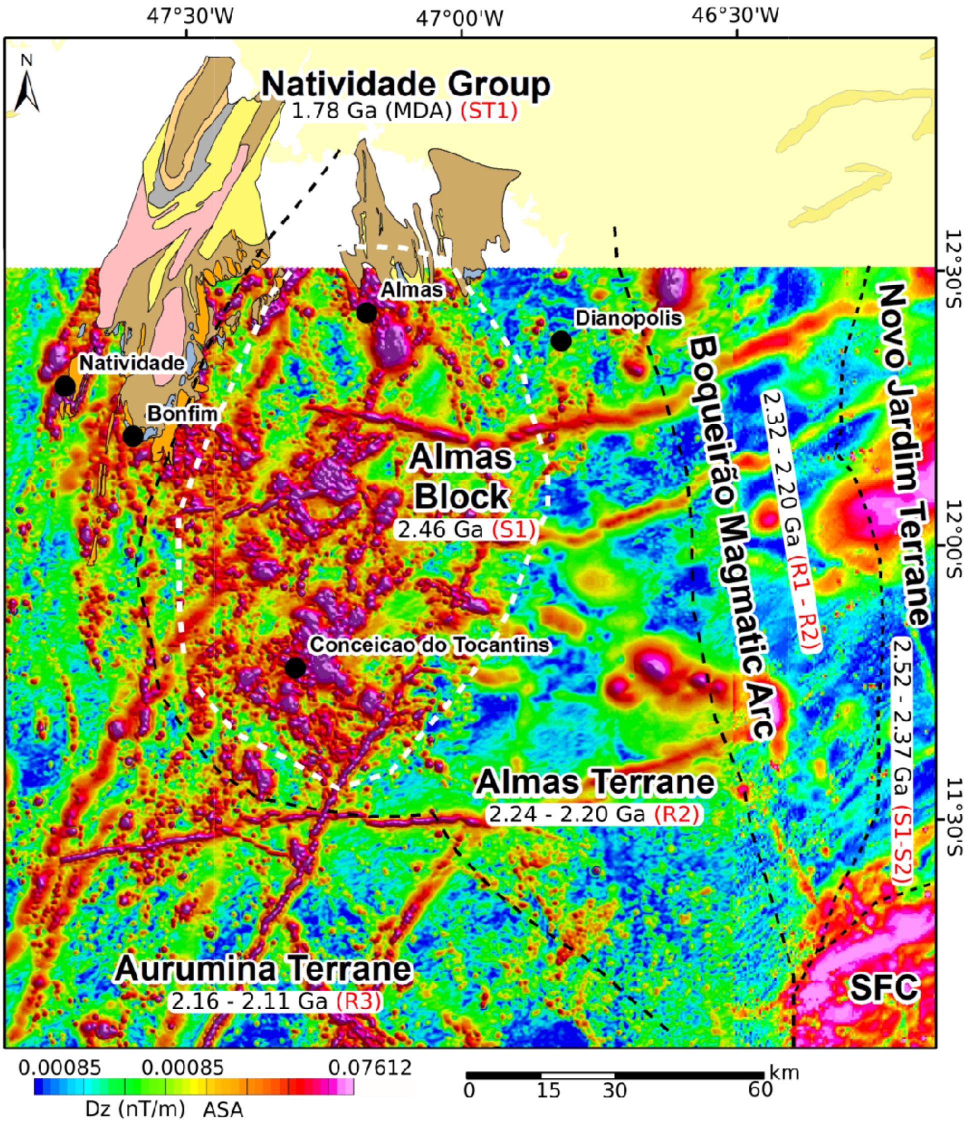


Fig. 18. Analytic signal amplitude (ASA) showing the spatial distribution of the high crystalline basement (Almas Block), relative to the Natividade Group outcrop area (overlay, lithology legend in Fig. 5) as well as the main cities and terranes (Modified from Sousa et al., 2016; Toscani et al., 2021; Martins-Ferreira et al., 2020). SFC: São Francisco Craton.

5.1 Geotectonic model

Although the Natividade Group is limited by normal or reverse faults with its basement, the Almas Bock, mainly the Conceição do Tocantins region, is considered as a high paleorelief region due to the following facts: i) In this region, there is no occurrence of the Veadeiros Supergroup sediments (even from the Araí or the Natividade groups); ii) In this region there are many quartzite layers (Água Suja Sequence) and several granitic units (as the Príncipe Intrusion) which are resistant to denudation processes (some of these rocks are ridge areas up to the present days); iii) The deposition of the shallow water turbidite present at the Natividade Group needed elevated source areas to control the sedimentation (Toscani et al., 2021); iv) The predominance of carbonates and mass flow deposits in the southern portion of Natividade Group, near to Almas Block, suggests a lower depth of the sea to the south of the basin. Further north, the predominance of fine-grained terrigenous sediments and the absence of flow deposits suggest a deeper basin (Toscani et al., 2021); v) It is common in rift-sag environments the preservation of elevated blocks as isostatic compensation mechanism; vi) Contrasting geophysical features of this area in comparison to the south and north regions (Fig. 18).

After the geotectonic models proposed by Marques (2009) and Martins-Ferreira et al. (2020) for the evolution of the Paleoproterozoic accretionary events in the western margin of the São Francisco Craton, this study allowed to add valuable constraints regarding the Natividade Basin (Fig. 19, Fig. 20), as follows:

i) The region was tectonically stable since the Rhyacian, after the Almas-Natividade Terrane amalgamation (Riachão do Ouro, Córrego do Paiol, Morro do Carneiro and Água Suja sequences stabilization);

ii) Following, in the Statherian (~ 1.78 Ga), the whole plate was exposed to crustal extension. This extension initiates in the south and decreases to the north, which explains the faults nucleation and maximum volcanic activity in the south and fast reduction northwards, in the direction of the Natividade Basin (Fig. 19). This crustal behavior explains why the area has experienced volcanism, but continental sedimentation ceased. Crustal thinning allowed magma to ascend in the south, but the extension was not enough to effectively break up the plate in the northern portion.

iii) After the volcanic pulses, the Natividade Basin was submitted to thermo-flexural subsidence that was responsible for creating the depositional space in which a complex environment association would develop, forming the Natividade Group. The zircon grains distribution pattern shows an important contribution from the Almas-Natividade Terrane (Almas Block), which is interpreted as the paleogeographic control of the high relief area that separated the Araí basin from the Natividade Basin.

This geotectonic model considers an erosive surface between the volcanic layers and the marine sedimentary deposits. However, this surface is not well documented in the field. Nonetheless, it is still corroborated by the small volume of acidic metavolcanic rocks and the nature of the contact of the Natividade Group succession and the crystalline basement.

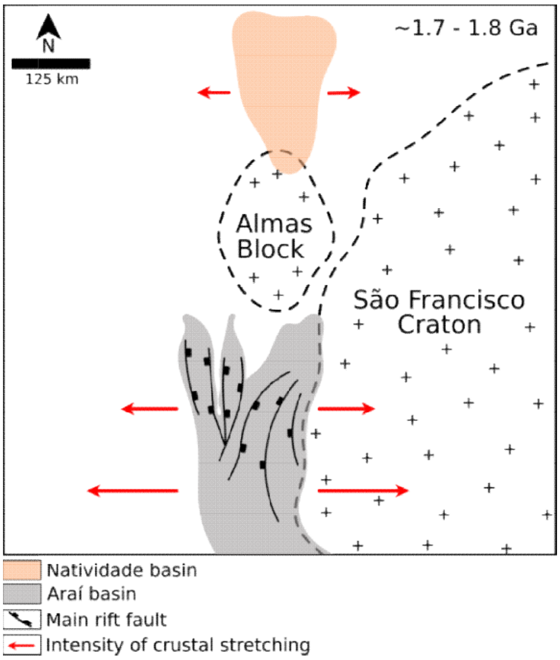


Fig. 19. Local geotectonic model at approximately 1.7 Ga, during the deposition of the Natividade and Araí groups (modified from Martins-Ferreira et al., 2018b). Notice that the normal faults (and consequently mechanic subsidence) are only present in the south, where the Araí rift has evolved. The Natividade Basin was developed exclusively by thermo-flexural subsidence.

The paleogeography of the crystalline basement was fundamental to the deposition control of the Natividade Group (Toscani et al., 2021). It was mainly related to the high paleorelief of the Almas Block (Fig. 18, Fig. 19, and Fig. 20) that allowed the formation of gravitational flows in the southeast and the deposition of siliciclastic and carbonatic sediments directly over the crystalline basement.

6. Conclusions

The data presented and analyzed in this work support the following conclusions:

- The Natividade Basin evolved in a time span between the Araí and the Traíras/Serra da Mesa groups. The volcanism pulses in the Natividade Group were just recorded locally in its basal sequence and had geochemical characteristics consistent with the acidic volcanic rocks of the Araí Group described by Silva (2020);
- In the Natividade Group, the metavolcanic rock dated at 1824 ± 25 Ma in conjunction with the absence of zircon grains younger than 1.77 Ga, based on our new detrital zircon U–Pb data, suggests that this group is not coeval with the Traíras and Serra da Mesa groups;
- The Natividade Basin was submitted to thermo-flexural subsidence, while the Araí Basin was mainly controlled by mechanic subsidence and the Traíras/Serra da Mesa groups deposition space was created by flexural subsidence at least 200 Ma later;

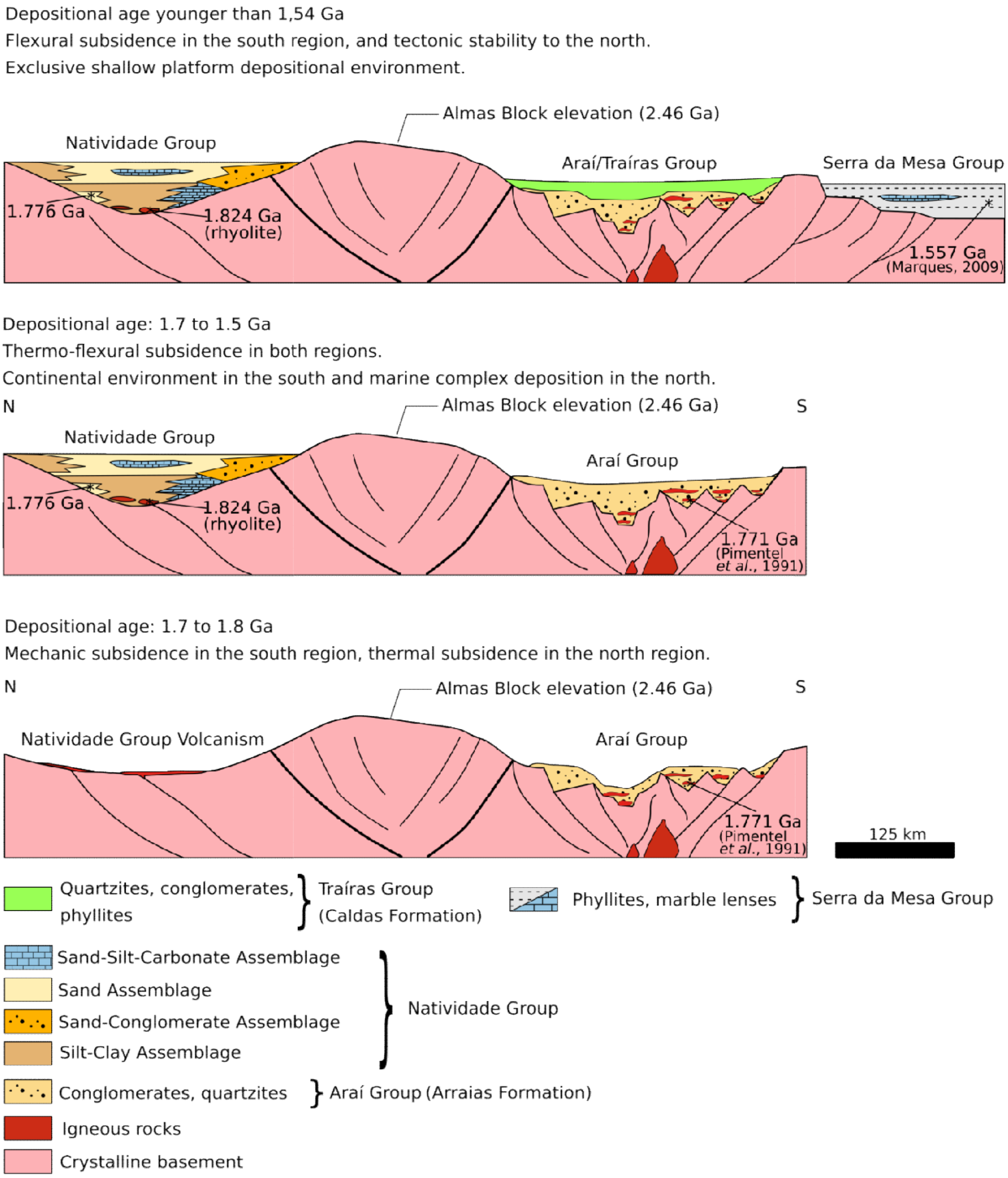


Fig. 20. Depositional model of the Natividade, Araí, Traíras, and Serra da Mesa groups (modified from Marques, 2009; Martins-Ferreira et al., 2018b). Note that the Serra da Mesa Group outcrops further to the west and would not be crossed strictly with an N–S profile.

- The source areas for the Natividade Group are more restricted than the areas that supplied sediments for the Araí, Traíras, and Serra da Mesa groups. This assertion is corroborated by detrital zircon provenance and by the inference regarding the paleorelief that controlled the Natividade Basin infilling; and
- The contrasting depositional environments observed in the Natividade Group, compared to the other Paleo-Mesoproterozoic rift-sag basins at Central Brazil, are explained by the subsidence and tectonic source areas, as well as regional and local paleorelief patterns.

7. Acknowledgments

We would like to thank the Brazilian National Council for Scientific and Technological Development (CNPq) for funding the fieldwork and the University of Brasilia (Geosciences Institute), and the Federal University of Ouro Preto for equipment and laboratories. Also, the journal reviewers whose contribution resulted in a significant improvement in the final manuscript.

8. References

Aerogeophysica Latinoamerica - AGP-LA. 2006. Levantamento Aerogeofísico do Estado do Tocantins. Programa Geologia do Brasil - CPRM. Relatório Final do Levantamento e Processamento dos Dados Magnetométricos e Gamaespectrométricos, 478p.

Alkmim F.F. 2004. O que faz de um cráton um cráton? O Cráton do São Francisco e as revelações almeidianas ao delimita-lo. In: Mantesso-Neto V., Bartorelli A., Carneiro C.D.R., Brito Neves B.B. (eds.), Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida. Brasil, Beca, 17-35p.

Alkmim, F.F. & Martins Neto, M.A. 2012. Proterozoic first order sedimentary sequences of the São Francisco Craton, eastern Brazil. Marine and Petroleum Geology, 33(1):127-139. DOI: https://doi.org/10.1016/j.marpetgeo.2011.08.011.

Allen, P.A. & Allen, J.R. 2005. Basin analysis. Oxford, Blackwell, 549p.

Almeida, F.F.M. 1977. O Cráton do São Francisco. Revista Brasileira de Geociências, 7(4):349-364.

Almeida, F.F.M., Hasui, Y., Brito Neves, B.B., Fuck, R.A. 1981. Brazilian structural provinces: an introduction. Earth-Science Reviews, 17(1):1-29. DOI: 10.1016/0012-8252(81)90003-9

Alvarenga, C.J.S., Dardenne, M.A., Botelho, N.F., Lima, O.N.B., Machado, M.A., Almeida, T. 2007. Nota Explicativa das folhas SD.23-V-C-III (Monte alegre de Goiás), SD.23-VC-V (Cavalcante), SD.23-V-C-VI (Nova Roma). CPRM, Brasília, 65p.

Assis, C.R.F., Moura, C.A.V., Milhomem Neto, J.M., Gorayeb, P.S.S., Dias, A.N.C. 2021. Zircon U-Pb geochronology and Lu-Hf isotope systematics of the Araguaia Belt basement Rocks: Evidence of links with the southeastern Amazonian Craton, Brazil. Precambrian Research, 356:106090. DOI: https://doi.org/10.1016/j.precamres.2020.106090

Babinski, M., Pedreira, A.J., Brito Neves, B.B., Van Schmus, W.R. 1999. Contribuição à geocronologia da Chapada Diamantina. In: VII Simpósio Nacional de Estudos Tectônicos. Lençóis, Brazil, Anais, 2:118-120.

Babinski, M., Van Schmus, W.R., Chemale, F., Brito Neves, B.B., Rocha, A.J.D. 1993. Idade isocrônica Pb/Pb em rochas carbonáticas da Formação Caboclo, em Morro do Chapéu. In: Pedreira, A.J., Misi, A., Dominguez, J.M.L. (Eds.), II Simpósio sobre o Craton do São Francisco. Brazilian Geological Society, Salvador, 160-163p.

Barbosa, O., Baptista, M.B., Braun, O.P., Dyer, R.G., Cotta, J.C. 1969. Geologia e inventário dos recursos minerais do Projeto Brasília. Rio de Janeiro, PROSPEC/DNPM, 225p.

Borges, C.C.A., Toledo, C.L.B., Silva, A.M., Chemale, F., Santos, B.A., Figueiredo, F.L., Zacchi, E.N.P. 2021. Unraveling a hidden Rhyacian magmatic arc through provenance of metasedimentary rocks of the Crixás greenstone belt, Central Brazil, Precambrian Research, 353:106022. DOI: https://doi.org/10.1016/j.precamres.2020.106022

Boynton, W.V. 1984. Cosmochemistry of the rare earth elements: meteorite studies. In: Henderson, P. (eds) Rare Earth Element Geochemistry. Elsevier, Amsterdam, 63-114p.

Bühn, B., Pimentel, M.M., Matteini, M., Dantas, E.L. 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). An. Acad. Bras. Cienc. 81:1-16. DOI: https://doi.org/10.1590/S0001-37652009000100011

Campos, J.E.G., Dardenne, M.A., Freitas-Silva, F.H., Martins-Ferreira, M.A.C. 2013. Geologia do Grupo Paranoá na porção externa da Faixa Brasília. Revista Brasileira de Geociências 43:461-476. DOI: 10.5327/Z2317-48892013000300004.

Campos, J.E.G., Martins Ferreira, M.A.C, Moura, F.G., Chemale, Jr.F. 2021. Discovery of Precambrian deep-water turbidites and submarine volcanism in the Brasilia Belt, central Brazil: The Quilombo Formation.. Journal of South American Earth Sciences. 108, 1–11. doi:https://doi.org/10.1016/j.jsames.2021.103226.

Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X. 2013. Updated. The ICS International Chronostratigraphic Chart. Episodes 36:199-204.

Cordeiro, P.F.O., de Oliveira, C.G., 2017. The Goiás Massif: implications for a pre-Columbia 2.2–2.0 Ga continent-wide amalgamation cycle in central Brazil. Precambrian Res. 298, 403–420.

Correia Filho, F. C. L., & Sá, A. M. 1980. Projeto Natividade. Relatório Final. Goiânia, DNPM/CPRM, 6:256p.

Costa, A.F.O., Danderfer, A., Bersan, S.M. 2018. Record of a Statherian rift-sag basin in the Central Espinhaço Range: Facies characterization and geochronology. Journal of South American Earth Sciences, 82:311-328. DOI: https://doi.org/10.1016/j.jsames.2017.10.014

Costa, J. B. S. 1984. Aspectos litoestruturais e evolução crustal da região centro-norte de Goiás.Tese de Doutorado. Centro de Geociências da Universidade Federal do Pará, Belém, 210p.

