UNIVERSIDADE FEDERAL DE MINAS GERAIS
Instituto de Geociências
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Ana Paula de Campos Daher

CARACTERIZAÇÃO GEOLÓGICA DOS DEPÓSITOS RECENTES NA SERRA DO TAMANDUÁ, NE DO QUADRILÁTERO FERRÍFERO

Belo Horizonte
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Dissertação apresentada ao Programa de Pós-Graduação em Geologia da Universidade Federal de Minas Gerais como requisito parcial para obtenção do título de Mestre em Geologia.

Orientador(a): Prof(a). Dr(a). Gabriel Jube Uhlein

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FOLHA DE APROVAÇÃO

Caracterização Geológica dos Depósitos Recentes na Serra do Tamanduá, NE do Quadrilátero Ferrífero

ANA PAULA DE CAMPOS DAHER

Dissertação submetida à Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em GEOLOGIA, como requisito para obtenção do grau de Mestre(a) em GEOLOGIA, área de concentração GEOLOGIA ECONÔMICA E APLICADA, pelo Programa de Pós-graduação em Geologia do Instituto de Geociências da Universidade Federal de Minas Gerais.

Aprovada em 31 de março de 2023, pela banca constituída pelos membros:

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Belo Horizonte, 31 de março de 2023.

À minha família e amigos, que por alguns anos me ouviram sem parar falando de geologia,
nos momentos de empolgação e nos momentos de ingratidão.

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Cada ser tem sonhos à sua maneira

Noite Severina, Lula Queiroga

RESUMO

O Quadrilátero Ferrífero é uma região mundialmente conhecida por seus depósitos de minerais metálicos de classe mundial. Nessa região, ocorrem unidades pré-cambrianas, recobertas, em algumas regiões, por coberturas sedimentares recentes. Elas têm sido mais detalhadamente estudadas desde os anos 90, abrangendo cartografia, caracterização faciológica e bioestratigráfica. Esse trabalho estuda uma bacia sedimentar localizada na Serra do Tamanduá, aqui chamada de Bacia da Bandeira. Além das descrições geológicas fornecidas e do mapeamento realizado, foram descritos três testemunhos de sondagem, detalhando o perfil estratigráfico dos sedimentos encontrados. Unificadas essas informações, uma base de dados ampla foi gerada, que permitiu a avaliação da bacia. Houve o agrupamento em três unidades estratigráficas, chamadas A, B e C. A unidade A é a mais antiga, ocorre em uma área restrita na porção central da bacia, corresponde a sedimentos cascalhosos a arenosos, com matriz caolinítica e fragmentos de filito, provenientes de unidades Arqueanas. O topo desta unidade é uma camada de sedimento orgânico. É interpretada como fluxos de detritos sobrepostos por sedimentos lacustres. O sedimento orgânico foi detalhado, revelando conteúdo rico em microfósseis, com idade do Eoceno tardio, comparável a outras unidades da região. A unidade A é sobreposta pela B, que predomina na região central da área, com sedimentos argilosos e arenosos, localmente cascalhosos, com ocorrências de nódulos e veios de óxido de manganês. São comuns os sedimentos de matriz areno argilosa caolinítica rica em clastos compatíveis com área fonte Arqueana, similares a diamictitos e tálus. Para essa unidade interpreta-se como resultante de sucessivos fluxos de detritos. A unidade C é aflorante, com sedimentos argilosos maciços a unidades similares a diamictitos, de matriz argilo arenosa e rico em clastos provenientes de unidades Proterozoicas. São materiais coluvionares, com transporte ao longo da vertente, por meio de eventos episódicos e intercaladas a solos residuais. Em A também ocorre solos lateríticos e canga, resultados de processos pedogenéticos. Há evidências de processos tectônicos influenciando a geração de espaço para as unidades sedimentares, interpretado especialmente pela distribuição lateral e pelo mecanismo de sedimentação. A bacia foi tridimensionalmente modelada ajudando na compreensão da distribuição desses sedimentos. Há similaridades importantes com outras bacias sedimentares no leste do Quadrilátero Ferrífero. O atual trabalho mostra o uso de técnicas simples de investigação para a descrição de uma bacia sedimentar cenozoica, e permite comparar e correlacionar as unidades estudadas com outras existentes.