Costa, L.A.M., Portela, A.C., Nilson, A.A., Vale, C.R.O., Marchetto, C.L.M., Santos, E.L., Meneghesso, G., Inda, H.A.V., Sterna, R., Marchetto, P., Baptista, M.B., Fratin, O., Mosmann, R., Oliveira, T.F.D., Silva, W.E. 1976. Projeto Natividade Área VI. Projeto Leste do Tocantins, Oeste do Rio São Francisco. Conv. DNPM/CPRM/PROPESC. (relatório final), Rio de Janeiro, 151p.

Coutts, D.S., Mattews, W.A., Hubbard, S.M. 2019. Assessment of widely used methods to derive depositional ages from detrital zircon populations. Geosci. Front. 10:1421-1435. Doi: https://doi.org/10.1016/j.gsf.2018.11.002

Cruz, E.L.C.C. 2001. A gênese e o contexto tectônico da mina Córrego Paiol, Terreno Almas-Conceição: um depósito de ouro hospedado em anfibolito do embasamento da Faixa de Dobramento Brasília. Doctoral dissertation, PhD thesis. Universidade de Brasília, 189p.

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017. The peraluminous Aurumina Granite Suite in central Brazil: An example of mantle-continental crust interaction in a Paleoproterozoic cordilleran hinterland setting? PrecambrianResearch, 299:75-100p. DOI: https://doi.org/10.1016/j.precamres.2017.07.029

Danderfer, A., De Waele, B., Pedreira, A.J., Nalini, H.A. 2009. New geochronological constraints on the geological evolution of Espinhaço basin within the São Francisco Craton - Brazil. Precambrian Research 170, 116-128. DOI: https://doi.org/10.1016/j.precamres.2009.01.002.

Danderfer, A., Lana, C.C., Nalini, H.A., Costa, A.F.O., 2015. Constraints on the Statherian evolution of the intraplate rifting in a Paleo-Mesoproterozoic paleocontinent: New stratigraphic and geochronology record from the eastern São Francisco Craton. Gondwana Research, 28:668-688.

Dantas, E.L., Horbe, A., Yokoyama, E., Peixoto, E.N., Jiménez, F.A.C., Garnier, J., Viegas, L.G.F., Hauser, N., Botelho, N.F., Rodrigues, S.W.P. 2018. Projeto Monte do Carmo - Tocantins. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Dardenne, M.A. 2000. The Brasília Fold Belt. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 31st International Geological Congress, 231-263.

Dardenne, M.A., Giustina, M.E.S.D., Sabóia, A.M., Bogossian, J., 2009. Datação geocronológica U-Pb da sequência vulcânica de Almas. Tocantins. SBG, Simp. Geol. Centro-oeste, 11, Anais, 1 cd-rom.

Dickinson, W.R., Gehrels, G.E. 2009. Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database. Earth and Planetary Science Letter 288:115-125. https://doi.org/10.1016/j.epsl.2009.09.013

Dyer, R.C. 1970. Grupo Araí - Um Grupo de Metamorfitos do Centro-Leste de Goiás. Revista da Escola de Minas. Ouro Preto, 28(2):55-63.

Franco, C.G.T., Almeida, M.A.R., Reis, S.T., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea IV. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Fuck, R.A., Dantas, E.L., Pimentel, M.M., Botelho, N.F., Armstrong, R., Laux, J.H., Junges, S.L., Soares, J.E., Praxedes, I.F. 2014. Paleoproterozoic crust-formation and reworking events in the Tocantins Province, central Brazil: A contribution for Atlantica supercontinent reconstruction. Precambrian Research, 244:53-74. DOI: https://doi.org/10.1016/j.precamres.2013.12.003

Fuck, R.A., Pimentel, M.M., Alvarenga, C.J.S., Dantas, E.L. 2017. The Northern Brasília Belt. In: São Francisco Craton, Eastern Brazil. Tectonic Genealogy of a Miniature Continent. Editors: Heilbron, M., Cordani, U.G., Alkmim, F.F. Regional Geology Reviews. Springer, 1ed, 205-220. DOI:10.1007/978-3-319-01715-0.

Geosoft. 2013. Oasis Montaj 7.5 - Mapping and Processing System. In: Quick Start Tutorials. Geosoft Incorporated, 258p.

Geosoft. 2019. Oasis MontajTM 9.6 Geosoft Inc. Toronto, Canadá.

Gorayeb P.S.S. 1996. Petrologia e evolução estrutural das rochas de alto grau de Porto nacional – TO. Tese de Doutorado. Centro de Geociências. Universidade Federal do Pará, Belém, 258p.

Gorayeb, P.S.S., Costa, J.B.S., Lemos, R.L., Gama, J.R.T., Bemerguy, R.L., Hasui, Y. 1988. O Pré-Cambriano da Região de Natividade, GO. Revista Brasileira de Geociências, 18:391-397.

Guadagnin, F., & Chemale, F., 2015. Detrital zircon record of the Paleoproterozoic to Mesoproterozoic cratonic basins in the São Francisco Craton. Journal of South American Earth Sciences, 60:104-116. DOI: https://doi.org/10.1016/j.jsames.2015.02.007

Guadagnin, F., Chemale, F., Magalhães, A.J., Santana, A., Dussin, I., Takehara, L. 2015. Age constraints on crystal-tuff from the Espinhaço Supergroup - Insight into the Paleoproterozoic to Mesoproterozoic intracratonic basin cycles of the Congo-São Francisco Craton. Gondwana Research, 27(1): 363-376. DOI: https://doi.org/10.1016/j.gr.2013.10.009

Hasui, Y., Costa, J.B.S., Saad, A.R., Campanha, V.A. 1990. O Grupo Natividade e sua correlação com o Grupo Bambuí. Geociências (UNESP. Impresso), São Paulo, v. Esp., n. Especial, 299-316p.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A. 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. Chem. Geol. 211: 47-69. DOI: https://doi.org/10.1016/j.chemgeo.2004.06.017

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., Essling, A.M. 1971. Precision measurement of the half-lives and specific activities of 235U and 238U. Physical Review C 4, 1889-1906.

Janousek, V., Farrow, C.M., Erban, V. 2006. Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). J. Petrol. 47:1255-1259. https://doi.org/10.1093/petrology/ egl013

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B. 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. J. Petrol., 27:745-750. DOI: https://doi.org/10.1093/petrology/27.3.745

Loureiro, H.S.C., Lima, E.S., Macedo, E.R., Silveira, F.V., Bahiense, I.C., Arcanjo, J.B.A., Moraes Filho, J.C., Neves, J.P., Guimarães, J.T., Teixeira, L.R., Abram, M.B., Santos, R.A., Melo, R.C. 2008. Projeto Barra-Oliveira dos Brejinhos Geological map. Brazilian Geological Survey and Bahia Mineral Research Company, scale 1:200000.

Ludwig, K.R., 2003. User's Manual for Isoplot/Ex Version 3.00dA Geochronology Toolkit for Microsoft Excel, No. 4. Berkeley Geochronological Center Special Publication, 70p.

Marini, O.J., Fuck, R.A., Danni, J.C. 1981. A evolução geotectônica da Faixa Brasília e seu embasamento. In: Simpósio sobre o Cráton do São Francisco e suas faixas marginais. Salvador. Anais. Salvador, SBG/BA, 100-113p.

Marques, G.C. 2009. Geologia dos grupos Araí e Serra da Mesa e seu embasamento no sul do Tocantins. Dissertação de Mestrado, Universidade de Brasília, 116p.

Martins, F.A.L. 1999. Análise faciológica e estratigráfica do Paleo-Mesoproterozóico: Sequência Araí no Parque Nacional Chapada dos Veadeiros, Goiás. Dissertação de Mestrado. IG-UnB, 137p.

Martins-Ferreira, M.A.C. 2017. Evolução tectônica das bacias Araí, Traíras e Paranoá na Faixa Brasília Norte. Tese de Doutorado. Instituto de Geociências. Universidade de Brasília, 202p.

Martins-Ferreira, M.A.C., Campos, J.E.G., Von Huelsen, M.G. 2018b. Tectonic evolution of the Paranoá basin: New evidence from gravimetric and stratigraphic data. Tectonophysics, 734:44-58. DOI: 10.1016/j.tecto.2018.04.004

Martins-Ferreira, M.A.C., Chemale, F., Coelho Dias, A.N., Campos, J.E.G. 2018a. Proterozoic intracontinental basin succession in the western margin of the São Francisco Craton: Constraints from detrital zircon geochronology. Journal of South American Earth Sciences, 81:165-176. DOI: 10.1016/j.jsames.2017.11.018.

Martins-Ferreira, M.A.C., Dias, A.N.C., Chemale., F., Campos, J.E.G., Seraine, M., Novais-Rodrigues, E., 2020. Multistage crustal accretion by magmatic flare-up and quiescence intervals in the western margin of São Francisco Craton: U-Pb-Hf and geochemical constraints from the Almas Terrane. Gondwana Research. 85:32-54. DOI: 10.1016/j.gr.2020.04.005

Matteini, M., Dantas, E.L., Pimentel, M.M., Alvarenga, C.J.S., Dardenne, M.A. 2012. U-Pb and Hf isotope study on detrital zircons from the Paranoá Group, Brasília Belt Brazil: Constraints on depositional age at Mesoproterozoic-Neoproterozoic transition and tectono-magmatic events in the São Francisco Craton. Precambrian Research, 206:168-181. DOI: 10.1016/j.precamres.2012.03.007

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett. 40 (1):25-32.

Moore, B. 1963. Geological reconnaissance of the southwest corner of the Maranhão Basin. Relatório nº 1854, PETROBRÁS/DEPEX, RJ.

Morbeck, E., Kuberek, N., Barreto, R., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea V. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Oliveira F.V. 2015. Um novo suplemento para a redução de dados U-Pb obtidos por LA-MC-ICPMS. Dissetação (Mestrado em Geonciência). Instituto de Geociências. Universidade de Brasília, 91p.

Oliveira, C.G., Dantas, E.L., Roig, H.L., Chemale, F., Della Giustina, M.E.S., Meneses, P.R., Vidotti, R.M., Souza, V.S. 2012. Projeto Natividade. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Palermo, N. 1989. Geologia e Mineralizações Auríferas da Região de Monte do Carmo, Goiás. Dissetação (Mestrado em Geonciência). Universidade Federal do Rio de Janeiro, 139p.

Pimentel, M.M. 2016. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. Brazilian Journal of Geology, 46(1):67-82. DOI: 10.1590/2317-4889201620150004.

Pimentel, M.M., Heaman, L., Fuck, R.A., Marini, O.J. 1991. U-Pb zircon chronology of Precambrian tin-bearing continental-type acid magmatism in central Brazil. Precambrian Research, 52(3-4):321-335. DOI: https://doi.org/10.1016/0301-9268(91)90086-P

Pinto C.P., Silva M.A. 2014. Mapa Geológico do Estado de Minas Gerais, Brasil. Escala 1:1.000.000. Belo Horizonte, CODEMIG - CPRM.

Reeves, C. 2005. Aeromagnetic surveys: principles, practice and interpretation. Delft: Geosoft, 155p.

Ress, C.B., Oliveira, L.M.C., Ribeiro, T.G.R., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea IX. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Rodrigues, J.B., Pimentel, M.M., Dardenne, M.A., Armstrong, R.A. 2010. Age, provenance and tectonic setting of the Canastra and Ibiá Groups (Brasília Belt, Brazil): Implications for the age of a Neoproterozoic glacial event in central Brazil. Journal of South American Earth Sciences, 29(2):512-521. DOI: 10.1016/j.jsames.2009.08.008

Rollinson, H.R. 1993. Using geochemical data: evolution, presentation, interpretation. Longman Scientific & Technical, New York, 352p

Saboia, A.M. 2009. O Vulcanismo em Monte do Carmo e Litoestratigrafia do Grupo Natividade, Estado de Tocantins. Dissertação (Mestrado em Geociências) - Universidade de Brasília, Brasília, 96p.

Saboia, A.M., Oliveira, C.G., Dantas, E.L., Cordeiro, P., Scandolara J.E., Rodrigues, J.B., Sousa, I.M.C. 2020a. The Siderian crust (2.47-2.3 Ga) of the Goiás Massif and its role as a building block of the São Francisco paleocontinent, 350:105901. DOI: https://doi.org/10.1016/j.precamres.2020.105901

Saboia, A.M., Oliveira, C.G., Dantas, E.L., Scandolara J.E., Cordeiro, P., Rodrigues, J.B., Sousa, I.M.C. 2020b. The 2.26 to 2.18 Ga Arc-Related Magmatism of the Almas-Conceição do Tocantins Domain: An Early Stage of the São Francisco Paleocontinent Assembly in Central Brazil, 104:102757. DOI: https://doi.org/10.1016/j.jsames.2020.102757

Santos, M.M., Lana, C., Scholz, R., Buick, I., Schmitz, M.D., Kamo, S.L., Gerdes, A., Cirfu, F., Tapster, S., Lancaster, P., Storey, C.D., Basei, M.A.S., Tohver, E., Alkmim, A., Nalini, H., Krambrock, K., Fantini, C., Wiedenbeck, M. 2017. A New Appraisal of Sri Lankan BB Zircon as a Reference Material for LA-ICP-MS U-Pb Geochronology and Lu-Hf Isotope Tracing. Geostandards and Geoanalytical Research, 1-24.

Schobbenhaus, C. & Bellizzia, A. (coords.). 2001. Mapa geológico da América do Sul, 1: 5.000.000. CGMW - CPRM - DNPM - UNESCO, Brasília.

Schobbenhaus, C. & Brito Neves, B.B. 2003. A Geologia do Brasil no contexto da plataforma Sul-Americana. In: Bizzi, L.A., Schobbenhaus, C., Vidoti, R.M., Gonçalves, J.H. (Eds). Geologia, Tectônica e Recursos Minerais do Brasil, CPRM, Serviço Geológico do Brasil, Brasília, 169-226p.

Schobbenhaus, C., Campos, D.A., Derze, G.R., Asmus, H.E. 1984. Mapa Geológico do Brasil e da Área Oceânica Adjacente, Incluindo Depósitos Minerais, escala 1:2500000. MME/DNPM, Brasília.

Schobbenhaus, C., Hoppe, A., Baumann, A., Lork, A., 1994. Idade U/Pb do vulcanismo Rio dos Remédios, Chapada Diamantina, Bahia. In: Congresso Brasileiro de Geologia, 38, Balneário Camboriú, Anais, 2:397-399.

Seraine, M., Campos, J.E.G., Martins-Ferreira, M.A.C., Giorgioni, M., Angelo, T.V. 2020. Tectonic significance of abrupt immature sedimentation in a shallow cratonic margin basin: The Arkose Level, Mesoproterozoic Paranoá Group. Journal of South American Earth Sciences, 97:102397. https://doi.org/10.1016/j.jsames.2019.102397

Sharman, G.R., Malkowski, M.A. 2020. Needles in a haystack: Detrital zircon U-Pb ages and the maximum depositional age of modern global sediment. Earth-Sci. Rev. 203, 103109. DOI: https://doi.org/10.1016/j.earscirev.2020.103109

Silva, C.C. 2020. Petrografia, geoquímica e geocronologia das rochas vulcânicas efusivas e piroclásticas da Formação Arraias, Grupo Araí, nordeste de Goiás. Tese de doutorado n° 163. Universidade de Brasília, Brasília-DF, 119p.

Silva, W.L., Kotschoubey, B., Lafon, J.M., Gallarza, M.A. 2005. Grupo Natividade e Grupo Araí: correlatos, mas diacrônicos. In: X Congresso Brasileiro de Geoquímica e II Simpósio de Geoquímica dos Países do Mercosul. Estratigrafia do Grupo Araí: registro de rifteamento Paleoproterozoico no Brasil Central de Galinhas, Pernambuco, Brasil, 2:1-4.

Silveira, E.M., Söderlund, U., Oliveira, E.P., Ernst, R.E., Menezes Leal, A.B. 2013. First precise U-Pb baddeleyite ages of 1500 Ma mafic dykes from the São Francisco Craton, Brazil, and tectonic implications. Lithos, 144-156.

Sláma J., Košler J., Condon D.J., Crowley J.L., Gerdes A., Hanchar J.M., Horstwood M.S.A., Morris G.A., Nasdala L., Norberg N., Schaltegger U., Schoene B., Tubrett M.N., Whitehouse M.J. 2008. Plešovice zircon – a new natural reference material for U–Pb and Hf isotopic microanalysis. Chem. Geol., 249:1-35. Doi: https://doi.org/10.1016/j.chemgeo.2007.11.005

Sousa I.M.C., Giustina M.E.S.D., Oliveira C.G. 2016. Crustal evolution of the northern Brasília Belt basement, central Brazil: A Rhyacian orogeny coeval with a pre-Rodinia supercontinent assembly. Precambrian Research, 273:129-150. https://doi.org/10.1016/j.precamres.2015.12.007

Tanizaki, M.L.N., Campos, J.E.G., Dardenne, M.A. 2015. Stratigraphy of the Araí Group: Record of Paleoproterozoic rifting in Central Brazil. Brazilian Journal of Geology, 45(1):95-108. DOI: 10.1590/23174889201500010007.

Teixeira, A.L.S., Lemos, I.G.S., Corrêa, R.M., Campos, J.E.G., Botelho, N.F., Horbe, A.M.C., Roig, H.L., Yokoyama, E., Almeida, T., Barbosa, P.F., Toledo, C.L.B., Martins-Ferreira, M.C. 2016. Projeto Almas - Tocantins - Subárea III. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Toscani, R., Campos, J.E.G., Matos, D.R., Martins-Ferreira, M.A.C. 2021. Complex depositional environments on a siliciclastic carbonate platform with shallow-water turbidites: The Natividade Group, central Brazil, Journal of South American Earth Sciences. DOI: http:/doi.org/10.1016/j.jsames.2020.102939

Turpin, L., Maruejol, P., Cuney, M., 1988. U-Pb, Rb-Sr and Sm-Nd chronology of granitic basement hydrothermal albitites and uranium mineralizations (Lagoa Real, South Bahia, Brazil). Contributions to Mineralogy and Petrology, 98:139-147.

Uhlein, A., Paim, P.S.G., Tassinari, C.C.G., Pedreira, A.J. 2015. Análise estratigráfica de bacias rifte Paleo-Mesoproterozoicas dos crátons Amazônico e São Francisco, Brasil. Geonomos, 23(2):1-13. DOI: https://doi.org/10.18285/geonomos.v23i2.707

Valeriano, C.D.M., Pimentel, M.M., Heilbron, M., Almeida, J.C.H. and Trouw, R.A.J., 2008. Tectonic evolution of the Brasília Belt, Central Brazil, and early assembly of Gondwana. Geological Society, London, Special Publications, 294(1):197-210.

CAPÍTULO 5

ARTIGO 3

Paleoproterozoic pre-rift evolution in the Western São Francisco Paleocontinent, Central Brazil: the Água Morna Formation, Araí Group

Toscani, R.[1]*; Campos, J.E.G.[2]; Martins-Ferreira, M.A.C.[3]

[1] Centro de Hidrografia da Marinha, Diretoria de Hidrografia e Navegação, Marinha do Brasil, Niteroi, Rio de Janeiro, RJ, Brazil.
[2]Instituto de Geociências, Universidade de Brasília, Campus Univ. Darcy Ribeiro, Asa Norte, 70910900 Brasília, DF, Brazil
[3]Faculdade de Ciências e Tecnologia, Universidade Federal de Goiás, Setor Conde dos Arcos, 74968755 Aparecida de Goiânia, GO, Brazil

* Corresponding Author: toscanisilveira@gmail.com

Abstract
The pre-rift stage is the least studied phase in Proterozoic rift-sag basin systems due to the small thickness of this type of succession, the difficulty of finding preserved and representative outcrops, and the deformation resulted from different tectonic superimposed processes. The term "pre-rift sequence" can have two connotations: all sedimentary records preexisting and non-related to rifting or the first sedimentary record related to the initial rifting process as a result of crustal stretching. The present study considers the pre-rift as part of the rifting development and formed during its progression. In this sense, the Água Morna Formation is interpreted as controlled by thermal subsidence and deposited in the initial stages of the Araí rift basin evolution, as the result of crustal cooling after passive asthenospheric uplift. The Água Morna Formation presents regional discontinuous distribution, small thickness, and high lateral homogeneity. The main sedimentary deposits are composed of immature, poorly sorted feldspar quartzite, often rich in pebbles with common cross-stratification. Minor metaconglomerate and metagreywacke deposits also occur. The depositional environment is interpreted as a fluvial braided system with active channels (quartzite and pebbly quartzite rich in trough cross-beds), bars (massive or stratified quartzite), and abandoned channels (metagreywacke). Geochronological data from detrital zircon grains indicate maximum depositional age of 2.15 Ga (Marques, 2009), which is coherent with the interpretation of provenance from local crystalline basement rocks. The sedimentological data presented in this study, associated with the geochronological data acquired showing absence of younger detrital zircon grains, provide a solid argument to separate the Água Morna Formation from the overlying Arraias Formation, at the base of the Araí Group stratigraphy.

Keywords*: pre-rift stage, thermal subsidence, braided river, Água Morna Formation, Araí Group.*

1. Introduction

In general, few studies detail the architecture of facies and depositional dynamics associated with the different stages of rifting, especially concerning its initial stages (Kifumb, 2017; Kifumbi et al., 2017). The occurrence of pre-rift sequences preserved in the Paleoproterozoic record is unusual. Thus, this study is relevant for a better understanding of the early stages of extensional processes that occurred during the Precambrian.

Pre-rift sequences can be related to two evolutionary concepts: i) including all sedimentary records preexisting before the rift basin evolution or ii) being part of the rifting processes and refereed to the initial stages of the rift-sag development (Holz et al., 2017). In this sense, the present study considers that the pre-rift phase represents the latest (ii), being the early stages of a broader extensional progression of a crustal segment.

The Araí Group consists of a sedimentary sequence related to different rift-type environments and is subdivided into the Água Morna and Arraias Formations, from base to top, respectively. This group was formed during the early Statherian when the São Francisco Craton witnessed a broad extensional event that generated several continental rift basins (Martins-Ferreira et al., 2018b and references therein).

The Araí Group (1.771 Ga) has been studied by several authors (Barbosa et al., 1969; Araújo & Alves, 1979; Marques, 2009; Tanizaki et al., 2015; Martins-Ferreira et al., 2018a; Silva, 2020) and dated by Pimentel et al. (1991). However, the basal Água Morna Formation has not yet been studied in terms of its sedimentological and geochronological characteristics, which led to the study of precarious interpretation models regarding the geotectonic evolution of the initial stages of the Araí basin.

The Água Morna Formation is mainly composed of metarkose, quartzite, and metaconglomerate (Tanizaki et al., 2015) and occurs in discontinuous distribution and small thickness, most frequently not well exposed due to the presence of talus detritus derived from the mountains and hills remnant from the Arraias Formation metasediments deposited over this unit.

The present study aims to present a detailed description and interpretation of the depositional environment of the Água Morna Formation, provide novel geochronological data obtained via detrital zircon geochronology and refine the geotectonic model regarding the controls over the deposition of this geological unit.

2. Geological setting

The present study focuses on the evolution of the Água Morna Formation, a sedimentary sequence belonging to the Araí Group (Martins-Ferreira, 2018a). This group is part of the Veadeiros Supergroup, a rift-sag type Proterozoic supersequence located in central Brazil (Figs. 1, 2, and 3).

The region is located in the domains of the Tocantins Structural Province (Fig. 2) (Almeida et al., 1981), an extensive Neoproterozoic orogenic system that is part of a wide and long Neoproterozoic-Cambrian orogenic system extending for thousands of kilometers across central and northern Brazil and NW Africa, in the Hoggar-Pharusian and Dahomey belts (Pimentel, 2016), developed during the Brasiliano-Pan-African orogeny (Fig. 1a). The province is comprised of three orogenetic belts: Brasília, Araguaia, and Paraguay (Almeida, 1977).

2.1 Tectonic Evolution

In Brazil, the Amazonian and São Francisco cratons are partially covered by rift, sag, and rift-sag type volcano-sedimentary units, deposited during the Paleoproterozoic and Mesoproterozoic (Fuck et al., 2014). In general, these basins are located at the margin or in the interior of the cratonic landmasses and are commonly surrounded by Neoproterozoic fold belts (Figs. 1a and 1b). In this study, it is worth mentioning the following supergroups: Espinhaço (eastern Brazil) and Veadeiros (central Brazil) (Figs. 1c and 1d) (Schobbenhaus & Brito Neves, 2003; Uhlein et al., 2015; Martins-Ferreira et al., 2018a).

The northern segment of the Brasília Belt is characterized by a general NE-SW structural trend and an overall east to southeast vergence (Fig. 2). The external zone of the Brasília Belt, where the study area is located, comprises a pile of sedimentary sequences deformed against the western margin of the São Francisco Craton, including significant exposures of the sialic basement (Fuck et al., 2017). The crystalline basement of the Brasília Belt is composed of a collage of arc-related terranes assembled and welded together during a Paleoproterozoic orogenic episode (Siderian and Rhyacian) (Fuck et al., 2014; Sousa et al., 2016; Cuadros et al., 2017a; Martins-Ferreira et al., 2020). This basement is dominated by large volumes of tonalite-trondhjemite-granodiorite (TTG) magmatism generated during the Siderian (Saboia et al., 2020a; Saboia et al., 2020b).

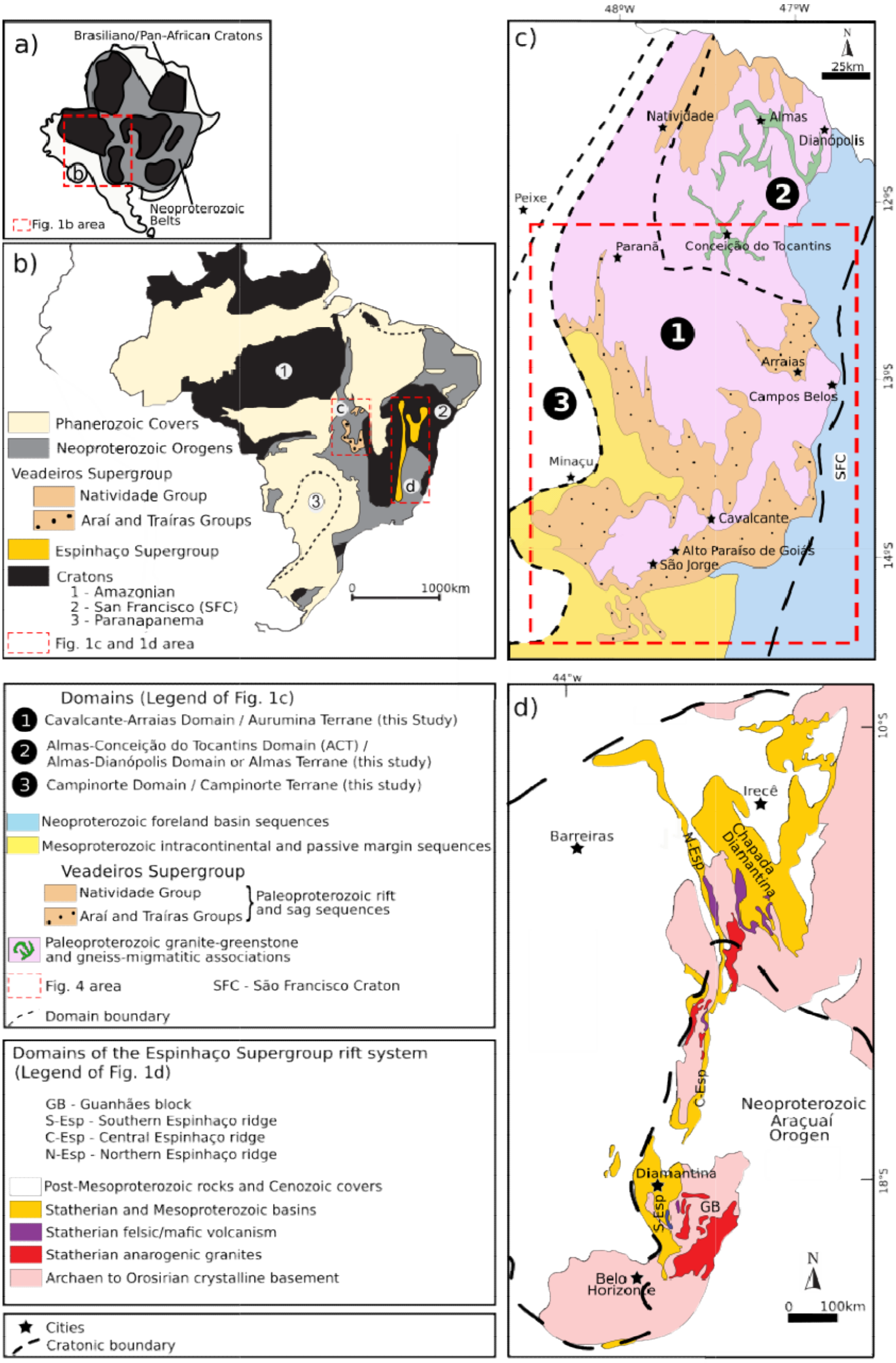


Fig. 1. Geological context maps showing: **a)** location of Archean/Paleoproterozoic cratons and Neoproterozoic belts and Fig. 1b area (red rectangle), **b)** map of the main cratons and basins in Brazil and Fig. 1c and 1d locations (red rectangles), **c)** geological map of the northern segment of the Brasília Belt showing three tectonic domains (modified from Fuck et al., 2014; Cordeiro & Oliveira, 2017; Martins-Ferreira et al., 2020), **d)** simplified geological map of Espinhaço Supergroup rift system (modified from Alkmim, 2004; Pinto & Silva, 2014; Magalhães et al., 2018).

During the evolution of the Brasília Belt crystalline basement, an accretionary orogeny was being developed with the amalgamation of micro-blocks in the São Francisco Craton western margin from 2.5 to 2.2 Ga (Fuck et al., 2014; Sousa et al., 2016; Martins-Ferreira et al., 2020). According to Cordeiro & Oliveira (2017), all rocks from the pre-Neoproterozoic in the central-northern part of the Brasília Belt are grouped in the Goiás Massif, which can be divided into four distinct tectonic domains: The Archean-Paleoproterozoic Crixás-Goiás Domain and the Paleoproterozoic Almas-Conceição do Tocantins, Cavalcante-Arraias and Campinorte Domains.

In the present study, it was applied the terminology of Martins-Ferreira et al. (2020), who defined the terms: Almas Terrane for the Almas-Conceição do Tocantins Domain; Aurumina Terrane for the Cavalcante-Arraias domain; and Campinorte Terrane for Campinorte Domain (Fig. 1c).

The crystalline basement underlying the Água Morna Formation is formed by the Aurumina Terrane (Cavalcante-Arraias Domain), which is characterized by peraluminous granites and tonalites/granodiorites of Aurumina Suite (2.11 to 2.16 Ga) (Cuadros et al., 2017a) and sequences of biotite-garnet paragneisses/mica-graphite schists of the Ticunzal Formation (2.16 to 2.19 Ga) (Cuadros et al., 2017b). According to Alvarenga et al. (2006), the Ticunzal Formation is presented by schists and paragneisses (commonly with graphite). In addition, to a lesser extent, micaceous quartzite and conglomerate also occur (Tanizaki et al., 2015).

2.2 Veadeiros Supergroup

The Veadeiros Supergroup sedimentary sequence is located in the Tocantins Structural Province (Almeida et al., 1981) (Fig. 2), which represents an extensive Neoproterozoic orogenic system in central Brazil. This province originated in the Brasiliano orogeny involving mainly the Amazonian, São Francisco-Congo, and Paranapanema (Rio de La Plata) cratons (Fuck et al., 2014; Pimentel, 2016).

This Supergroup represents extensional basins successions in the Northern Brasília Belt that evolved from the Paleoproterozoic (Statherian) to the beginning of the Neoproterozoic (Tonian), and includes the Araí, Traíras, and Paranoá groups, besides the Quilombo Formation and may include the units with geographic and geochronological similarities of the Natividade, Serra da Mesa, and Canastra groups (Fig. 3) (Martins-Ferreira et al., 2018a; Toscani et al., 2021a; Toscani et al., 2021b).

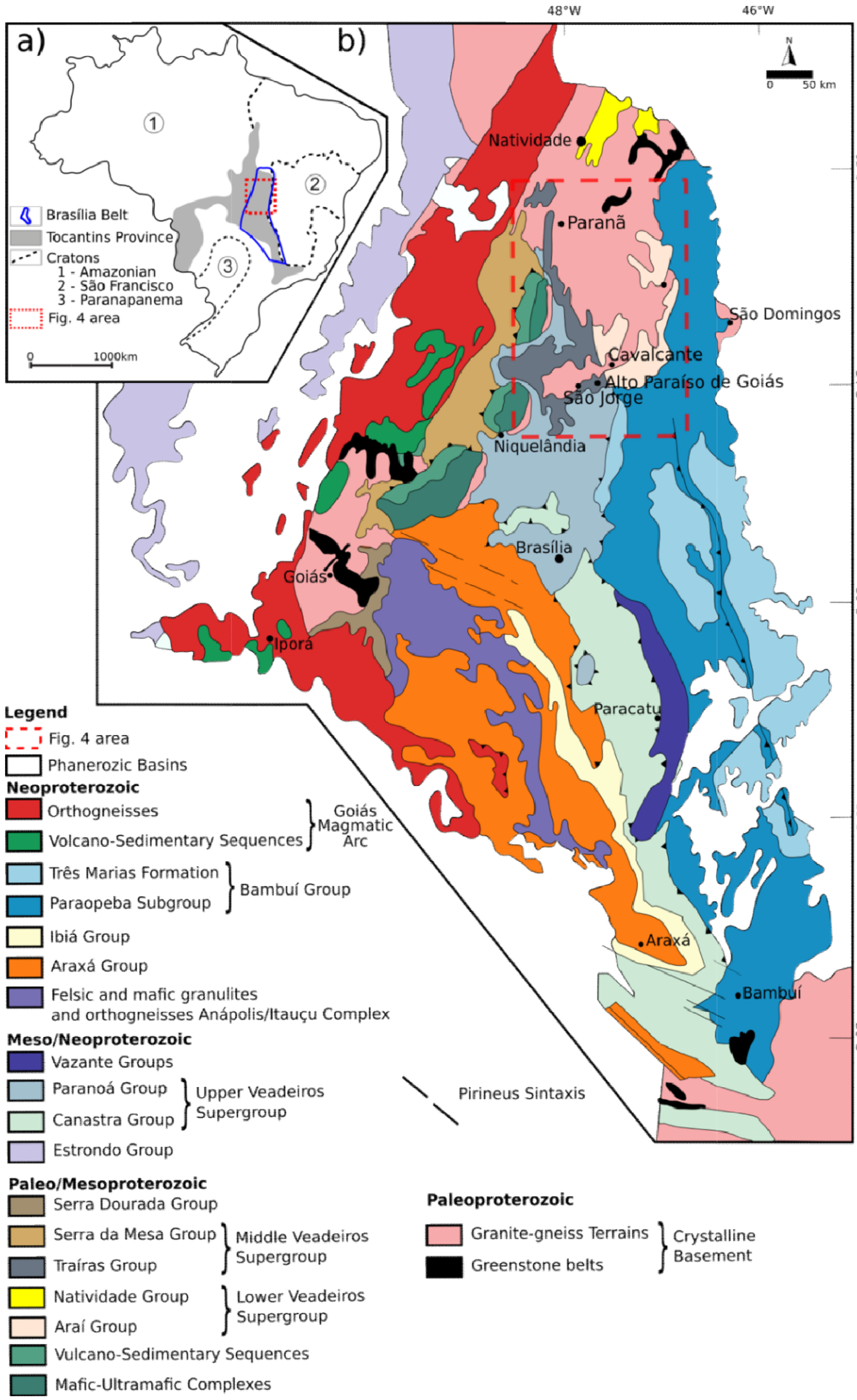
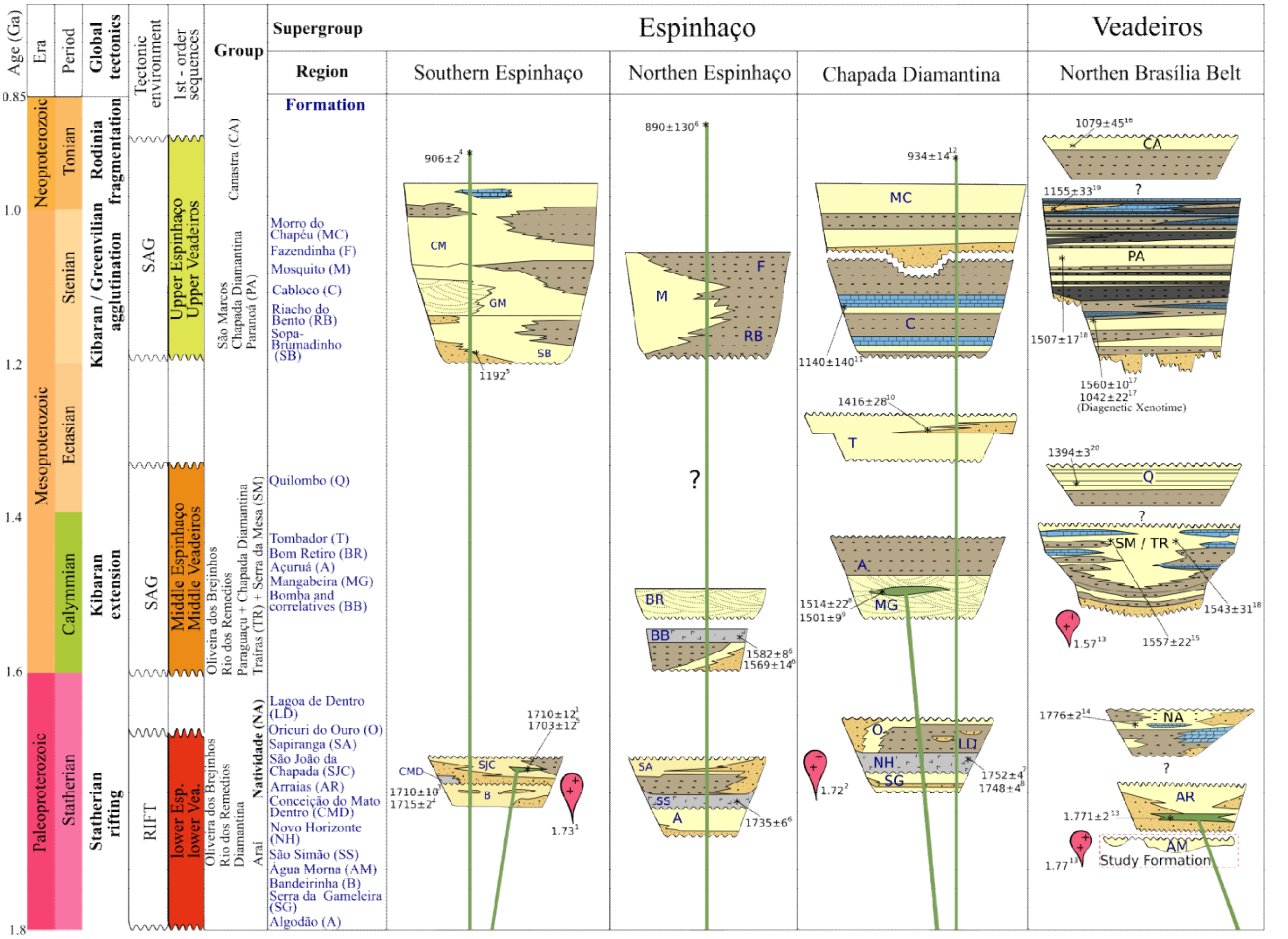


Fig. 2. Geological context maps showing: **a)** the location of Brasilia Belt, Tocantins Province, and Cratons: Amazonian, São Francisco, and Paranapanema (adapted from Sousa et al., 2016), **b)** geological map of the Brasília Belt, where the Araí Group outcrops in the northeast (adapted from Dardenne, 2000; Fuck et al., 2017).