Palavras-chave: Bacia Bandeira; colúvio; bioestratigrafia.

ABSTRACT

The Quadrilátero Ferrífero is a region of globally known for its world class metal ore deposits. In this area, pre-cambrian units occur, locally covered by recent sedimentary units. Those sediments have been detailed studied since the 90's, comprehended cartography, facies and biostratigraphic analysis. This paper studies one sedimentary basin located in Serra do Tamanduá, so called Bacia Bandeira. Aside from the geologic description and the mapping information given, three drillhole cores were described, in detail of stratigraphical profile of the encountered sediments. That information was unified, a wide drillhole was generated, which allowed the basin evaluation. Three stratigraphic units were proposed, so called units A, B and C. The unit A is the oldest, occurring in a restrict area in the central portion of the basin, consists in gravel to sandy material, with clayey portions and rich in caolinitic matrix and phyllite fragments from Archean units. The top of this unit is an organic sediment layer. It was interpreted as debris flow covered by lacustrine sediments. This organic-rich layer was further studied revealing a rich microfossil content, with upper Eocene age and comparable to other organic-rich units described in the region. The unit A is overlaid by unit B, which prevails in the central portion of the area and is composed of clay and sandy sediments, commonly gravel in a caolinitic matrix, fragments of phyllites and schists, besides quartz vein of Archean origin, with local occurrences of nodules and veins of manganese oxide, consisting in diamict-like and talus sediments. Successive debris flow is interpreted for this unit. Unit C occurs in outcrops, consisting in diamict-like sediments, in which matrix is clay sand silty, with clasts of Proterozoic units. This is a coluvionar material, with slope transportation from its source area, with episodic events interbedded with residual soils. In C, there is also lateritic soils and canga, representing pedogenetic processes. There is evidence of tectonic influence on the basin geometry, interpreted by sediments distribution and the sedimentary mechanism. This basin was tridimensional modelled, helping the comprehension of the spatial distribution of these sediments. There are remarkable the similarities of Bandeira Basin's sediments to other basins in the eastern portion of Quadrilátero Ferrífero. This dissertation shows simple applied geological use of field investigation for the description for a Cenozoic sedimentary basin, comparing and correlating the studied units to other known.

Palavras-chave: Bacia Bandeira; debris flow; biostratigrphy.

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APRESENTAÇÃO

Essa dissertação, submetida ao Programa de Pós-Graduação em Geologia do Instituto de Geociências da Universidade Federal de Minas Gerais (IGC-UFMG), traz os resultados do trabalho de mestrado intitulado Caracterização Geológica dos Depósitos Recentes na Serra do Tamanduá, NE do Quadrilátero Ferrífero.

É um trabalho dividido em sete capítulos, em que o primeiro apresenta a introdução e a motivação do desenvolvimento do trabalho. Os objetivos são apresentados, assim como uma contextualização rápida da localização da área de estudo.

O capítulo dois apresenta o aparato metodológico utilizado para desenvolver a pesquisa.

É trazido um capítulo de contextualização geológica a nível regional, trazendo de forma abrangente o contexto geológico do Quadrilátero Ferrífero. De forma sintética, a contextualização geológica e estrutural dos depósitos sedimentares recentes já conhecidos na região, discutindo de forma rápida o que a literatura compreende como gênese para eles.

Os capítulos seguintes compreendem os artigos científicos que foram gerados a partir desse trabalho.

O primeiro artigo, intitulado *Characterization of Bandeira Sedimentary Basin on Serra do Tamanduá, Northeastern Region of Quadrilátero Ferrífero, Minas Gerais, Brazil*, foi submetido ao periódico Brazilian Journal of Geology. Nesse artigo se faz uma descrição detalhada dos litotipos encontrados na agora denominada Bacia Bandeira. É feita uma comparação entre as fácies litológicas encontradas e aquelas relacionadas na bibliografia. Com isso, é feita a caracterização da bacia, bem como proposta uma interpretação de gênese para ela, assim como simulado o modelo geológico para essa bacia.