1. Dussin (1994) 2. Turpin et al. (1988) 3. Brito Neves et al. (1979) 4. Abreu (1991) 5. Chemale (2012) 6. Danderfer et al. (2009) 7. Schobbenhaus et al. (1994) 8. Babinski et al. (1999) 9. Silveira et al. (2013) 10. Guadagnin & Chemale (2015) 11. Babinski et al. (1993) 12. Loureiro et al. (2008) 13. Pimentel et al. (1991) 14. Toscani et al. (2021b) 15. Marques (2009) 16. Rodrigues et al. (2010) 17. Matteini et al. (2012) 18. Martins-Ferreira et al. (2018a) 19. Seraine et al. (2020) 20. Campos et al. (2020)

Fig. 3. Chronostratigraphic chart comparing the Veadeiros Supergroup sequences with its correlatives from the Espinhaço Supergroup (after Guadagnin & Chemale, 2015; Martins-Ferreira et al., 2018a; Toscani et al., 2021a; Toscani et al., 2021b). The geologic time scale is from Cohen et al. (2013).

The Veadeiros Supergroup is divided into three major sedimentary sequences (Fig. 3). The first sequence of Paleoproterozoic age is comprised by the Araí Group and is known as Lower Veadeiros (Statherian), which represents the pre and syn-rift phases. The second sequence is the Middle Veadeiros, of Mesoproterozoic age (Calymmian to early Ectasian) and consists of the Traíras Group and its probable lateral equivalent, the Serra da Mesa Group, which together represent the intracratonic sag phase of the basin (Martins-Ferreira et al., 2018a). The Middle Veadeiros sequence is correlated to the lower and middle Espinhaço Supergroup, which occurs in the eastern margin of the São Francisco Craton (Guadagnin & Chemale, 2015; Guadagnin et al., 2015). The third sequence, in the Upper Veadeiros, is interpreted as a late Mesoproterozoic (Stenian to early Tonian), represented by the Paranoá Group, which occurs in an Intra/Pericratonic sag basin type (Campos et al., 2013; Martins-Ferreira et al., 2018b; Seraine et al., 2020).

The Araí Group (Barbosa et al., 1969; Dyer, 1970), which previously included the Traíras sequence, was interpreted as a rift-sag basin with a maximum depositional age of 1,771 Ma (Pimentel et al., 1991; Tanizaki et al., 2015). According to geochronological and stratigraphic data presented in Martins-Ferreira et al. (2018a), the Statherian Araí Group consists only of the Água Morna and Arraias formations. In contrast, the Traíras Group, with maximum deposition age at 1,543 ± 31 Ma, represents a Calymmian sag-type basin deposited over the Araí Group or locally directly over the crystalline basement and might have coexisted in time with the Serra da Mesa Group, possibly as part of the same sag basin system. These two distinct basins, Araí and Traíras, are also related to different pulses of anorogenic magmatism, respectively the Pedra Branca Suite (1.77 Ga; Pimentel et al., 1991) and the Serra da Mesa Suite (Fig. 3) (1.57 Ga; Pimentel et al., 1991).

According to Tanizaki et al. (2015), The Água Morna Formation is composed mainly of coarse-grained metarkose and feldspar quartzite with clasts mainly represented by quartz and quartz veins. Secondarily, micaceous and metaconglomerate quartzites occur, interspersed and interfingered with metarkose. Formally, it was subdivided into three lithofacies: i) Matrix-supported metaconglomerate; ii) feldspar quartzite; iii) metagreywacke. The presence of sedimentary structures is common, including ripple marks, tabular and trough cross-stratification (Tanizaki, 2013). Thus, it was interpreted that the Água Morna Formation was deposited in continental conditions in braided fluvial systems dominated by sands (Tanizaki, 2013; Tanizaki et al., 2015).

The Arraias Formation is a continental sedimentary package subdivided into five members: Cubículo, Prata, Mutum, Ventura, and Buracão. These units are interdigitated, with lateral and vertical variations and hundreds of meters of thicknesses. It represents the deposits of sedimentary environments such as alluvial fan, braided river, aeolian, and lacustrine (Tanizaki et al., 2015).

2.3 Espinhaço Supergroup

In the Espinhaço Supergroup, two rifting processes related to the Statherian and Calymmian periods have been identified and are known as Tuxás and Tupinaés events, both events associated with intracontinental extension (Danderfer et al., 2015; Costa et al., 2018). The Espinhaço Basin outcrops in three geographic regions known as Serra do Espinhaço Meridional (Southern Espinhaço range), Serra do Espinhaço Setentrional (Northern Espinhaço range), and Chapada Diamantina (Diamantina Plateau) (Guadagnin et al., 2015) (Figs. 1d and 3).

Statherian magmatism in the Southern Espinhaço Range is represented by the Conceição do Mato Dentro Formation, which consists of meta-igneous, dated at 1.72 Ga (Brito Neves et al., 1979; Dossin et al., 1993; Costa et al., 2018). In the Northern Espinhaço Range, this event is known as the Botuporã rift, which is represented by the Algodão (1,775 ± 5 Ma) and Sapiranga (1,740 ± 10Ma) volcano-sedimentary successions (Danderfer et al., 2015; Costa et al., 2018). In the Diamantina Plateau, the Tuxás event is represented by U-Pb ages of 1,752 ± 4 Ma (Schobbenhaus et al., 1994) and 1,748 ± 1 Ma (Babinski et al., 1994, 1999) obtained from volcanic rocks of the Rio dos Remédios Formation (Costa et al., 2018).

In this context, the Paleo/Mesoproterozoic Espinhaço and Veadeiros Supergroups have been postulated to be chrono-correlated, and their main evolutionary stages are linked to equivalent regional or global tectonic processes (Fig. 3) (Guadagnin & Chemale, 2015 and references therein).

The Bandeirinha Formation is considered the basal unit of the Espinhaço Supergroup, deposited into a homonymous Paleoproterozoic Basin, located in a wide area between the São Francisco Craton and the Araçuaí Fold Belt (Almeida, 1977; Chaves & Brandão, 2004; Simplicio & Basilici, 2015). This unit presents lithological and stratigraphic similarities with the Água Morna Formation (Veadeiros Supergroup).

The Bandeirinha Formation consists of continental deposits (250 m thick) mostly composed of laminated sandstone packages interbedded with conglomerate beds (Simplicio & Basilici, 2015). Silva (1998) previously interpreted this lithostratigraphic unit as a result of coastal and braided river depositional process, where the interbedded conglomerate represented mainly mass flow deposits in proximal areas of alluvial fans related to the tectonic activity (Simplicio & Basilici, 2015). According to Simplicio & Basilici (2015), the sandstone beds are deposited in an eolian sand sheet paleoenvironment, whereas the sandy conglomerate beds were formed in ephemeral river channels with highly concentrated underwater flows.

Danderfer et al. (2015) correlated in time the Bandeirinha sequence with the basal sequences of the Araí Group and the rift sequences of the Northern Espinhaço (Algodão and Sapiranga systems).

2.4 Statherian rift stages and Calymmian sag basins in Veadeiros Supergroup

Regarding the Statherian rift stages of the Araí Group, Tanizaki et al. (2015) divided into four tectonic-sequences: pre-rift (Água Morna Formation), rift (Arraias Formation), transitional (Caldas Formation), and post-rift (Traíras Formation) based on their main lithological and sedimentary environment characteristics, but without basis on geochronology data. More recent studies indicate that the Traíras Formation is a separate Group, disconnected from the Arraias

Group and showing maximum depositional age-related to the Calymmian (1,543 ± 31 Ma) (Martins-Ferreira et al., 2018a; Martins-Ferreira et al., 2018b). Both extensional pulses, Statherian Araí, and Calymmian Traíras have associated anorogenic magmatism, respectively related to the Pedra Branca (1.77 Ga) and Serra da Mesa suites (1.57 Ga) (Pimentel et al., 1991; Marini et al., 1992).

The pre-rift and rift sequences of the Araí Group correspond respectively to the Água Morna and Arraias formations. Tanizaki et al. (2015), based on the proposed rift models of Falvey (1974), Prosser (1993), and McKenzie (1978), related the Água Morna Formation to the pre-rift phase and the Arraias Formation to the rift phase.

According to Tanizaki et al. (2015), the Água Morna Formation shows no evidence of significant faults or records of associated volcanism. This suggests deposition in a wide and shallow depression at the elastic deformational limit of the upper crust. In this proposed model, isostatic compensation adjustments due to the rise of the asthenosphere (thermal subsidence) are responsible for the creation of the sedimentary space (Falvey, 1974; McKenzie, 1978). This phase would occur before the nucleation of major faults and the individualization of the grabens that host the overlapping units.

The Arraias Formation is characterized by sediments accumulated during the syn-rift phase of the Araí Basin (Tanizaki et al., 2015). The extensional regime is controlled by mechanical subsidence. Widespread alluvial fan systems controlled by normal faults occur, marking the brittle rupture of the upper crust and the subsidence of the first half grabs of the Araí Basin. On this tectonic regime, the entire continental sequence of the Araí Basin was deposited, with intercalation of bimodal volcanism (Pimentel et al., 1991; Tanizaki, 2013; Tanizaki et al., 2015).

In the Calymmian, the Traíras Group represents an intracontinental sag-type basin, separated from the rift-related Arraias Formation by a timespan of at least 228 Ma, marked by a significant unconformity, followed by conglomerates that rework the Arraias Formation (Martins-Ferreira et al., 2018b).

3. Material and methods

Systematic fieldwork in the area began in 2010, which resulted in the following studies: geological mapping of the Paranã - São Salvador regions (Campos et al., 2010), the review of the Araí Group Stratigraphy (Tanizaki, 2013), and the upgrade of the knowledge of the regional geology in the north Goiás State and South Tocantins State (Martins-Ferreira, 2017).

More recently, in January 2018, February 2019, and February 2020, the research team involved with the present study carried out three more field surveys aimed at petrologic investigation and recognition of stratigraphic columns (Fig. 4).

The geochronological information was selected from published literature and systematized according to the stratigraphic position, regional correlation of the different units previously sampled, and data debugging (regarding the data quality).

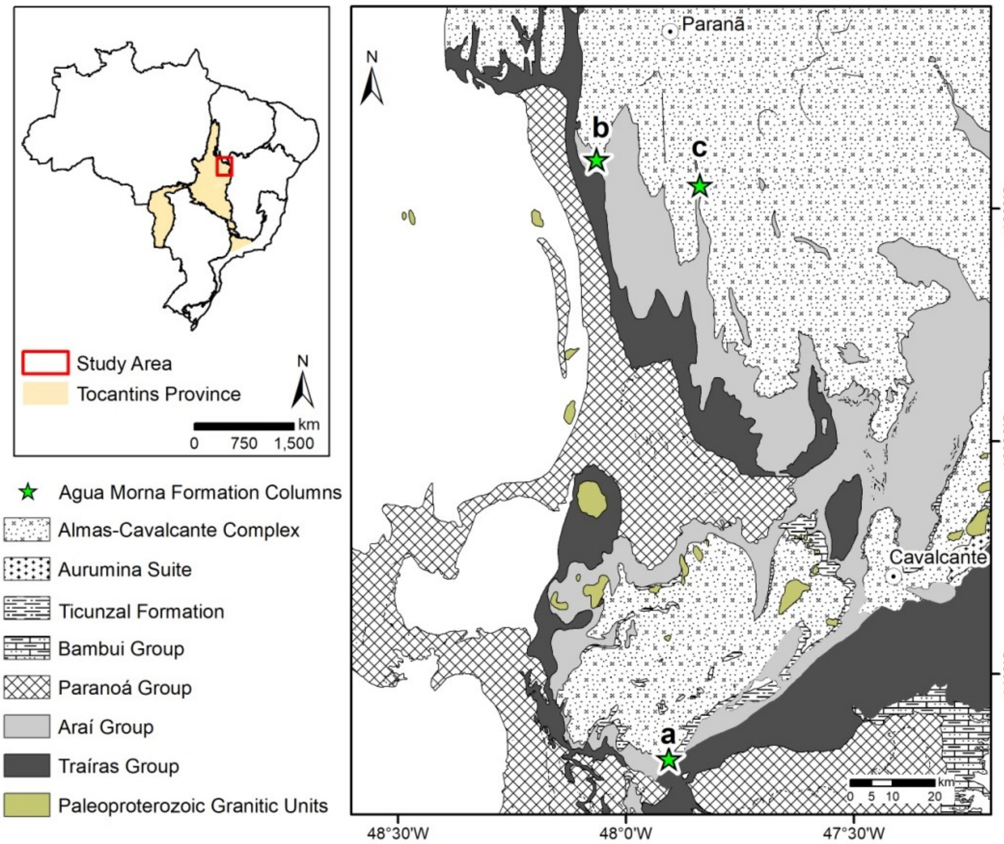


Fig. 4. Geological context map showing lithostratigraphic columns of different areas in the Água Morna Formation (Araí Group). The letters "a" to "c" show the locations of the columns according to Fig. 8 (Modified from Schobbenhaus & Bellizia, 2001).

4. Results

4.1 The Água Morna Formation geology

As described in the Geological Settings, Tanizaki (2013) and Tanizaki et al. (2015) divided the Água Morna Formation into three facies. This study brings additional fieldwork data and interpretations, which allows a more detailed description of these facies, as follows:

i) Matrix-supported metaconglomerate: composed of fine-grained metaconglomerate and coarse quartzite with clasts of quartz, feldspar, quartz veins, and quartzite (Fig. 5). The lithic fragments are rounded to angular, with an average size of 5 mm. The quartz-feldspar matrix has medium to coarse grain size, with a low occurrence of sericite. Planar cross-bedding and trough cross-bedding with dimensions of up to 50 cm are observed (Figs. 5a and 5b). More rarely, another variety of this facies occurs with larger clasts up to 10 cm in diameter (Fig. 5c). These clasts are sub-angular with low sphericity and are composed mainly of quartzite.

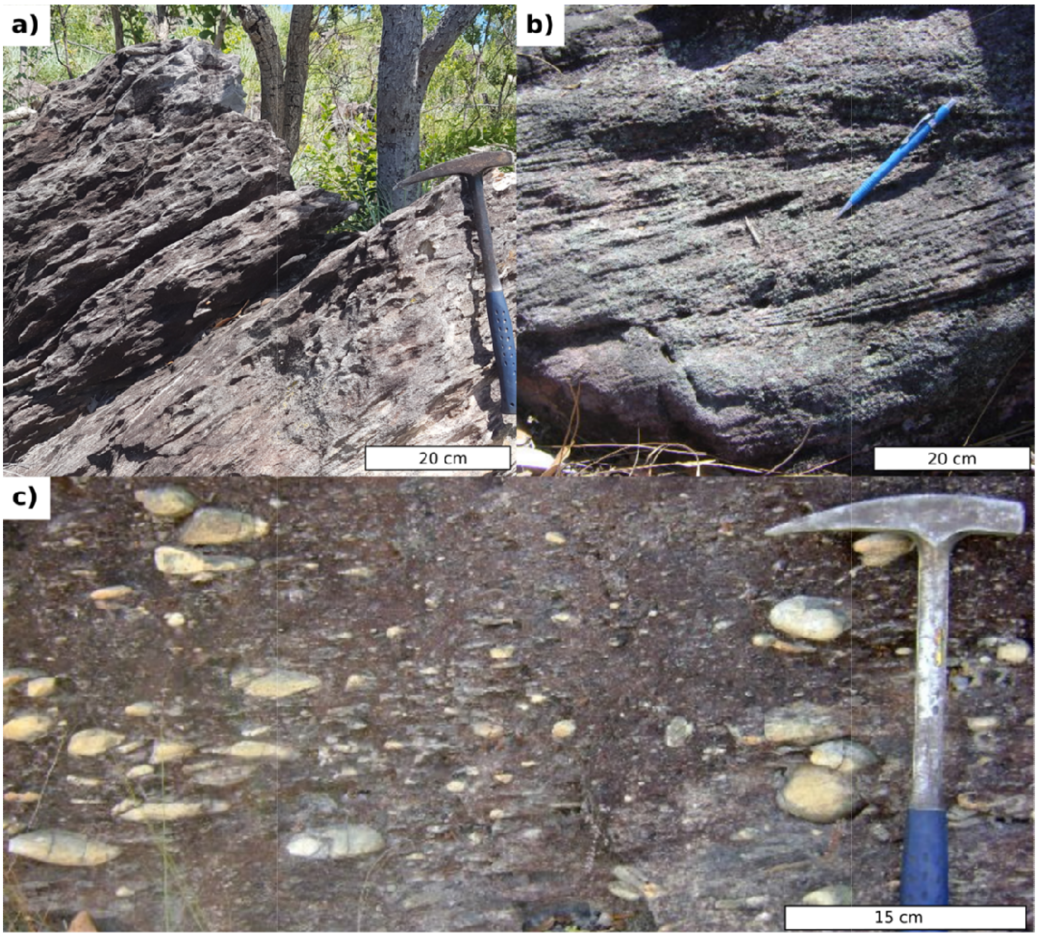


Fig. 5. Outcrops photographs showing: a) general aspect of horizontally stratified matrix-supported metaconglomerate (23L 193806E; 8567449S), b) cross-stratification structure in fine-grained metaconglomerate (22L 820500E; 8573711S), c) metaconglomerate with sub-angular quartzite clasts of up to 10 cm in their long axis (23L 193561L; 8566550S).

ii) Feldspar quartzite/Metarkose: most abundant facies in this Formation, outcropping in hills up to 100 meters high (Fig. 6a). It is composed of metric levels of metarkose and feldspar quartzite and pebbly quartzite, poorly selected, with medium to coarse grain size (Fig. 6b).

In this facies, a considerable variety of sedimentary structures occur: planar cross-stratification (Figs. 6c and 6d), parallel laminated-stratification, overturned cross-stratification (Fig. 7a), and trough cross-stratification (Fig. 7b) with small, medium, and large sizes (10 cm to 2 m); in addition, wavy marks and cut and fill structures (Fig. 7c) can also be seen.

Occasionally, isolated clasts of quartzite and quartz of veins, sub-rounded to angular, with sizes ranging from 5 to 10 cm, are observed in feldspar quartzite or metarkose beds (Fig. 7d).

iii) Metagreywacke: least abundant facies of the Água Morna Formation. It consists of micaceous feldspar quartzite with fine-medium grain size (Fig. 7e and 7f). This facies occurs at local levels in the middle of the arkose package (Tanizaki, 2013).

The three main facies described above occur in randomly organized stratigraphic successions, the feldspar quartzite/metarkose facies predominate widely, and the metaconglomerate and metagreywacke facies occur subordinately. The presence of pebbly quartzite is quite common in the whole succession. The channeled cross-stratification (trough cross-stratification) represents the most common sedimentary structure observed in all sandy facies.

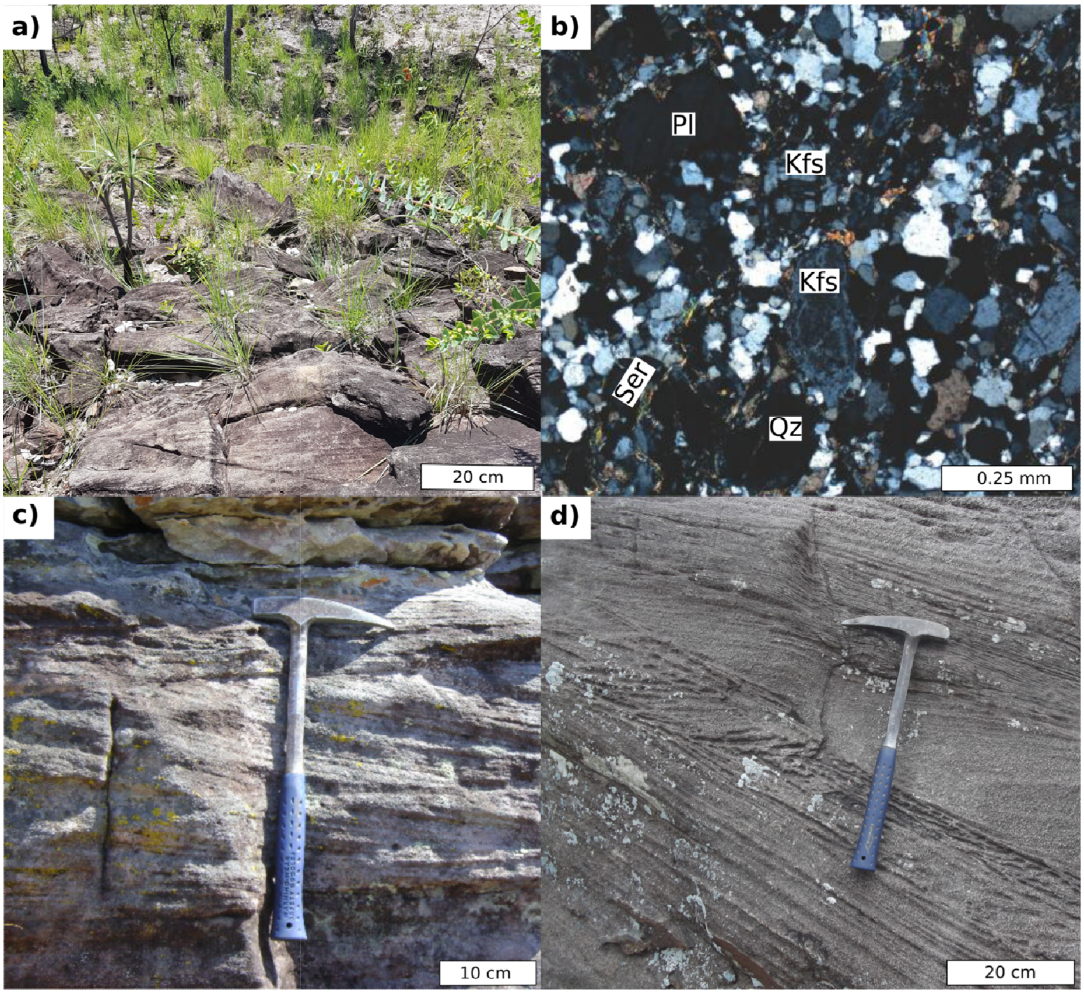


Fig. 6. Outcrop photographs showing: a) general aspect of stratified feldspar quartzite (23L 193806E; 8567449S), b) thin section viewed in cross-polarized light (XPL) of feldspar quartzite (quartz (Qz) + K-feldspar (Kfs) + plagioclase (Pl) + sericite (Ser)) (from Tanizaki, 2013), c) cross-stratification structure in feldspar quartzite (22L 820500E; 8573711S), d) cross-stratification structure in metatarkose (23L 186501E; 8431116S).

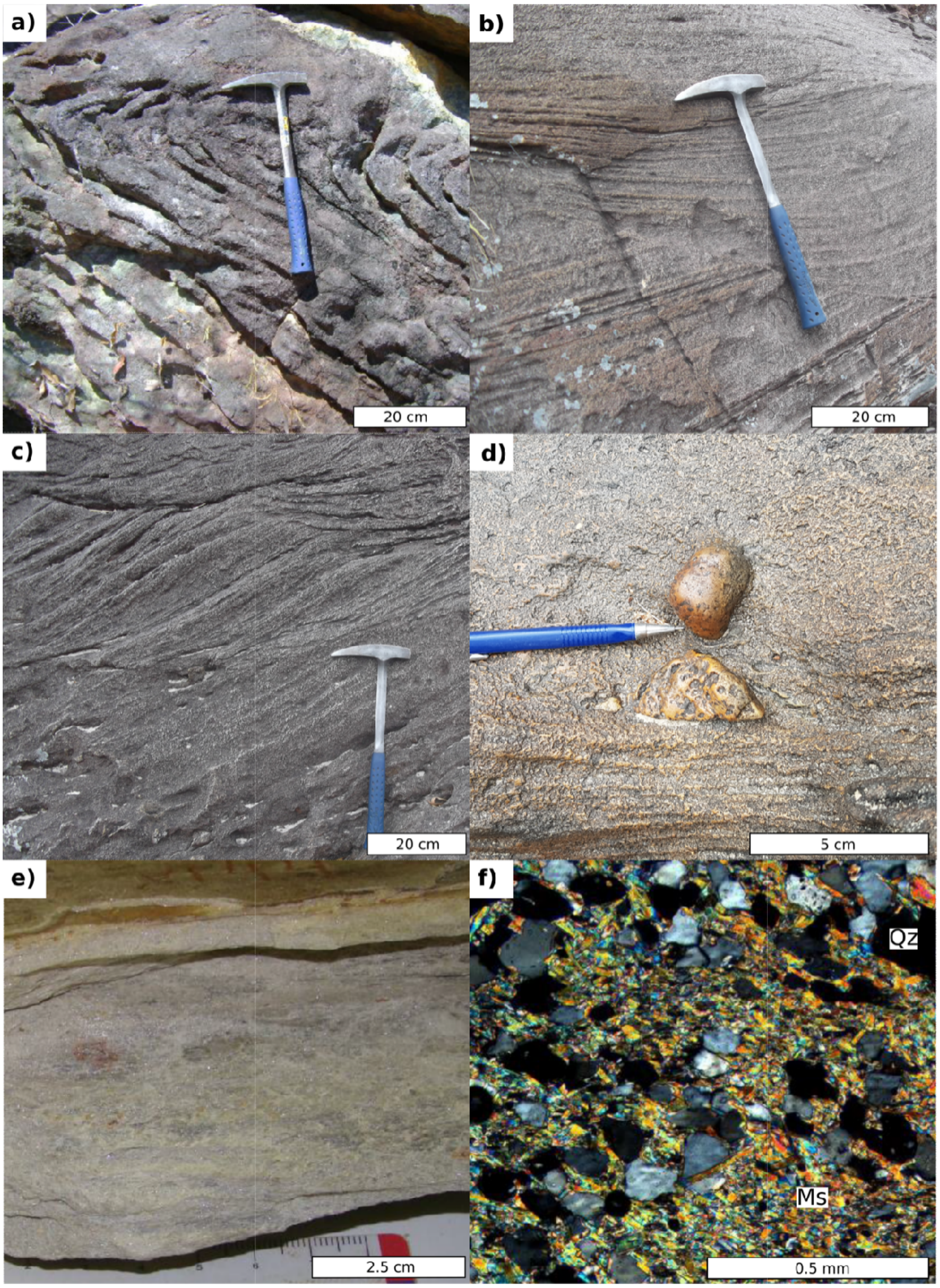


Fig. 7. Outcrop photographs showing: **a)** overturned cross stratification in feldspar quartzite (23L 193561E; 8566550S), **b)** trough cross-stratification in metarkose (23L 186501E; 8431116S), **c)** cut and fill structure in metarkose (23L 186501E; 8431116S), **d)** isolated clasts of quartz in metarkose (23L 186955E; 8432193S), **e)** detail of metagreywacke sample (from Tanizaki, 2013), **f)** thin section (crossed polarized light) of metagreywacke (quartz (Qs) + muscovite (Ms)) (from Tanizaki, 2013).

Based on the rocks described in this topic, it was possible to synthesize in table 1 the sedimentary facies, with their respective metamorphic designation and probable depositional conditions.

Table 1. Facies designation, correlative terms in the sedimentary nomenclature, and the associated depositional conditions (After Tanizaki, 2013; Tanizaki et al., 2015).

Facies (F)	Metamorphic rock	Sedimentary Corresponding Rocks	Probable Depositional Conditions
i	Matrix-supported metaconglomerate	Matrix-supported conglomerate	Turbulent currents that occur during flooding events or small gravitational flow deposits
ii	Feldspar quartzite/Metarkose	Feldspar sandstone/Arkose	Nuclei of lateral and longitudinal sand bars
iii	Metagreywacke	Greywacke	Abandoned channels due to the migration of lateral and longitudinal bars after flooding events

4.2 Lithostratigraphy

After careful analysis of the described facies and reviewing the geological contributions of previous studies by Tanizaki (2013), Tanizaki et al. (2015), and Martins-Ferreira et al. (2018a), it was possible to compose three stratigraphic columns representative of the Água Morna Formation in the two most representative regions (this study, Fig. 8).

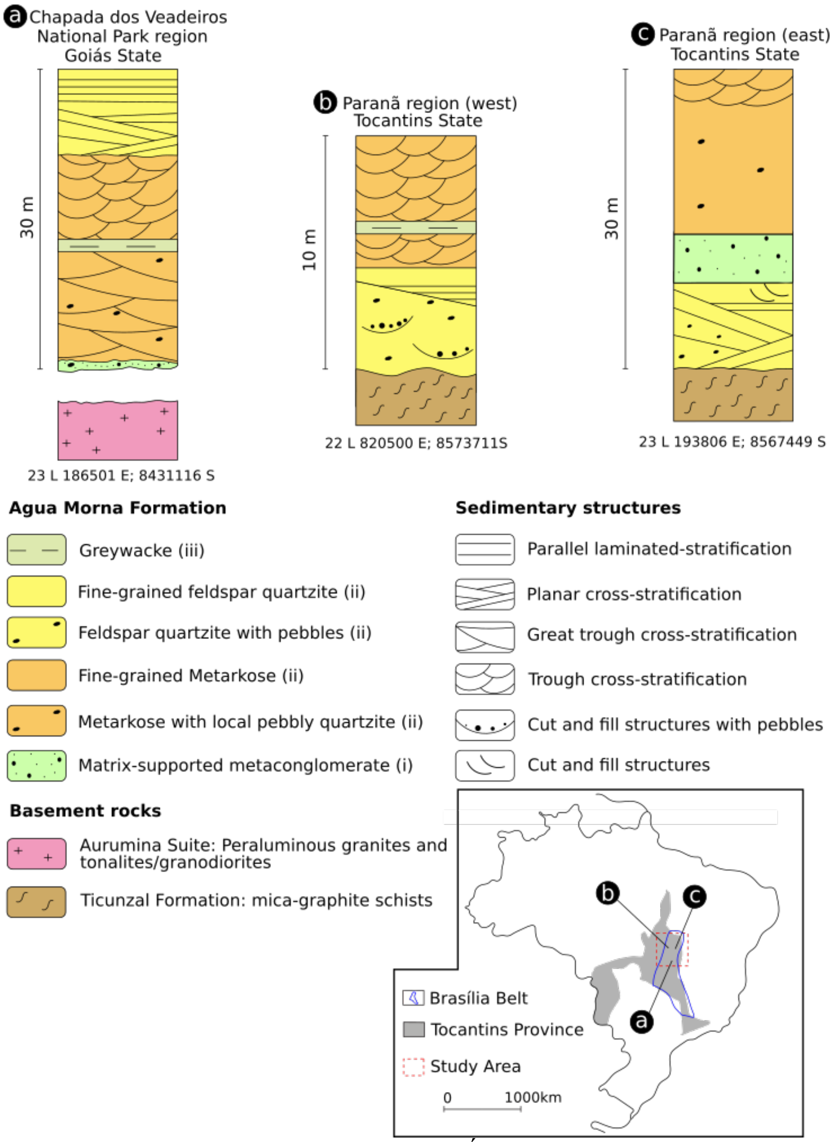


Fig. 8. Lithostratigraphic columns of different locations in the Água Morna Formation. The letters “a” to “c” indicate the locations of the columns shown in Fig. 4.

In the Chapada dos Veadeiros National Park (Fig. 8a), thin layers of matrix-supported metaconglomerate can be observed in the basal portion of the sequence (i). These rocks are overlaid by a thick sedimentary pack of feldspar quartzite and metarkose (ii), which may be intercalated with thin layers of metagreywacke (iii).

Further north, in the Paranã region (Figs. 8b and 8c), the basal portion is formed by feldspar quartzite (ii). It may contain matrix-supported metaconglomerate packages (i) and thin metagreywacke layers (iii). In the upper portions, metarkose prevails with local occurrence of pebbly quartzite (ii).

In all the described columns, several sedimentary structures occur (Fig. 8), such as planar cross-stratification, parallel laminated-stratification, overturned cross-stratification, trough cross-stratification, and cut and fill structure.

4.3 Geochronological data

The knowledge evolution in the last decade regarding the Veadeiros Supergroup is remarkable, starting with the proposition of the Veadeiros Supergroup itself, previously undefined, the establishment of a chronostratigraphic correlation between the Veadeiros and Espinhaço supergroups, as well as the redefinition of the Araí Group containing the Água Morna and Arraias Formations only, after geochronological and stratigraphic data revealed that the Traíras Formation belonged to a much younger basin, resulting in the proposition of the Traíras Group (Martins-Ferreira et al., 2018a). In addition, a considerable amount of detailed data was acquired via geological mapping, including petrological, stratigraphic, and geochronological studies (Tanizaki et al., 2015; Toscani et al., 2021a; Toscani et al., 2021b). In this way, it was possible to reinterpret detrital zircon data of literature.

Thus, samples PM 255 and PM 267, classified by Maques (2009) as belonging to the Traíras Group, were reclassified as feldspar quartzite, the main facies of the Água Morna Formation (Fig. 9). It is worth noting that one of the researchers in this study was in attendance in the fieldwork during the collection of these rock samples.

Sample PM 255 (Fig. 9a) yielded a single Neoarchean grain of 2.71 Ga, a minor Siderian source of ~2.44 Ga (Marques et al., 2009), and a significant Rhyacian source ranging from 2.25 to 2.05 Ga (Marques et al., 2009). Sample PM 267 (Fig. 9b) yielded a more prominent Siderian source from 2.47 to 2.32 Ga and also a significant Rhyacian source from 2.28 to 2.11 Ga (Marques et al., 2009).

5. Discussion

5.1 Depositional System of the Água Morna Formation

As previously described, the absence of significant faults and the lack of associated syn-sedimentary volcanism in the Água Morna Formation indicates that the basin was formed in a wide and shallow depression, at the limit of the elastic deformation of the upper crust (Tanizaki et al., 2015; Martins-Ferreira et al., 2018a).

More precisely, Tanizaki (2013) suggests that the Água Morna Formation was deposited in continental conditions with the presence of a sand-dominated braided river system. This system is rich in planar and trough cross-stratification structures related to channelized conditions, and the presence of massive to stratified sediments was interpreted as the nuclei of lateral and longitudinal sand bars. This depositional system thus is representative of a wide and shallow basin environment with high detritus load and high-energy transport conditions.

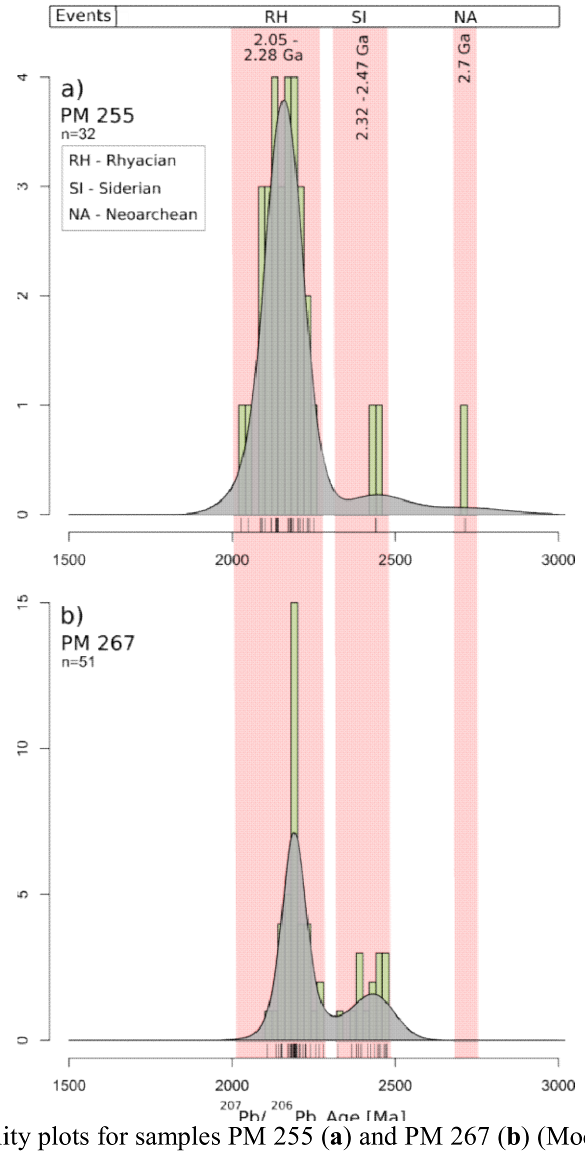


Fig. 9. Histogram, relative probability plots for samples PM 255 (**a**) and PM 267 (**b**) (Modified from Marques et al., 2009). It is possible to visualize a significant influence of ages related to the following age intervals: Neoarchean (NA), Siderian (SI), and Rhyacian (RH).

The pebbly deposits represent records of turbulent currents that occur during flooding events or small gravitational flow deposits, as expected in the braided systems, and cause the mixture of fine and coarse material in episodic sedimentation (Fig. 10). The fine-grained material related to the metagreywacke deposits is considered to represent abandoned channels due to the migration of lateral and longitudinal bars after flooding events.

In general, the Água Morna basin can be classified as a sag-intracontinental basin. In this sequence, a system of rivers that migrate to a central location was developed, creating relatively undeveloped river deposits, both laterally and vertically, if compared to the fluvial systems formed in the rift stage (Fig.10) (Tanizaki, 2013; Tanizaki et al., 2015).