O segundo artigo, chamado *A new Paleogene palynological record of the Quadrilátero Ferrífero (Minas Gerais, Brazil): age and paleoenvironment of the basal portion of the Bandeira Basin - Serra do Tamanduá,* está em construção e está apresentado nesse trabalho de forma preliminar. O artigo apresenta detalhamento de uma camada em que foi encontrado material rico em matéria orgânica em um dos testemunhos descritos na Bacia Bandeira. É feita a contagem dos palinomorfos identificados e discutida sua relevância no contexto local, bem como comparadas as ocorrências com os palinomorfos já identificados nas bacias sedimentares da porção leste do Quadrilátero Ferrífero.

Os capítulos seguintes trazem uma síntese das conclusões e, a seguir, perspectivas de outros trabalhos e as referências utilizadas.

1. INTRODUÇÃO

O Quadrilátero Ferrífero é uma região de grande interesse econômico, por ter sido desde o séc. XVII explorada para os minerais metálicos existentes em depósitos de diferentes contextos de formação. Por esse interesse, as unidades que potencialmente contém minério, bem como suas encaixantes, todas Pré-Cambrianas, têm sido extensamente estudadas (Dorr, 1969, Lobato *et al.*, 2005, Farina *et al.*, 2016).

Apesar de não esgotar o campo de estudo dessas unidades, o conhecimento das unidades geológicas de idade Cenozoicas existentes no Quadrilátero Ferrífero é ainda bastante restrito. Elas comumente têm uma caracterização geológica pouco descritiva e uma classificação, muitas vezes, inconsistente. Excetuam-se poucos exemplos para os quais os sedimentos tiveram uma avaliação geológica e bioestratigráfica e estrutural abrangente, culminando na caracterização de algumas bacias muito específicas e localizadas, a exemplo das bacias de Gandarela e Fonseca (Maizatto, 2001).

Esse trabalho se propõe a trazer uma descrição detalhada da classificação dos materiais genericamente classificados como unidades detrito-lateríticas, já mapeados na região da Serra do Tamanduá, no nordeste do Quadrilátero Ferrífero.

1.1.Objetivos

O trabalho consiste em avançar nas informações existentes na região nordeste do Quadrilátero Ferrífero sobre as coberturas sedimentares recentes. É caracterizada a Bacia Bandeira, bacia sedimentar na Serra do Tamanduá, apresentando sua estratigrafia e interpretando seu processo de formação. Para isso, serão atendidos alguns objetivos específicos, que se constituem de:

- Realizar uma análise litológica e, a partir disso, discutir os tipos de sedimentos encontrados, sua relação, espessuras e distribuição lateral e definir unidades litoestratigráficas para essa bacia.
- Discutir a relação dos sedimentos encontrados na Bacia Bandeira com outras bacias já descritas na porção leste do Quadrilátero Ferrífero, bem como comparar as litofácies identificadas com aquelas já relatadas na bibliografia.
- Estabelecer uma idade para a Bacia Bandeira.

Por fim, pretende-se evidenciar as possibilidades de aplicação de metodologias simples que permitam trabalhos mais detalhados nessas unidades sedimentares.

1.2.Localização da Área de estudo

A área de estudo se localiza na região limítrofe entre os municípios de Barão de Cocais e São Gonçalo do Rio Abaixo, cujas sedes municipais estão a 45 e 65 km de distância de Belo Horizonte. A área tem um total de 13 km² e apresenta acessos intermunicipais e locais em toda a região (Fig. 1). O acesso até a área, iniciado em Belo Horizonte, segue pela BR 381 em direção a leste até a saída para Barão de Cocais, a partir de onde se toma a MG 436 em direção a sul e logo a seguir a MG 129 em direção a leste.