The existence of an erosive unconformity between the Água Morna and Arraias formations as well as the classification of the Água Morna as a pre-rift, the fault-absent basin can be corroborated by the following observations in the dataset:

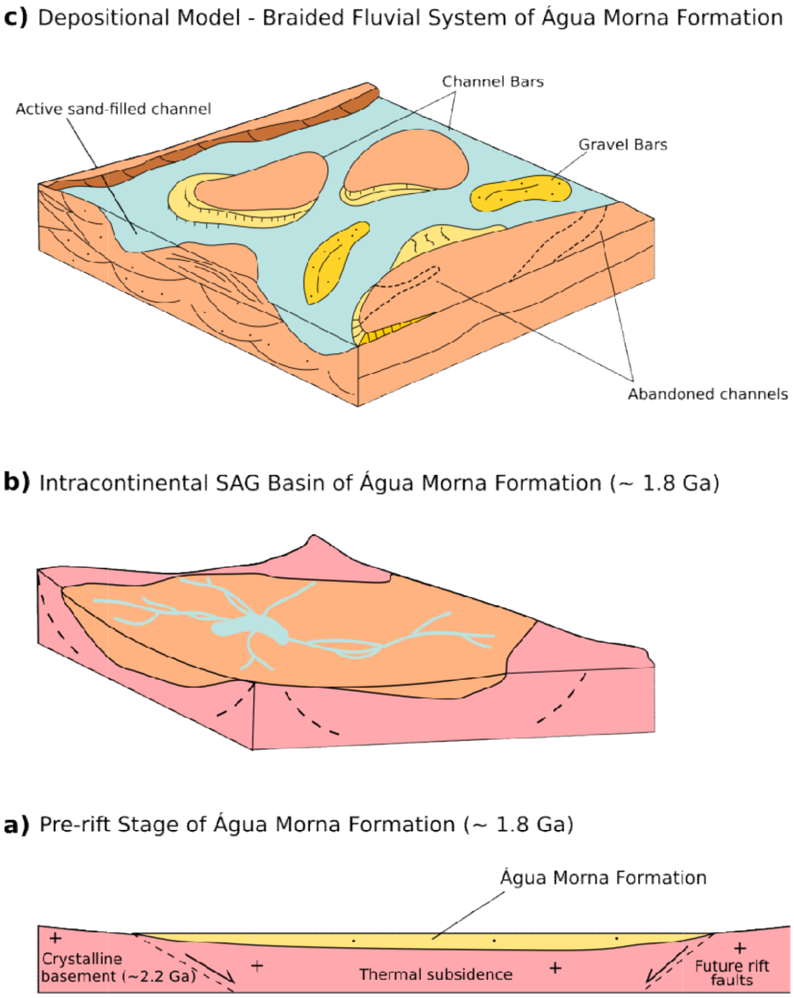


Fig. 10. Depositional model of the Água Morna Formation: **a)** pre-rift stage (modified from Ponte Filho, 1992; Neumann et al., 2008), **b)** braided fluvial system of Água Morna Formation (modified from Tanizaki, 2013), **c)** depositional model of braided fluvial system (adapted from Scherer et al., 2014; Kifumbi et al., 2017; future brittle faults represented in dashed lines).

- Absence of detrital zircon grains younger than 2.15 Ga at the basal succession. If this unit were at least coeval to the syn-rift volcanism, it would be expected younger grains of the bi-modal volcanic rocks dated at 1.77 Ga;
- The presence of well-rounded pebbles of quartzite and metarkose in the Arraias Formation is similar to those rocks found in the Água Morna Formation. If these units were coeval, the sandstone arkose would not be a reworked clast, considered the time needed to achieve the sufficient burial depth and later uplift that would be required for lithification, exposure, and erosion before clast formation;
- Absence of thick conglomerate succession, typical of alluvial fan deposition, related to normal fault scarps. Coarse-grained deposits should be quite commonly observed if the sandstone were related to the mechanical subsidence; and
- Discontinuity in the regional distribution of sediments in the Água Morna Formation, due to erosion and non-deposition.

5.2 Pre-rift stage of the Água Morna Formation

The global Paleoproterozoic extensional process known as Statherian Taphrogenesis allowed the formation of relatively synchronic continental basins with great variety in tectonic, magmatic, and sedimentary records, including the Araí rift system (Brito Neves et al., 1995; Tanizaki, 2013).

The Araí system was classified as a passive rift by Tanizaki (2013) and Martins-Ferreira et al. (2018b). Tensional stresses caused by passive rifting in the continental lithosphere tend to result in crustal collapse facilitated by normal faulting, which can allow hot mantle rocks to penetrate the lithosphere. Volcanic activity is hence only a secondary process during passive rifting (Allen & Allen, 2005; McKenzie, 1978). When compared to other examples of Statherian rifts as in Siberia (Guryanov & Peskov, 2017) and North China (Lu et al., 2002), the volcanic activity in the Araí Rift is scarce, with maximum thicknesses of 100 m for acid volcanism and rare occurrence of basalts (Alvarenga et al., 2007; Martins-Ferreira et al., 2018b; Toscani et al., 2021b; Silva, 2020).

In the present study, the rift model proposed by Falvey (1974) fits adequately in fieldwork and literature data from the Água Morna Formation and the Araí rift. In this model, the rift is divided into pre-rift, rift, and post-rift phases. According to this author, the uplift at the crust is caused by thermal expansion and phase-boundary migration in the lithosphere, which leads to crustal thinning by erosion and subsequent subsidence. Thus the pre-rift stage indicates very early regional tectonic activity (heating), which is a forerunner to the rift valley stage

(Falvey, 1974). Other examples of pre-rift basins around the world are the basin of Gabon (Precambrian-Cretaceous) (Mounguengui et al., 2002) and the intracratonic rift basins developed in northeastern Brazil during the early Cretaceous (Lourenço et al., 2021). In this last example, it is worth mentioning the sequence of Rio do Peixe (Devonian), which marks the pre-rift stage of the Neocomian-Barremian rift event in the South Atlantic opening (Lourenço et al., 2021).

The tectonic model proposed for the Araí rift by Martins-Ferreira et al. (2018a) led to the conclusion that only the pre-rift (Água Morna Formation) and rift (Arraias Formation) phases are preserved today or that the Araí rift might not have evolved to a post-rift sag phase.

According to Kifumbi (2017), there are two possible interpretations for the mechanism of formation of a rift basin. The first is during the initial stage of the rift, where the large, shallow basin is formed with the sedimentary input of fluvial systems (Morley, 2002; Kuchle & Scherer, 2010; Kuchle et al., 2011). The second possibility is that the initial tectonics induces several isolated basins associated with faults (Prosser, 1993; Bosence, 1998; Gawthorpe & Leeder, 2000).

In this study, the term pre-rift is used for the initial rift phase, as adopted by several authors (Falvey, 1974; Bueno et al., 2007; Bosence, 1998; Mounguengui et al., 2002; Staton, 2009; Rapozo et al., 2021). The Água Morna Formation is included in this phase, mainly characterized by the deposition of sediments before major faults are generated. These sediments are preserved only in the lower portion of the faults (Bosence, 1998; Miall, 2000).

Smaller, local faults generated at this stage do not affect the main drainage network, but they can redirect the drains in parallel directions (Gawthorpe & Leeder, 2000). After this initial stage, due to the progressive increase in tectonic activity with the evolution of the rift, the faults expand and connect laterally, continuing the rifting process.

According to Tanizaki et al. (2015), the Água Morna Formation was originated at the limit of the elastic deformation of the upper crust (thermal subsidence). The mechanism that created space for this sedimentation is therefore related to isostatic compensation adjustments and is mainly associated with the rising asthenosphere (Falvey, 1974; McKenzie, 1978).

All of these processes occurred before the nucleation of the main rift faults and the individualization of the grabens (Martins Ferreira et al., 2018c) that host the overlapping units, characterizing this unit as a product of the pre-rift phase of the basin (Tanizaki et al., 2015).

The recent study by Matenco & Haq (2020) reinforces this mechanism of subsidence, stating that space can be created by the overlying (or laterally displaced) sagging, brought on by thermal cooling of the stretched lithosphere, sometimes assisted by dynamic asthenospheric effects, conditioned by the presence of inherited rheological weakness zones, or by extreme lithospheric thinning effects driven by the exhumation of continental mantle lithosphere.

Thus, the Água Morna Formation is a wide and shallow sag-intracontinental basin, originated by a thermal subsidence mechanism, which is the basin supplied by braided river systems (Fig. 10), where the exposed basement is the main source area.

The pre-rift phase ends when the first major faults of the syn-rift phase develop, causing much deeper depressions in the surface of the crust (Kifumbi, 2017). The culmination of this process is known as the "climax stage", where transverse fault sedimentary systems are more prominent. Finally, there is the post-rift phase, which is marked by the end of active tectonism, a regional decrease in subsidence, with increasing progradational or aggradational conditions in depocentres (Prosser, 1993; Kuchle, 2010; Henstra et al., 2016; Kifumbi et al., 2017; Matenco & Haq, 2020).

5.3 Provenance and regional correlations

In the detrital zircon histograms, it is possible to identify two primary sources of Siderian (2.47 to 2.32 Ga) and Rhyacian (2.28 to 2.05 Ga) (Figs. 9 and 11) sediment. In addition, it is worth noting the presence of an isolated Neoarchean zircon age (2.71 Ga) (Figs. 9 and 11).

The Neoarchean detrital zircon age (2.71 Ga; Maques, 2009), according to Martins-Ferreira et al. (2018a), could be related to rocks from the granite-greenstone terranes from the Crixás or Goiás regions (Borges et al., 2017; Borges et al., 2021) or even from the Quadrilátero Ferrífero (South of São Francisco Craton) (Farina et al., 2016).

The Siderian source (2.47 to 2.32 Ga; Marques, 2009) can be related to the first magmatic pulses of the Cavalcante-Almas-Natividade block, varying from 2.3 to 2.4 Ga (Cruz, 2001; Cruz et al., 2003; Cuadros et al., 2017b). More specifically, it can be related to tonalitic/granodioritic rocks of the Almas Terrane (2.2 Ga to 2.5 Ga) (Fuck et al., 2014; Sousa et al., 2016; Saboia et al., 2020a). Recently, Martins-Ferreira et al. (2020) detailed two episodes of accretion for the Almas Terrane: i) early Siderian - episode S1 (2.52 to 2.46 Ga - Novo Jardim Terrane) and ii) Late Siderian - episode S2 (2.43 to 2.37 Ga - Novo Jardim Terrane).

Finally, an important zircon contribution ranging from 2.28 to 2.05 Ga (Marques, 2009) is related to the Rhyacian. According to Guadagnin & Chemale (2015), the Rhyacian age distribution is the most frequent age found in the Paleoproterozoic to Mesoproterozoic basins in the São Francisco Craton.

The source of these sediments is most probably related to the Cavalcante-Arraias Domain (Aurumina Terrane). In this domain, peraluminous granites and tonalites/granodiorites from the Aurumina Suite (2.11 to 2.16 Ga) (Cuadros et al., 2017a) and sequences of biotite-garnet paragneisses/mica-graphite schists of Ticunzal Formation (2.16 to 2.19 Ga) occur (Cuadros et al., 2017b). The Riachão do Ouro Group (2.24 to 2.20 Ga) (Almas Granite-Greenstone Terrane) (Costa, 1984; Cruz & Kuyumjian, 1998) and Boqueirão Magmatic Arc (2.32 to 2.2 Ga; Martins-Ferreira et al., 2020) could also represent important source areas.

Based on the stratigraphy proposed by Martins-Ferreira et al. (2018a) and detrital zircon data (Fig. 11), the dissociation between the Água Morna Formation (maximum depositional age of 2.15 Ga), the Arraias Formation (1.77 Ga depositional age due to the presence of volcanic rocks) and the Traíras Group (maximum depositional age of 1.54 Ga) are evident.

The Bandeirinha Formation is considered to be the basal unit of the southern Espinhaço Supergroup with maximum depositional age of 1737 ± 11 Ma (Fig. 11) (Santos et al., 2013). This unit consists of continental deposits composed of laminated sandstone packages interbedded with conglomerate beds and has three depositional systems: dominant braided river deposits, alluvial fans, and subordinate eolian sediments (Silva, 1998; Simplicio & Basilici, 2015). According to Santos et al. (2013), this unit is part of the initial stage of the rift system (Prosser, 1993), given the disconnection of the Bandeirinha Formation outcrop regions, the small area of deposition, the subaerial character of the basin with sufficient water to supply the fluvial systems during their development, the dominantly longitudinal drainage systems and paleorelief marked by small fault scarps and local areas with axial topographic highs.

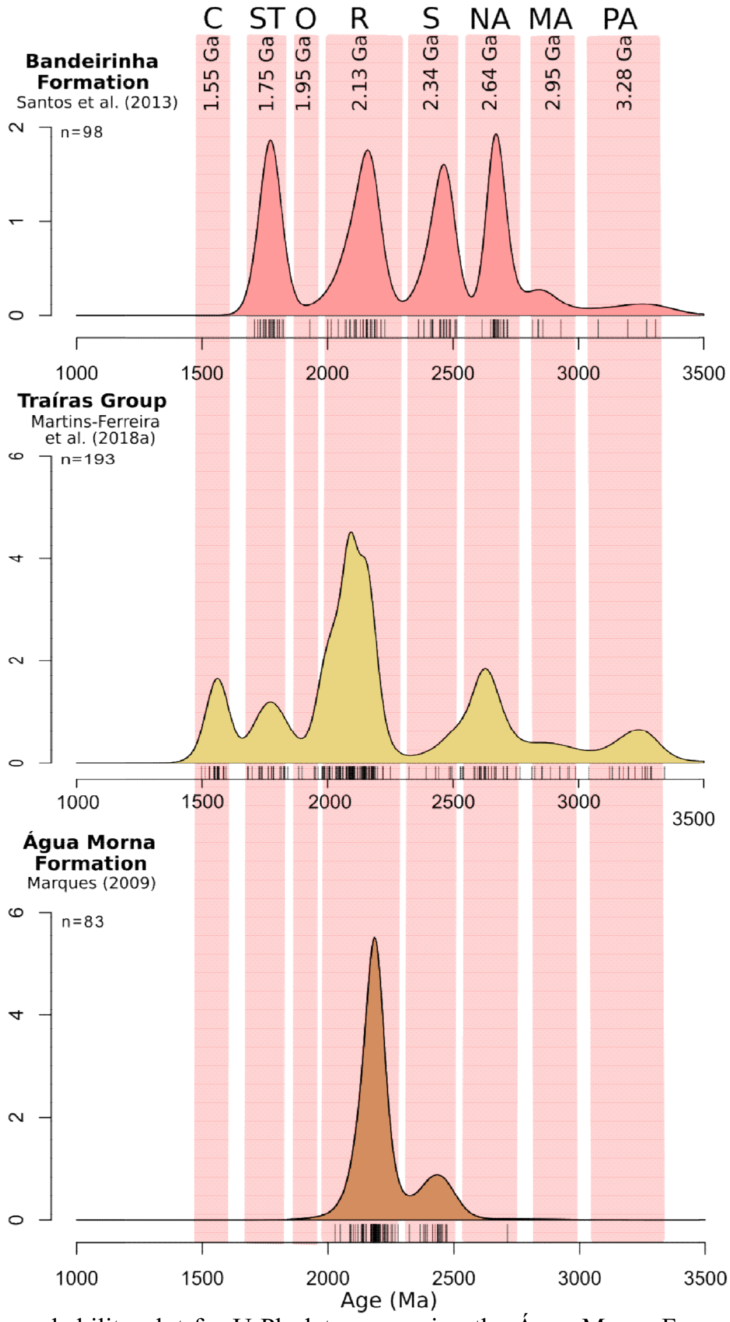


Fig. 11. Normalized age probability plot for U-Pb data comparing the Água Morna Formation, Traíras Group and Bandeirinha Formation (data respectively from Marques, 2009; Martins-Ferreira et al., 2018a; Santos et al., 2013). C: Calymmian; ST: Statherian; O: Orosirian; R: Rhyacian; S: Siderian; NA: Neoarchean; MA: Mesoarchean; PA: Paleoarchean.

Therefore, the main characteristics described in the literature for the Bandeirinha Formation are compatible with those described for the Água Morna Formation, such as lithological features, sedimentary environment, initial rift stage, discontinuity of the outcrops, and thermal subsidence mechanism. The older sedimentary source ages, however, vary significantly between the two, as shown in Fig. 11, since these basins were located far from each other.

6. Conclusions

The data presented and discussed in this work support the following conclusions:

- The Água Morna Formation is a sag-intracontinental basin, originated by thermal subsidence, filled by braided channels, where the local basement is the main source area.
- The absence of significant faults, thick deposits of conglomerate, and syn-sedimentary volcanism in the Água Morna Formation indicate the deposition of the basin in the pre-rift stage. This assumption is corroborated by the lack of the syn-rift typical faciology, including alluvial fans, aeolian dune systems, lacustrine, and associated fluvial environments.
- The facies and sedimentary structures found in this study indicate that the Água Morna Formation was deposited in continental conditions with the presence of a sand-dominated braided river system.
- At the end of the pre-rift phase, the first faults of the Araí rift caused the depressions, which allowed the preservation of the Água Morna Formation deposits. The surface that separates the Água Morna and Arraias formations represent an erosive unconformity.
- It is possible to interpret two main sources area ages, including: i) Siderian (2.47 to 2.32 Ga), interpreted as derived from the volcano-sedimentary sequences and intrusive rocks from the Almas Terrane, and ii) Rhyacian (2.28 to 2.05 Ga) derived from the Aurumina Terrane.
- Possibly, the Água Morna Formation can be correlated with the Banderirinha Formation (Espinhaço Supergroup) due to their similarities in terms of lithological features, sedimentary environment, and their position in the initial Statherian rift stage.

7. References

Abreu, F.R. 1991. Estudo das Mineralizações Auríferas Filoneanas da região da cidade de Diamantina/MG (Unpublished Msc. dissertation). Universidade de Campinas.

Alkmim F.F. 2004. O que faz de um cráton um cráton? O Cráton do São Francisco e as revelações almeidianas ao delimita-lo. In: Mantesso-Neto V., Bartorelli A., Carneiro C.D.R., Brito Neves B.B. (eds.), Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida. Brasil, Beca, 17-35.

Allen, P.A. & Allen, J.R. 2005. Basin analysis. Oxford, Blackwell, 549p.

Almeida, F.F.M. 1977. O Cráton do São Francisco. Revista Brasileira de Geociências, 7(4):349-364.

Almeida, F.F.M., Hasui, Y., Brito Neves, B.B., Fuck, R.A. 1981. Brazilian structural provinces: an introduction. Earth-Science Reviews, 17(1):1-29. DOI: 10.1016/0012-8252(81)90003-9

Alvarenga C.J.S., Botelho N.F., Dardenne M.A., Lima O.N.B., Machado M.A. 2006. Nota Explicativa da Folha SD.23-V-C-V (Cavalcante). Escala 1:100.000. Goiás, UnB/CPRM. 76p.

Alvarenga, C.J.S., Dardenne, M.A., Botelho, N.F., Lima, O.N.B., Machado, M.A., Almeida, T. 2007. Nota Explicativa das folhas SD.23-V-C-III (Monte alegre de Goiás), SD.23-VC-V (Cavalcante), SD.23-V-C-VI (Nova Roma). CPRM, Brasília, 65p.

Araújo, V.A., & Alves, A.C. 1979. Projeto Canabrava-Porto Real, Relatório Final. CPRM, Goiânia, 191p.

Babinski, M., Brito Neves, B.B., Machado, N., Noce, C.M., Uhlein, A., Van Schmus, W.R. 1994. Problemas da metodologia U/Pb em zircões de vulcânicas continentais: caso do Grupo Rio dos Remédios, Supergrupo Espinhaço, no Estado da Bahia. In: Congresso Brasileiro de Geologia, 42, Balneário Camboriú, Anais, 2:409-410.

Babinski, M., Pedreira, A.J., Brito Neves, B.B., Van Schmus, W.R. 1999. Contribuição à geocronologia da Chapada Diamantina. In: VII Simpósio Nacional de Estudos Tectônicos. Lençóis, Brazil, Anais, 2:118-120.

Babinski, M., Van Schmus, W.R., Chemale, F., Brito Neves, B.B., Rocha, A.J.D. 1993. Idade isocrônica Pb/Pb em rochas carbonáticas da Formação Caboclo, em Morro do Chapéu. In: Pedreira, A.J., Misi, A., Dominguez, J.M.L. (Eds.), II Simpósio sobre o Craton do São Francisco. Brazilian Geological Society, Salvador, 160-163p.

Barbosa, O., Baptista, M.B., Braun, O.P., Dyer, R.G., Cotta, J.C. 1969. Geologia e inventário dos recursos minerais do Projeto Brasília. Relatório Prospec/DNPM, Rio de Janeiro, 225p.

Borges, C.C.A., Toledo, C.L.B., Silva, A.M., Chemale, F., Jost, H., Lana, C.C. 2017. Geochemistry and isotopic signatures of metavolcanic and metaplutonic rocks of the Faina and Serra de Santa Rita greenstone belts, Central Brazil: evidences for a Mesoarchean intraoceanic arc. Precambrian, 353:106022. DOI: https://doi.org/10.1016/j.precamres.2017.02.017.

Borges, C.C.A., Toledo, C.L.B., Silva, A.M., Chemale, F., Santos, B.A., Figueiredo, F.L., Zacchi, E.N.P. 2021. Unraveling a hidden Rhyacian magmatic arc through provenance of metasedimentary rocks of the Crixás greenstone belt, Central Brazil, Precambrian Research, 353:106022. DOI: https://doi.org/10.1016/j.precamres.2020.106022

Bosence, D.W.J. 1998. Stratigraphic and sedimentological models of rift basins. In: Purser, B.H. & Bosence, D.W.J. (ed.). Sedimentation and tectonics of rift basins: Red Sea - Gulf of Aden. London: Chapman & Hall, 9-25p.

Brito Neves, B.B., Kawashita, K., Cordani, U.G., Delhal, J. 1979. A evolução geocronológica da Cordilheira do Espinhaço; dados novos e integração. Revista Brasileira de Geociências, 9(1):71-85.

Brito Neves, B.B., Sá, J.M., Nilson, A.N., Botelho, N.F. 1995. A Tafrogênese Estateriana nos blocos Paleoproterozoicos da América do Sul e processos subsequentes. Geonomos, 3:1-21.

Bueno, G.V., Zacharias, A.A., Oreiro, S.G., Cupertino, J.A., Falkenhein, F.U.H., Neto, M.A.M. 2007. Bacia de Pelotas. Boletim de Geociências da Petrobras, 15(2):551-559.

Campos, J.E.G., Almeida, T., Borges, W.R., Botelho, N.F., Dantas, E.L., Moura, M.A. 2010. Projeto Paranã - São Salvador do Tocantins. Undergraduate Final Essay, Institute of Geosciences, University of Brasília (Unpublished).

Campos, J.E.G., Dardenne, M.A., Freitas-Silva, F.H., Martins-Ferreira, M.A.C. 2013. Geologia do Grupo Paranoá na porção externa da Faixa Brasília. Revista Brasileira de Geociências 43:461-476. DOI: 10.5327/Z2317-48892013000300004.

Campos, J.E.G., Martins Ferreira, M.A.C., Moura, F.G., Chemale Jr, F. 2021. Discovery of Precambrian deep-water turbidites and submarine volcanism in the Brasilia Belt, central Brazil: The Quilombo Formation. Journal of South American Earth Sciences, 108:103226. DOI: https://doi.org/10.1016/j.jsames.2021.103226

Chaves M.L.S.C & Brandão P.R.G. 2004. Diamante variedade carbonado na Serra do Espinhaço (MG/BA) e sua enigmática gênese. Revista Escola de Minas, 57:33-38.

Chemale Jr., F., Dossin, I.A., Alkmim, F.F., Martins, M.S., Queiroga, G., Armstrong, R., Santos, M.N. 2012. Unravelling a Proterozoic basin history through detrital zircon geochronology: the case of the Espinhaço Supergroup, Minas Gerais, Brazil. Gondwana Res. 22:200-206.

Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X. 2013. Updated. The ICS International Chronostratigraphic Chart. Episodes 36:199-204.

Cordeiro, P.F.O. & Oliveira, C.G. 2017. The Goiás Massif: implications for a pre-Columbia 2.2-2.0 Ga continent-wide amalgamation cycle in central Brazil. Precambrian Res. 298:403-420. Https://doi.org/10.1016/j.precamres.2017.06.021.

Costa, J. B. S. (1984). Aspectos lito-estruturais e evolução crustal da região centro-norte de Goiás. Tese de Doutorado, Instituto de Geociências, Universidade Federal do Pará, 210 p.

Costa, A.F.O., Danderfer, A., Bersan, S.M. 2018. Record of a Statherian rift-sag basin in the Central Espinhaço Range: Facies characterization and geochronology. Journal of South American Earth Sciences, 82:311-328. DOI: https://doi.org/10.1016/j.jsames.2017.10.014

Cruz, E.L.C.C. & Kuyumjian, R.M., 1998. The geologyandtectonicevolutionofthe Tocantins granite-greenstoneterrane, Almas-Dianópolis region, Tocantins State, Central Brazil. Revista Brasileira de Geociências, 28(2):173-182.

Cruz, E. L. C. C., Kuyumjian, R. M., Boaventura, G. R. 2003. Low-K calc-alkaline granitic series of southeastern Tocantins State: Chemical evidence for two sources for the granite gneissic complexes in the Paleoproterozoic Almas-Dianópolis Terrane. Revista Brasileira de Geociencias, 33(2):125-136.

Cruz, E.L.C.C. 2001. A gênese e o contexto tectônico da mina Córrego Paiol, Terreno Almas-Conceição: um depósito de ouro hospedado em anfibolito do embasamento da Faixa de Dobramento Brasília. Doctoral dissertation, PhD thesis. Universidade de Brasília, 189p.

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017a. The peraluminous Aurumina Granite Suite in central Brazil: An example of mantle-continental crust interaction in a Paleoproterozoic cordilleran hinterland setting? Precambrian Research, 299:75-100. DOI: https://doi.org/10.1016/j.precamres.2017.07.029

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017b. The Ticunzal formation in central Brazil: record of Rhyacian sedimentation and metamorphism in the western border of the São Francisco Craton. J. S. Am. Earth Sci. 79:307-325. DOI: https://doi.org/10.1016/j.jsames.2017.08.014

Danderfer, A., Lana, C.C., Nalini, H.A., Costa, A.F.O. 2015. Constraints on the Statherian evolution of the intraplate rifting in a Paleo-Mesoproterozoic paleocontinent: New stratigraphic and geochronology record from the eastern São Francisco Craton. Gondwana Research, 28:668-688.

Dardenne, M.A. 2000. The Brasília Fold Belt. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 31st International Geological Congress, 231-263.

Dossin, I.A., Dossin, T. M., Charvet, J., Cocherie, A., Rossi, P. 1993. Single-Zircon dating by step-wise Pb-evaporation of Middle Proterozoic magmatism in the Espinhaço Range, southeastern São Francisco Craton (Minas gerais, Brazil). Anais II Simpósio Craton São Francisco, Salvador, 39-42.

Dyer, R.C. 1970. Grupo Araí - Um Grupo de Metamorfitos do Centro-Leste de Goiás. Revista da Escola de Minas. Ouro Preto, 28(2):55-63.

Falvey, D.A. 1974. The development of continental margins in plate tectonic theory. Australian Petroleum Exploration Journal, 14:95-106.

Farina, F., Albert, C., Martínez Dopico, C., Aguilar Gil, C., Moreira, H., Hippertt, J.P., Cutts, K., Alkmim, F.F., Lana, C. 2016. The Archean-Paleoproterozoic evolution of the Quadrilátero Ferrífero (Brasil): current models and open questions. J. S. Am. Earth Sci. 68:4-21. DOI: https://doi.org/10.1016/j.jsames.2015.10.015

Fuck, R.A., Dantas, E.L., Pimentel, M.M., Botelho, N.F., Armstrong, R., Laux, J.H., Junges, S.L., Soares, J.E., Praxedes, I.F. 2014. Paleoproterozoic crust-formation and reworking events in the Tocantins Province, central Brazil: A contribution for Atlantica supercontinent reconstruction. Precambrian Research, 244:53-74. DOI: https://doi.org/10.1016/j.precamres.2013.12.003

Fuck, R.A., Pimentel, M.M., Alvarenga, C.J.S., Dantas, E.L. 2017. The Northern Brasília Belt. In: São Francisco Craton, Eastern Brazil. Tectonic Genealogy of a Miniature Continent. Editors: Heilbron, M., Cordani, U.G., Alkmim, F.F. Regional Geology Reviews. Springer, 1ed, 205-220. DOI:10.1007/978-3-319-01715-0.

Gawthorpe, R.L. & Leeder, M. R. 2000. Tectono-sedimentary evolution of active extensional basins. Basin Research, 12(3-4):195-218.

Guadagnin, F., & Chemale, F. 2015. Detrital zircon record of the Paleoproterozoic to Mesoproterozoic cratonic basins in the São Francisco Craton. Journal of South American Earth Sciences, 60:104-116. DOI: https://doi.org/10.1016/j.jsames.2015.02.007

Guadagnin, F., Chemale, F., Magalhães, A.J., Santana, A., Dossin, I., Takehara, L. 2015. Age constraints on crystal-tuff from the Espinhaço Supergroup - Insight into the Paleoproterozoic to Mesoproterozoic intracratonic basin cycles of the Congo-São Francisco Craton. Gondwana Research, 27(1):363-376. DOI: https://doi.org/10.1016/j.gr.2013.10.009

Guryanov, V.A. & Peskov, A.Y. 2017. Ulkan Paleorift Structure in the South-Eastern Environs of the Siberian Platform: Age, Conditions, Sources, and Geodynamic Setting. Geosciences Research, 2(2):59-71. DOI: https://dx.doi.org/10.22606/gr.2017.22001

Henstra, G.A., Grundvag, S.-A., Johannessen, E.P., Kristensen, T.B., Midtkandal, I., Nystuen, J.P., Rotevatn, A., Surlyk, F., Sather, T., Windelstad, J. 2016. Depositional processes and stratigraphic architecture within a coarse-grained rift-margin Turbidite system: the Wollaston Forland Group, east Greenland. Mar. Petrol. Geol. 76:187-209.

Holz, M., Vilas-Boas, D.B., Troccoli, E.B., Santana, V.C., Vidigal-Souza, P.A. 2017. Conceptual Models for Sequence Stratigraphy of Continental Rift Successions. Stratigraphy & Timescales, 2:119-186. DOI: https://doi.org/10.1016/bs.sats.2017.07.002

Kifumb, C. 2017. Estratigrafia de alta resolução dos estágios iniciais de rifteamento, Bacia de Sergipe-Alagoas, Dissertação de Mestrado, Universidade Federal do Rio Grande do Sul, 74p.

Kifumbi, C., Scherer, C.M.D.S., Jones, F.H., Kuchle, J. 2017. High resolution stratigraphy of initial stages of rifting, Sergipe-Alagoas Basin, Brazil. Brazilian Journal of Geology, 47(4):657-671.

Kuchle J. & Scherer C.M.S. 2010. Sismoestratigrafia de bacias rifte: técnicas, métodos e sua aplicação na Bacia do Recôncavo. Boletim de Geociências da Petrobras, 18(2):33-60.

Kuchle, J. 2010. Análise tectono-estratigráfica de bacias rifte. Tese de doutorado. Universidade Federal do Rio Grande do Sul, 186p.

Kuchle, J., Scherer, C.M.S., Born, C.C., Alvarenga, R. S., Adegas, F. 2011. A contribution to regional stratigraphic correlations of the Afro-Brazilian - The Dom João Stage (Brotas Group and equivalent units - Late Jurrassic) in: Northeastern Brazilian sedimentary basins. Journal of South American Earth Science, 31:358-371.

Loureiro, H.S.C., Lima, E.S., Macedo, E.R., Silveira, F.V., Bahiense, I.C., Arcanjo, J.B.A., Moraes Filho, J.C., Neves, J.P., Guimarães, J.T., Teixeira, L.R., Abram, M.B., Santos, R.A., Melo, R.C. 2008. Projeto Barra-Oliveira dos Brejinhos Geological map. Brazilian Geological Survey and Bahia Mineral Research Company, scale 1:200000.

Lourenço, M. C. M., De Sá, E. F. J., Córdoba, V. C., Pichel, L. M. 2021. Multi-scale tectono-stratigraphic analysis of pre- and syn-rift sequences in the Rio do Peixe Basin, NE Brazil. Marine and Petroleum Geology, 130:105127.

Lu, S.N., Yang, C.L., Li, H.K., Li, H.M. 2002. A group of rifting events in the terminal Paleoproterozoic in the North China Craton. Gondwana Research, 5(1):123-131. DOI: http://dx.doi.org/10.1016/S1342- 937X(05)70896-0.

Magalhães, J.R., Pedrosa-Soares, A., Dossin, I., Müntener, O., Pinheiro, M.A.P., Silva L.C., Knauer, L.G., Bouvier, A., Baumgartner, L. 2018. First Lu-Hf, δ18O and trace elements in zircon signatures from the Statherian Espinhaço anorogenic province (Eastern Brazil): geotectonic implications of a silicic large igneous province. Brazilian Journal of Geology, 48(4):735-759. DOI: 10.1590/2317-4889201820180046.

Marini, J.O., Botelho, N.F., Rossi, Philippe. 1992. Elementos Terras Raras em granitóides estaníferos de Goiás. Revista Brasileira de Geociências, 22(1):61-72.

Marques, G.C. 2009. Geologia dos grupos Araí e Serra da Mesa e seu embasamento no sul do Tocantins. Dissertação de Mestrado, Universidade de Brasília, 116p.

Martins-Ferreira, M.A.C. 2017. Evolução tectônica das bacias Araí, Traíras e Paranoá na Faixa Brasília Norte. Tese de Doutorado. Instituto de Geociências. Universidade de Brasília, 202p.

Martins-Ferreira, M.A.C., Chemale, F., Coelho Dias, A.N., Campos, J.E.G. 2018a. Proterozoic intracontinental basin succession in the western margin of the São Francisco Craton: Constraints from detrital zircon geochronology. Journal of South American Earth Sciences, 81:165-176. DOI: https://doi.org/10.1016/j.jsames.2017.11.018.

Martins-Ferreira, M.A.C., Campos, J.E.G., Von Huelsen, M.G. 2018b. Tectonic evolution of the Paranoá basin: New evidence from gravimetric and stratigraphic data. Tectonophysics, 734:44-58. DOI: https://doi.org/10.1016/j.tecto.2018.04.004

Martins-Ferreira, M. A. C., Campos, J. E. G., VonHuelsen, M. G., Neri, B. L. 2018c. Paleorift structure constrained by gravity and stratigraphic data: the Statherian Araí rift case. Tectonophysics, 738, 64-82.

Martins-Ferreira, M.A.C., Dias, A.N.C., Chemale., F., Campos, J.E.G., Seraine, M., Novais-Rodrigues, E. 2020. Multistage crustal accretion by magmatic flare-up and quiescence intervals in the western margin of São Francisco Craton: U-Pb-Hf and geochemical constraints from the Almas Terrane. Gondwana Research. 85:32-54. DOI: https://doi.org/10.1016/j.gr.2020.04.005

Matenco, L.C., & Haq, B.U. 2020. Multi-scale depositional successions in tectonic settings. Earth Sci. Rev. 200:102991. https://doi.org/10.1016/j.earscirev.2019.102991.

Matteini, M., Dantas, E.L., Pimentel, M.M., Alvarenga, C.J.S., Dardenne, M.A. 2012. U-Pb and Hf isotope study on detrital zircons from the Paranoá Group, Brasília Belt Brazil: Constraints on depositional age at Mesoproterozoic-Neoproterozoic transition and tectono-magmatic events in the São Francisco Craton. Precambrian Research, 206:168-181. DOI: 10.1016/j.precamres.2012.03.007

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters, 40:25-32.

Miall, A.D. 2000. Principles of sedimentary basin analysis. 3. ed. New York: SpringerVerlag, 616p.

Morley, C.K. 2002. Evolution of large normal faults: Evidence from seismic reflection data. The American Association of Petroleum Geologists Bulletin, 86(6):961-978.

Mounguengui, M.M., Lang, J., Guiraud, M., Jocktane, O. 2002. Sedimentary dynamics and structural geology of pre-rift deposits of the Cretaceous Interior Basin of Gabon. J. Afr. Earth Sci 35:315-329. DOI: https://doi.org/10.1016/S0899-5362(02)00035-0

Neumann, V. H., Aragão, M. A. F., Valença, L. M. M., Leal, J. P. 2008. Ambientes Lacustres (Cap. 5). In: Silva et al., Eds. Ambientes de Sedimentação Siliciclástica do Brasil, Beca-BALL Edições, São Paulo, 343p.

Pimentel, M.M. 2016. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. Brazilian Journal of Geology, 46(1):67-82. DOI: 10.1590/2317-4889201620150004.

Pimentel, M.M., Heaman, L., Fuck, R.A., Marini, O.J. 1991. U-Pb zircon chronology of Precambrian tin-bearing continental-type acid magmatism in central Brazil. Precambrian Research, 52(3-4):321-335. DOI: https://doi.org/10.1016/0301-9268(91)90086-P

Pinto C.P., & Silva M.A. 2014. Mapa Geológico do Estado de Minas Gerais, Brasil. Escala 1:1.000.000. Belo Horizonte, CODEMIG - CPRM.

Ponte Filho, F.C. 1992. Análise geohistórica do poço 2-AP-1-CE, bacia do Araripe. 2º Simpósio Sobre Bacias Cretáceas Brasileiras, Rio Claro, UNESP/IGCE, 85-89.

Prosser, S. 1993. Rift-related linked depositional systems and their seismic expression. Geological Society, London, Special Publications, 71:35-66.

Rapozo, B. F., Córdoba V.C., Antunes, A.F. 2021. Tectono-stratigraphic evolution of a cretaceous intracontinental rift: Example from Rio do Peixe Basin, north-eastern Brazil. Marine and Petroleum Geology Volume 126, 27p. https://doi.org/10.1016/j.marpetgeo.2021.104899

Rodrigues, J.B., Pimentel, M.M., Dardenne, M.A., Armstrong, R.A. 2010. Age, provenance and tectonic setting of the Canastra and Ibiá Groups (Brasília Belt, Brazil): Implications for the age of a Neoproterozoic glacial event in central Brazil. Journal of South American Earth Sciences, 29(2):512-521. DOI: 10.1016/j.jsames.2009.08.008

Saboia, A.M., Oliveira, C.G., Dantas, E.L., Cordeiro, P., Scandolara J.E., Rodrigues, J.B., Sousa, I.M.C. 2020a. The Siderian crust (2.47-2.3 Ga) of the Goiás Massif and its role as a building block of the São Francisco paleocontinent, 350:105901. DOI: https://doi.org/10.1016/j.precamres.2020.105901

Saboia, A.M., Oliveira, C.G., Dantas, E.L., Scandolara J.E., Cordeiro, P., Rodrigues, J.B., Sousa, I.M.C. 2020b. The 2.26 to 2.18 Ga Arc-Related Magmatism of the Almas-Conceição do Tocantins Domain: An Early Stage of the São Francisco Paleocontinent Assembly in Central Brazil, 104:102757. DOI: https://doi.org/10.1016/j.jsames.2020.102757

Santos, M.N., Chemale Jr., F., Dossin, I.A., Martins, M., Assis, T.A.R., Jelinek, A.R., Guadagnin, F., Armstrong, R. 2013. Sedimentological and paleoenvironmental constraints of the Statherian and Stenian Espinhaço rift system, Brazil. Sediment. Geol. 290:47-59.

Scherer, C.M.S., Jardim de Sá E.F., Córdoba V.C., Sousa D.C., Aquino M.M., Cardoso F.M.C. 2014. Tectono-stratigraphic evolution of the Upper Jurassic-Neocomian rift succession, Araripe Basin, Northeast Brazil. Journal of South American Earth Sciences, 49:106-122.