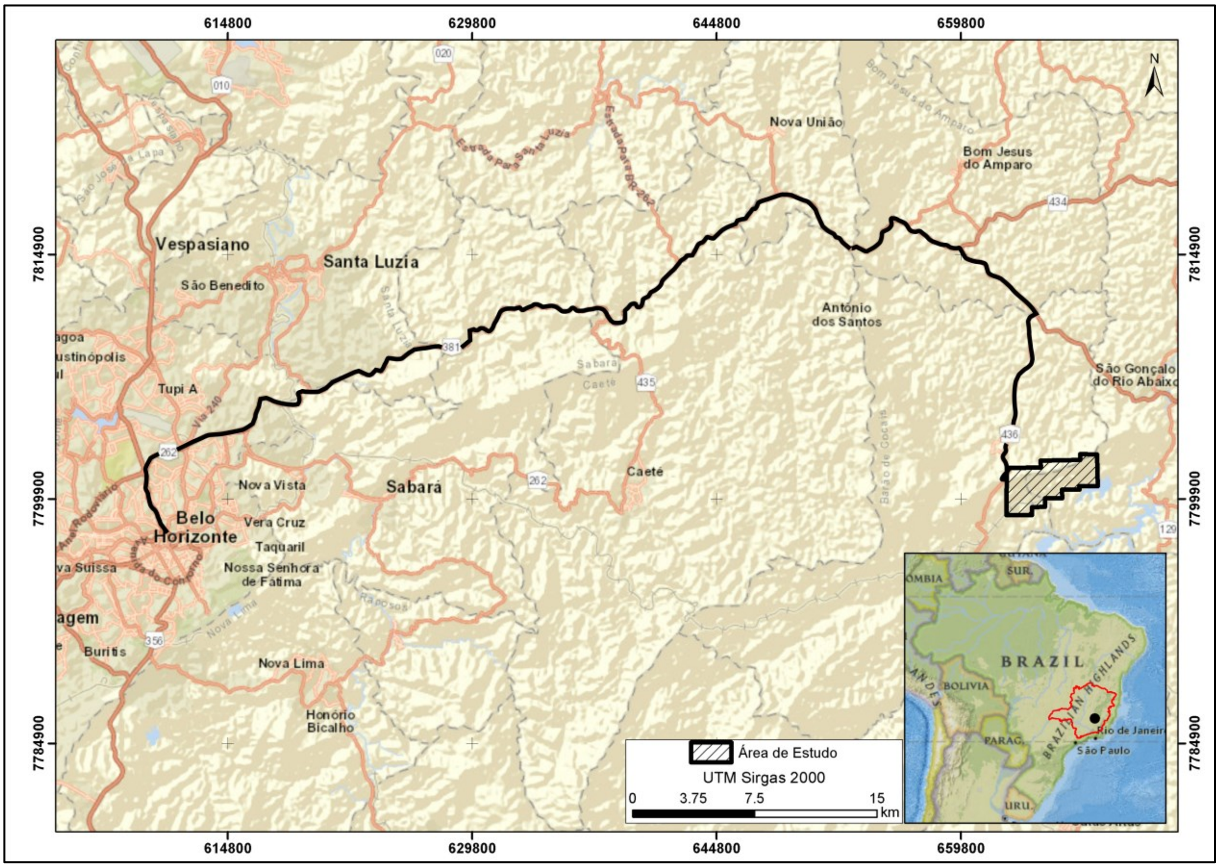

Fig. 1 – Localização da área de estudo em relação ao município de Belo Horizonte, com trajeto sinalizado em linha preta.

2. MATERIAIS E MÉTODOS

O desenvolvimento das atividades contou com compilado de referências, descrição dos materiais encontrados em afloramentos e em testemunhos de sondagem. A descrição desses materiais permitiu a realização de amostragem, que resultou em alíquotas para a análise petrográfica. Um horizonte, em específico, foi analisado para palinomorfos, de forma a permitir a identificação de micro fósseis.

2.1. Levantamento Bibliográfico

A busca por referências foi feita baseando-se em trabalhos com foco no Quadrilátero Ferrífero. Inicialmente, a busca contemplou trabalhos que tivesse foco descritivo nos materiais sedimentares cujas ocorrências já tivessem sido mapeadas. Os trabalhos pioneiros nesse quesito são encontrados no compilado apresentado por Dorr (1969), cuja bibliografia também inclui mapas geológicos na escala 1:50.000. Esses mapas não apresentam base de dados digital, de forma que eles foram considerados para consulta apenas. Os trabalhos de Balthazar *et al.*, 2005, e Endo *et al.*, 2020 apresentam bases de dados digitais, de forma que foram a principal base para a análise de distribuição dos depósitos a nível regional. Adicionalmente, utilizou-se imagens de satélite de bases públicas e disponíveis no *software* QGIS, versão 3.22.

Referências de trabalhos mais recentes incluem principalmente a descrição dos sedimentos encontrados nas bacias de Fonseca, em maior volume, e de Gandarela (Maizatto, 2001). Pontualmente, são tratados outros depósitos sedimentares nas porções sul e oeste do Quadrilátero.

Após uma campanha de reconhecimento de campo, um mapa geológico de detalhe foi feito na região da Bacia Bandeira, a partir dos dados levantados. Foi feito um comparativo com os mapas geológicos existentes nas bases digitais, de forma a compreender como a representação desses sedimentos são feitas.

2.2. Descrição e Amostragem

Foram utilizados 320m de testemunhos de sondagem chave na região de interesse, com nomenclatura (MAD-FSE0001, MAD-FSE0002 e MAD-FSE0003). Esses furos foram descritos, focando em itens como cor, granulometria, arredondamento e esfericidade dos grãos, composição e, quando possível, tipos de contato. A descrição desses litotipos foi utilizada como base para agrupá-los em unidades litológicas.

Com a descrição dos testemunhos, amostras representativas de cada intervalo descrito foram coletadas, nomeadas e tiveram registro fotográfico feito antes e após a amostragem. A quantidade de amostras foi feita considerando os ensaios esperados para cada material, como laminação. Foi gerada uma base de dados com esse material de descrição e amostragem.

2.3. Análise Petrográfica

Alguns dos trechos encontrados nos testemunhos correspondem a sedimentos com alguma integridade. Foram selecionados trechos cuja composição dos clastos e/ou concreções pudessem ser analisadas sob o microscópio de luz refletida.

As amostras escolhidas foram encaminhadas ao Laboratório de Laminação do Centro de Pesquisas Manoel Teixeira da Costa do IGC/UFMG. Foram feitas lâminas delgadas dessas amostras.

3. CONTEXTUALIZAÇÃO GEOLÓGICA REGIONAL

A região do Quadrilátero Ferrífero (QF), definido por Dorr (1969), abrange uma área de 12.000km² e localiza-se na porção sudeste do Cráton São Francisco (Fig. 2; Alkmin, 2004). É uma denominação que leva em consideração a grande ocorrência de minério de ferro, particularmente estudada pela parceria USGS-DNPM que originou o primeiro grande trabalho de compilado acerca dos aspectos geológicos locais.

É uma região de enorme interesse econômico devido aos depósitos de grande tonelagem e de classe mundial. Além disso, é de uma complexidade lito estrutural singular, tendo se tornado uma das regiões mais estudadas no Brasil. No que diz respeito à litoestratigrafia, se apresenta uma subdivisão nas seguintes macro unidades, conforme Endo *et al.* (2020):

- Complexos Metamórficos: correspondente às rochas granito-gnáissicas arqueanas a proterozoicas;
- Supergrupo Rio das Velhas: *greenstone belt* Arqueano de rochas metavulcânicas e metassedimentares;
- Supergrupo Minas: rochas metassedimentares proterozoicas;
- Supergrupo Estrada Real: depósito metassedimentar de bacia restrita de idade Pré-Cambriana;
- Grupo Barbacena: rochas metassedimentares e metavulcânicas máficas e ultramáficas;
- Supergrupo Espinhaço: metarenitos e metaconglomerados;
- Unidades sedimentares: depósitos sedimentares terrígenos do Paleógeno ao Holoceno.