Schobbenhaus, C. & Brito Neves, B.B. 2003. A Geologia do Brasil no contexto da plataforma Sul-Americana. In: Bizzi, L.A., Schobbenhaus, C., Vidoti, R.M., Gonçalves, J.H. (Eds). Geologia, Tectônica e Recursos Minerais do Brasil, CPRM, Serviço Geológico do Brasil, Brasília, 169-226p.

Schobbenhaus, C. & Bellizzia, A. (coords.). 2001. Mapa geológico da América do Sul, 1: 5.000.000. CGMW - CPRM - DNPM - UNESCO, Brasília.

Schobbenhaus, C., Hoppe, A., Baumann, A., Lork, A. 1994. Idade U/Pb do vulcanismo Rio dos Remédios, Chapada Diamantina, Bahia. In: Congresso Brasileiro de Geologia, 38, Balneário Camboriú, Anais, 2:397-399.

Seraine, M., Campos, J.E.G., Martins-Ferreira, M.A.C., Giorgioni, M., Angelo, T.V. 2020. Tectonic significance of abrupt immature sedimentation in a shallow cratonic margin basin: The Arkose Level, Mesoproterozoic Paranoá Group. Journal of South American Earth Sciences, 97:102397. https://doi.org/10.1016/j.jsames.2019.102397

Silva, R.R. 1998. As bacias proterozóicas do Espinhaço e São Francisco em Minas Gerais: Uma abordagem do ponto de vista da estratigrafia de sequências. Geonomos, 6:1-12.

Silva, C.C. 2020. Petrografia, geoquímica e geocronologia das rochas vulcânicas efusivas e piroclásticas da Formação Arraias, Grupo Araí, nordeste de Goiás. Tese de doutorado n° 163. Universidade de Brasília, Brasília-DF, 119p.

Silveira, E.M., Söderlund, U., Oliveira, E.P., Ernst, R.E., Menezes Leal, A.B. 2013. First precise U-Pb baddeleyite ages of 1500 Ma mafic dykes from the São Francisco Craton, Brazil, and tectonic implications. Lithos, 144-156.

Simplicio, F. & Basilici, G. 2015. Unusual thick eolian sand sheet sedimentary succession: Paleoproterozoic Bandeirinha Formation, Minas Gerais. Braz. J. Geol. 45(1):3-11. DOI:https://doi.org/10.1590/2317-4889201530133

Sousa, I.M.C., Giustina M.E.S.D., Oliveira C.G. 2016. Crustal evolution of the northern Brasília Belt basement, central Brazil: A Rhyacian orogeny coeval with a pre-Rodinia supercontinent assembly. Precambrian Research, 273:129-150. https://doi.org/10.1016/j.precamres.2015.12.007.

Tanizaki, M.L.N. 2013. Geologia do Grupo Araí: exemplo de rifte continental no Brasil Central. Dissertação de Mestrado, Universidade de Brasília, 13p.

Tanizaki, M.L.N., Campos, J.E.G., Dardenne, M.A. 2015. Stratigraphy of the Araí Group: Record of Paleoproterozoic rifting in Central Brazil. Brazilian Journal of Geology, 45(1):95-108. DOI: 10.1590/23174889201500010007.

Toscani, R., Campos, J.E.G., Martins-Ferreira, M.A.C., Matos, D.R., Borges, C.C.A., Dias, A.N.C., Chemale Jr, F. 2021b. The Natividade Basin evolution (central Brazil) constrained by U/Pb geochronology, sedimentology, and paleogeography, Journal of South American Earth Sciences. Submitted.

Toscani, R., Campos, J.E.G., Matos, D.R., Martins-Ferreira, M.A.C. 2021a. Complex depositional environments on a siliciclastic carbonate platform with shallow-water turbidites: The Natividade Group, central Brazil, Journal of South American Earth Sciences. DOI: http:/doi.org/10.1016/j.jsames.2020.102939.

Uhlein, A., Paim, P.S.G., Tassinari, C.C.G., Pedreira, A.J. 2015. Análise estratigráfica de bacias rifte Paleo-Mesoproterozoicas dos crátons Amazônico e São Francisco, Brasil. Geonomos, 23(2):1-13. DOI: 10.18285/geonomos.v23i2.707.

CAPÍTULO 6

DISCUSSÃO E CONCLUSÃO INTEGRADA

5.1 Discussão Integrada

O presente estudo contribuiu de forma significativa com a ampliação do conhecimento sobre as bacias metassedimentares Paleo/Mesoproterozoicas situadas na porção externa da Faixa Brasília Setentrional, especialmente no que tange ao Grupo Araí (Formação Água Morna) e ao Grupo Natividade.

Inicialmente, durante a acreção orogênica que ocorreu entre 2,5 a 2,2 Ga, houve amalgamação dos microblocos que compõem o Cráton São Francisco, formando na região os Terrenos Aurumina (2,16 - 2,11 Ga) e Almas (2,24 - 2,20 Ga) (Fuck et al., 2014; Cuadros et al., 2017; Martins-Ferreira et al., 2020).

Após esse processo de colagem crustal, a região experimentou um período de estabilidade tectônica que perdurou até o início do Estateriano (~1,78 Ga), quando essa área foi submetida a processos de extensão crustal que atuaram de forma mais intensa na porção sul, gerando as fases pré-rifte e rifte da Bacia Araí com magmatismo bimodal bem marcado na Formação Arraias. Ao norte, na região de Natividade, houve apenas pequenos pulsos magmáticos, sem o desenvolvimento de fases de rifteamento (subsidência mecânica).

Na região próxima às localidades de Paranã, Arraias, Monte Alegre de Goiás e Alto Paraíso de Goiás, houve a deposição da Formação Água Morna, a qual marca o processo inicial que culminaria com o rifteamento crustal (fase pré-rifte) controlado por subsidência termal conforme modelo proposto por Falvey (1974). Essa unidade é depositada em bacia rasa, ampla e descontínua, sem a presença de falhamentos significativos. Os depósitos são característicos de rios entrelaçados dominados por areias, com canais ativos, barras laterais e canais abandonados. As principais áreas fontes são o embasamento local, com picos no Sideriano (2,47 a 2,32 Ga; Marques, 2009) e no Riaciano (2,28 a 2,05 Ga; Marques, 2009) que compõem, respectivamente, os terrenos Almas e Aurumina. A ausência de grãos de zircão mais jovens que 2,15 Ga, além das características geológicas dessa bacia, indicam que a deposição desta unidade é anterior ao vulcanismo do rifte Araí.

Possivelmente, a Formação Água Morna apresenta correlação com a Formação Bandeirinha, posicionada na base do Supergrupo Espinhaço (Silva, 1998). A Formação Bandeirinha é caracterizada por depósitos continentais ricos em quartzitos intercalados com delgadas camadas e lentes de conglomerados, sendo também relacionada a depósitos continentais (leques aluviais, rios entrelaçados e dunas eólicas) e aos estágios iniciais de rifte (Silva, 1998; Simplicio & Basilici, 2015). Vale ressaltar que a idade máxima de deposição de

1,74 Ga (Santos et al., 2013) não é um fator excludente para essa correlação, uma vez que é possível haver diacronismo com relação ao início dos processos de extensão crustal quando consideradas diferentes regiões.

Posteriormente, após a deposição da Formação Água Morna, ocorreu à nucleação das falhas principais do rifte Araí, com a deposição de espessos pacotes de sedimentos continentais da Formação Arraias em sistemas deposicionais de leques aluviais (muito espessos), fluviais, eólicos e lacustres (Tanizaki et al., 2015).

Até o presente estudo, não há relatos da ocorrência de rochas relacionadas ao pós-rifte do Grupo Araí. Ou seja, essa fase pode não ter sido preservada no registro geológico, ou o rifte Araí não chegou a desenvolver esse estágio.

O próximo registro sedimentar significativo ocorre ao norte, denominado de Grupo Natividade, com idade máxima de deposição de 1,78 Ga. Essa sucessão é separada do Grupo Araí (ao sul) pelo Bloco Almas (2,46 Ga; Martins-Ferreira et al., 2020). O Grupo Natividade apresenta registro vulcânico restrito (1,82 Ga), possivelmente relacionado ao magmatismo que gerou o rifte do Araí. Isso é reforçado quando se compara a geoquímica das rochas ácidas do Grupo Araí (Silva, 2020) com a metavulcânica (dacito) do Grupo Natividade, em que se observa significativa semelhança entre os padrões de elementos maiores e terras raras.

Entretanto, no Grupo Natividade não há indícios de processos de rifteamento, sem a presença de falhamento significativo nem de depósitos continentais típicos da Formação Arraias. Na realidade, o Grupo Natividade é caracterizado por uma bacia controlada por subsidência termo-flexural originada durante o rebalanço isostático posterior ao rifte Araí. O paleorelevo elevado do Bloco Almas permitiu uma bacia mais rasa na porção sul do Grupo Natividade com a deposição de carbonatos em uma plataforma mista e turbiditos de águas rasas. Para norte, com o aprofundamento da bacia, houve a deposição de sedimentos siliciclásticos finos.

Por fim, no Calimiano, após um lapso temporal maior que 200 Ma, houve a deposição dos grupos Traíras e Serra da Mesa (com idades máximas de deposição, respectivamente, de 1,54 Ga e 1,55 Ga) controlados por subsidência flexural, sendo consideradas bacias do tipo sag-intracontinental (Martins-Ferreira et al., 2018). Esses grupos são constituídos por arenitos, lutitos e carbonatos com diferenças metamórficas e variações laterais oriundas de mudanças de paleorelevo e fontes de sedimentos distintas.

Uma observação importante é referente à interpretação que as fácies conglomeráticas do Grupo Natividade são relacionadas aos fluxos de detritos subaquosos associados à turbiditos de água rasa e não aos depósitos gravitacionais do tipo *fan delta*. Assim, na tabela 1, são listados os principais argumentos que permitem confirmar a interpretação proposta:

Tabela 1. Principais diferenças entre os fluxos de detritos subaquosos associados à turbiditos de água rasa (Grupo Natividade) e os depósitos gravitacionais do tipo *fan delta* (Fenton & Wilson, 1985; Gawthorpe & Colella, 1990; Mutti et al., 2007).

Tipos de fluxos gravitacionais	Turbiditos de água rasa (Grupo Natividade)	*Fan delta*
Geometria dos depósitos	Depósitos com ampla continuidade lateral. Apresentam-se estratificados com contatos abruptos de fácies arenosas e argilosas	Depósitos maciços ou pouco estratificados, com pequena continuidade lateral e comumente com gradação normal
Características dos conglomerados	Clastos mineralogicamente maturos compostos por quartzito e veios de quartzo. Ausência de clastos de composição imatura (granítica, vulcânica, xistosas...)	Clastos imaturos com ampla predominância de rochas do embasamento local como granitos, vulcânicas e xistos. Rochas submetidos a pequeno transporte
Ambiente deposicional	Rochas siliciclásticas do Grupo Natividade se interdigitam com diversos tipos carbonatos (inclusive estromatólitos), indicando deposição em águas rasas	Associados a águas mais profundas, no sopé de falhas de maiores rejeitos que controlam a própria deposição gravitacional

Por fim, a correlação direta entre os grupos Natividade e Araí é impossibilidade em função de dois argumentos principais:

- ausência de depósitos continentais na bacia Natividade, principalmente de sedimentos de leques aluvionares comuns no Grupo Araí; e
- descontinuidade das rochas sedimentares e estruturas tectônicas que é observada entre estas sucessões sedimentares. Entre o extremo norte de ocorrência do Grupo Araí e o extremo sul das áreas cartografadas como Grupo Natividade existe uma faixa de cerca de 100 km sem a presença de rochas atribuídas a estas unidades.

5.2 Conclusões

5.2.1 Grupo Natividade

No que tange ao Grupo Natividade, os dados apresentados e analisados permitiram alcançar as seguintes conclusões:

- O mapeamento geológico permitiu observar uma predominância de carbonatos, quartzitos seixosos e conglomerados mais ao sul, e a ocorrência de filitos e metarritmitos mais ao norte, indicando um aprofundamento da bacia de sul para norte;
- Existem quatro associação de fácies correspondendo às condições específicas de deposição:
  - Areno-silto-carbonática – plataforma mista com deposição siliciclástica e carbonática;
  - Areno-conglomerática – turbiditos de água rasa controlados pelo paleorelevo;
  - Arenosa – plataforma interna em condições de *backshore* e *foreshore*; e
  - Silto-argilosa – plataforma externa siliciclástica.
- O Grupo Natividade é caracterizado por uma plataforma mista com ocorrência de turbiditos de água rasa (depósitos de fluxo de massa). O embasamento apresenta importante fator na sedimentação, visto que o paleorelevo permitiu uma complexa deposição lateral de

sedimentos, com plataformas mista (siliciclástica-carbonática), interna e externa (siliciclástica);

- O vulcanismo observado no Grupo Natividade é restrito espacialmente e ocorre diretamente sobre o embasamento. Suas características geoquímicas são compatíveis com o vulcanismo ácido do Grupo Araí;
- A rocha metavulcânica ácida apresentou idade de 1824 ± 25 Ma; e a idade máxima de deposição das rochas metassedimentares foi de 1775 ± 2,45 Ma. Esses dados geocronológicos em conjunto com dados sedimentológicos indicam que o Grupo Natividade teve sua evolução sedimentar entre os grupos Araí e Traíras/Serra da Mesa; e
- O modelo de deposição observado no Grupo Natividade é único quando comparado às outras bacias rifte-sag Paleo-Mesoproterozoicas. Isso é explicado pelo tipo de subsidência (termo-flexural), bem como pelo paleorelevo local e regional.

5.2.2 Formação Água Morna

Em relação à Formação Água Morna, o estudo permitiu enumerar às seguintes conclusões:

- A Formação Água Morna foi depositada em uma bacia do tipo sag-intracontinental, submetida à subsidência termal, com preenchimento por depósitos de rios entrelaçados (Falvey, 1974; Tanizaki et al., 2015), em que o embasamento local é a fonte principal de sedimentos;
- A ausência de falhamentos significativos, depósitos espessos de conglomerados e vulcanismo sinsedimentar indicam uma deposição em uma fase de pré-rifte conforme modelo de Falvey (1974); e
- Há duas fontes principais de sedimentos. A primeira do Sideriano (2,47 a 2,32 Ga; Marques, 2009) relativa ao Terreno Almas e a segunda do Riaciano (2,28 a 2,05 Ga; Marques, 2009) oriunda do Terreno Aurumina.

5.2.3 Conclusões Gerais

Integrando os dados dos capítulos 3, 4 e 5, e adotando o modelo de rifteamento proposto por Falvey (1974) (pré-rifte, rifte e pós-rifte) é possível enumerar às seguintes conclusões:

- A Formação Água Morna marca o estágio pré-rifte (subsidência termal) do evento extensional da Bacia Araí. A subsidência mecânica posterior com o a nucleação das falhas da fase rifte, permitiu a preservação da Formação Água Morna em depressões pouco extensas;
- Após a deposição da Formação Água Morna, ocorreu à nucleação das falhas e a deposição da Formação Arraias, com uma associação dos sistemas deposicionais de leques aluviais, fluviais, eólicos e lacustres típicos da fase sin-rifte. Em seguida, mais ao norte, separado pelo

Bloco Almas (2,46 Ga; Martins-Ferreira et al., 2020), houve a deposição do Grupo Natividade, com vulcanismo restrito e de características semelhantes ao vulcanismo ácido do rifte Araí. Por fim, separados por um lapso temporal de cerca de 200 Ma (Martins-Ferreira et al., 2018) houve a deposição dos Grupos Traíras/Serra da Mesa; e

- A proveniência dos sedimentos do Grupo Natividade é mais restrita quando comparada com as observadas nos grupos Araí, Traíras e Serra da Mesa. Isso é corroborado pelos histogramas de U/Pb de zircão detrítico e pela interferência do paleorelevo na deposição do Grupo Natividade.

5.3 Referências

Cuadros, F.A., Botelho, N.F., Fuck, R.A., Dantas, E.L. 2017. The peraluminous Aurumina Granite Suite in central Brazil: An example of mantle-continental crust interaction in a Paleoproterozoic cordilleran hinterland setting? PrecambrianResearch, 299:75-100p. DOI: https://doi.org/10.1016/j.precamres.2017.07.029

Falvey, D.A. 1974. The development of continental margins in plate tectonic theory. Australian Petroleum Exploration Journal, 14:95-106.

Fenton, M.W. & Wilson, C.J.L. 1985. Shallow-water turbidites: an example from the Mallacoota Beds, Australia. Sedimentary Geology, 45:31-260.

Fuck, R.A., Dantas, E.L., Pimentel, M.M., Botelho, N.F., Armstrong, R., Laux, J.H., Junges, S.L., Soares, J.E., Praxedes, I.F. 2014. Paleoproterozoic crust-formation and reworking events in the Tocantins Province, central Brazil: A contribution for Atlantica supercontinent reconstruction. Precambrian Research, 244:53-74. DOI: https://doi.org/10.1016/j.precamres.2013.12.003

Gawthorpe R. L. & Colella A. 1990. Tectonic controls on coarsegrained delta depositional systems in rift basins. In: Colella, A.& Prior, D.(Eds.), Coarse-grained Deltas, Spec. Publ. Int. Assoc. Sediment., 10, p. 113–120.

Marques, G.C. 2009. Geologia dos grupos Araí e Serra da Mesa e seu embasamento no sul do Tocantins. Dissertação de Mestrado, Universidade de Brasília, 116p.

Martins-Ferreira, M.A.C., Chemale, F., Coelho Dias, A.N., Campos, J.E.G. 2018. Proterozoic intracontinental basin succession in the western margin of the São Francisco Craton: Constraints from detrital zircon geochronology. Journal of South American Earth Sciences, 81:165-176. DOI: https://doi.org/10.1016/j.jsames.2017.11.018.

Martins-Ferreira, M.A.C., Dias, A.N.C., Chemale., F., Campos, J.E.G., Seraine, M., Novais-Rodrigues, E., 2020. Multistage crustal accretion by magmatic flare-up and quiescence intervals in the western margin of São Francisco Craton: U-Pb-Hf and geochemical constraints from the Almas Terrane. Gondwana Research. 85:32-54. DOI: 10.1016/j.gr.2020.04.005

Mutti, E., Tinterri, R., Magalhaes, P.M., Bastam, G. 2007. Deep-Water Turbidites and Their Equally Important Shallower Water Cousins. Adapted from Extended Abstract prepared for presentation at AAPG Annual Convention, Long Beach, California, April 1-4.

Santos, M.N., Chemale Jr., F., Dossin, I.A., Martins, M., Assis, T.A.R., Jelinek, A.R., Guadagnin, F., Armstrong, R. 2013. Sedimentological and paleoenvironmental constraints of the Statherian and Stenian Espinhaço rift system, Brazil. Sediment. Geol. 290:47-59.

Silva, C.C. 2020. Petrografia, geoquímica e geocronologia das rochas vulcânicas efusivas e piroclásticas da Formação Arraias, Grupo Araí, nordeste de Goiás. Tese de doutorado n° 163. Universidade de Brasília, Brasília-DF, 119p.

Silva, R.R. 1998. As bacias proterozóicas do Espinhaço e São Francisco em Minas Gerais: Uma abordagem do ponto de vista da estratigrafia de sequências. Geonomos, 6:1-12.

Simplicio, F. & Basilici, G. 2015. Unusual thick eolian sand sheet sedimentary succession: Paleoproterozoic Bandeirinha Formation, Minas Gerais. Braz. J. Geol. 45(1):3-11. DOI:https://doi.org/10.1590/2317-4889201530133

Tanizaki, M.L.N., Campos, J.E.G., Dardenne, M.A. 2015. Stratigraphy of the Araí Group: Record of Paleoproterozoic rifting in Central Brazil. Brazilian Journal of Geology, 45(1):95-108. DOI: 10.1590/23174889201500010007.