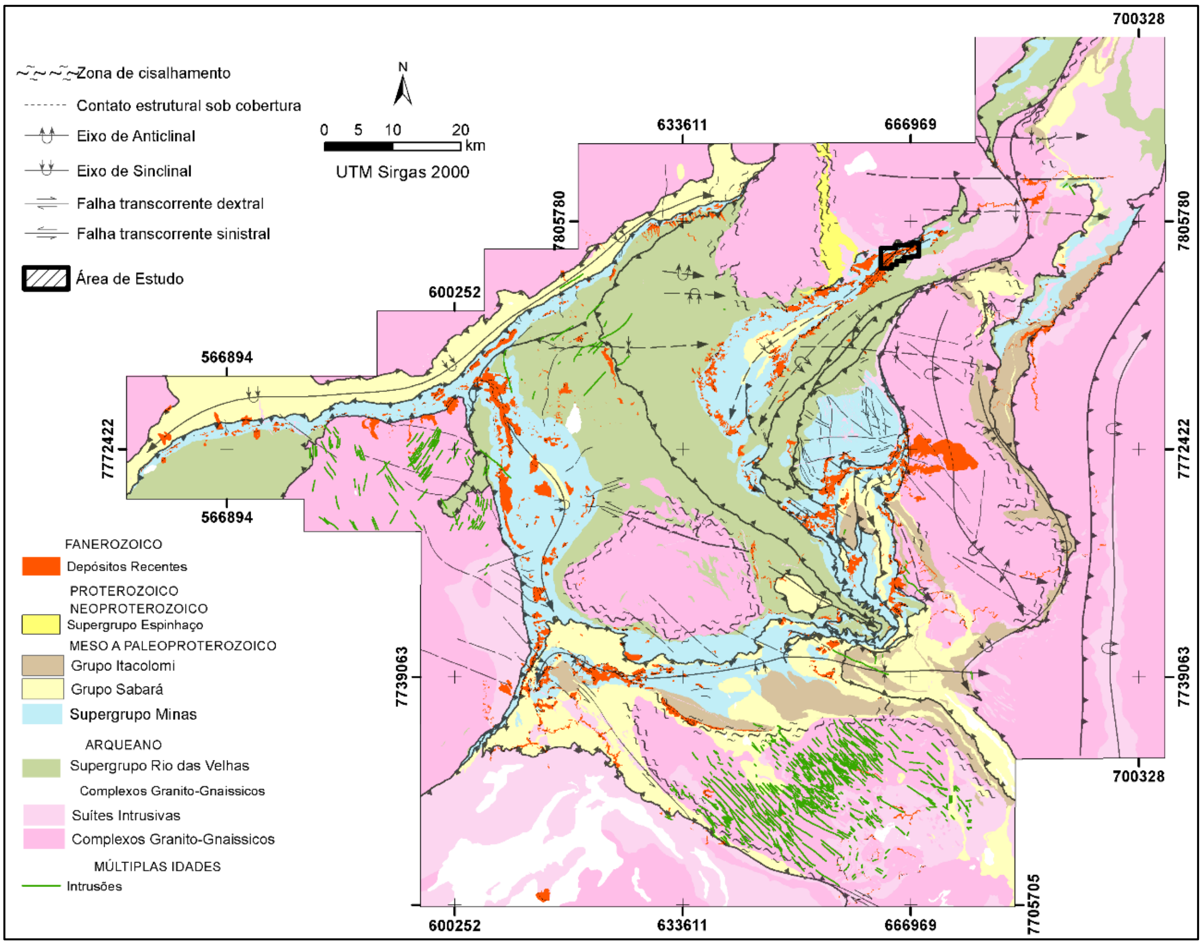

Fig. 2 – Mapa geológico das principais unidades do Quadrilátero Ferrífero. Modificado de Endo *et al.* (2019).

3.1.Litoestratigrafia Geral do Quadrilátero Ferrífero

O embasamento cristalino é constituído por gnaisses formados entre 3,22 e 2,68 Ga (Farina *et al.,* 2016), de composição TTG (trondhjemito-tonalito-granodiorito) representados pelos Complexos Belo Horizonte, Caeté, Santa Bárbara, Bação e Bonfim e por intrusões graníticas (Fig. 2), anfibolíticas e pegmatíticas em corpos menores. O contato do embasamento com as rochas supracrustais é de natureza tectônica.

Sobreposto ao embasamento cristalino afloram rochas do Supergrupo Rio das Velhas em grande parte do Quadrilátero Ferrífero (Fig. 3). Inicialmente caracterizado em Dorr (1969) como *Greenstone Belt* de idade Arqueana, com xistos, filitos, formações ferríferas e quartzitos subordinados, atualmente conta com uma subdivisão em grupos Nova Lima e Maquiné. Essas unidades também podem ser subdivididas em fácies, conforme Balthazar e Zuchetti (2007), que apresentam conotação genética e evolutiva, considerando o contexto de *Greenstone*.

O Supergrupo Rio das Velhas é sotoposto às rochas do Supergrupo Minas, apresentando contato tectônico, erosivo ou discordância angular. Pode ser subdividido em grupos Caraça, Itabira, Piracicaba e Sabará. O Grupo Caraça, unidade basal, constitui-se de rochas de contexto continental a transicional para ambiente plataformal, com conglomerados e quartzitos caracterizando a Formação Moeda, e filitos predominantemente na Formação Batatal.

O Grupo Caraça é sobreposto pelo Grupo Itabira, em contato normal, o qual corresponde a depósitos de plataforma profunda de sedimentos francamente químicos a químico clásticos. Este subdivide-se em Formação Cauê, composta de itabiritos silicosos e corpos de hematita compacta, de espessura máxima de 500 m, e na Formação Gandarela, composta por itabiritos dolomíticos, dolomitos, filitos e filitos hematíticos e dolomito ferruginoso, com espessura de até 750 m (Dorr, 1969). O contato entre as duas unidades é transicional, com a Formação Gandarela sobreposta à Formação Cauê.

Essas unidades, Formação Cauê e Formação Gandarela, são marcadas na geomorfologia regional por constituírem as cristas das serras que marcam o contorno do Quadrilátero Ferrífero. São, também, fontes dos depósitos de ferro e manganês da região, continuamente explorados desde o início do séc. XIX.

A Formação Gandarela tem contato de topo brusco a localmente erosivo com o Grupo Piracicaba. Esse grupo corresponde a quartzitos e filitos intercalados e com granocrescência ascendente. São rochas cuja gênese é correlacionada a ambiente de talude ou corrente de turbidez, com espessura de até 1300 m. Pode ser subdividido em formações Cercadinho, Fecho do Funil, Taboões e Barreiro, sendo as duas últimas de ocorrência restrita.

No topo do Supergrupo Minas está o Grupo Sabará, em contato erosivo com o Grupo Piracicaba, representando rochas metavulcanossedimentares com granocrescência para o topo (Figura 3). Tem espessura de até 3500 m, com grauvacas, conglomerados líticos, diamictitos e metapelitos.

O Supergrupo Estrada Real corresponde às unidades dos grupos Sabará e Itacolomi, em uma classificação indicada em Endo *et al.*, (2020). O Grupo Sabará é subdividido em formações Saramenha (Almeida *et al.*, 2005), Córrego do Germano e Catarina Mendes (Endo *et al.*, 2020). É uma sequência de clorita xisto, mica xistos, metagrauvacas, quartzitos, metarritmitos, metadiamictitos, formação ferrífera bandada granular e quartzitos ferruginosos. Apresenta contatos gradacionais a erosivos entre as unidades. O Grupo Itacolomi é composto das formações Florália e Pico do Itacolomi (Endo *et al.*, 2020), que ocorrem na região leste e sudeste do Quadrilátero. São ortoquartzitos a quartiztos estratificados com trilhas de óxidos, metaconglomerados e subordinadamente filitos.

Há uma série de suítes intrusivas máficas e ultramáficas na forma de diques, principalmente de direção NW-SE. Ocorrem em enxames como nas porções sul e leste ou em corpos maiores como na região nordeste do Quadrilátero. Essas rochas ocorrem intrudindo em todas as unidades mapeadas, de Arqueanas a Proterozoicas.

Por fim, há coberturas detrito-lateríticas e bacias sedimentares por toda a região, em áreas restritas, preferencialmente cobrindo unidades do Supergrupo Minas.

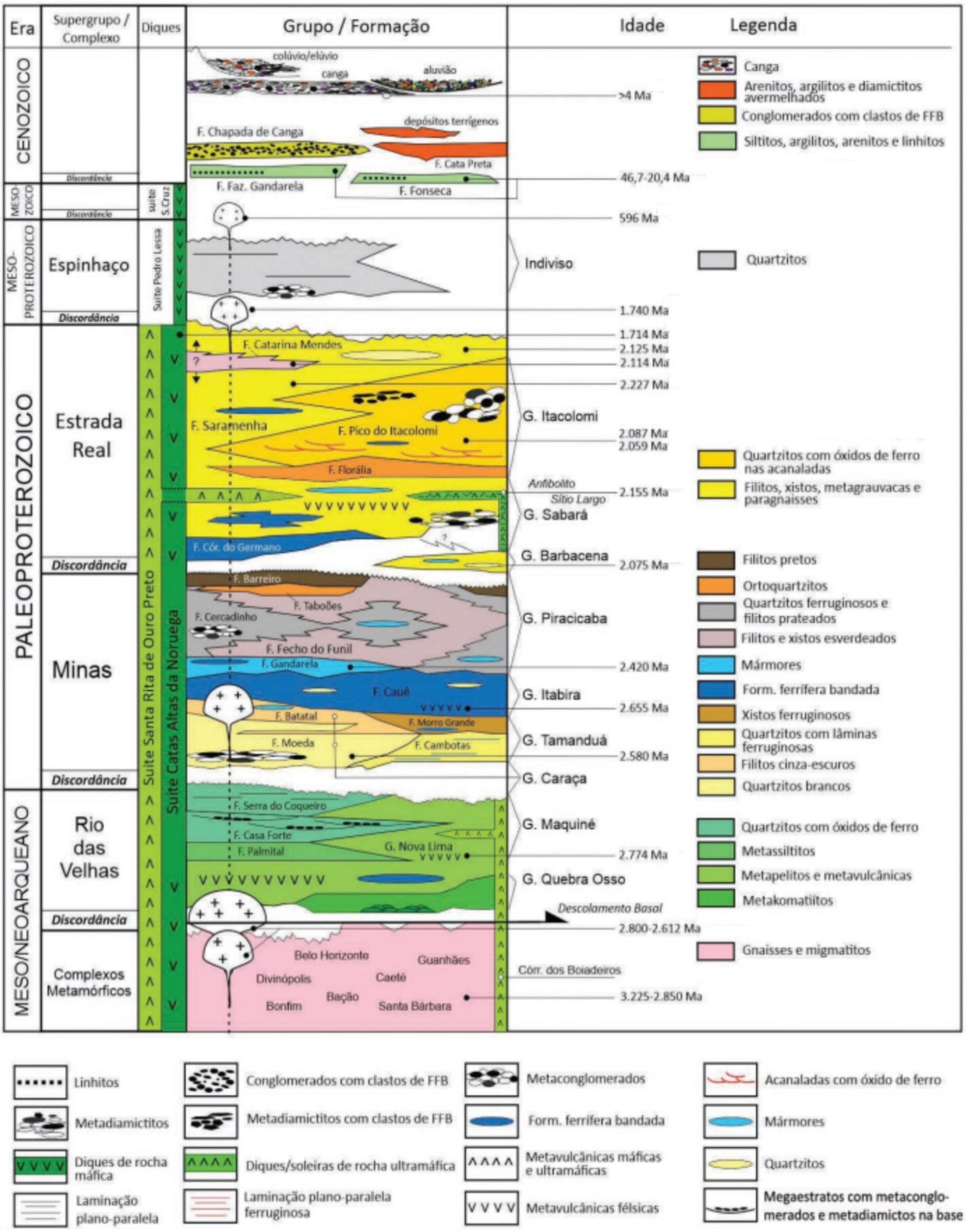

Fig. 3 – Coluna estratigráfica com as relações entre as grandes unidades e os litotipos que as constituem. Endo *et al.*, 2020.

3.2.Depósitos Sedimentares Recentes

Na publicação comemorativa de cinquenta anos de mapeamento do Quadrilátero Ferrífero, foi apresentada uma compilação lito estratigráfica e estrutural, com um modelo de evolução tectônica regional abrangente, não necessariamente diferente daqueles anteriormente existentes. Destaca-se nesse trabalho um capítulo dedicado à apresentação dos depósitos cenozoicos no Quadrilátero Ferrífero, compilado por Castro e Varajão (2020) e por Varajão *et al.* (2020).

Esse tipo de abordagem é um pouco distinto daquele realizado por Balthazar *et al.* (*op cit.*), uma vez que ao longo dos anos 2000 muitos trabalhos foram realizados e o volume de informação a respeito desses depósitos tem crescido. Portanto, o volume apresenta aqueles trabalhos detalhados já abordados por Dorr (*op cit.*), apresenta o caso de mais um tipo de depósito encontrado na região leste do QF, bem como discute os trabalhos que descrevem os depósitos recentes encontrados, principalmente, no Sinclinal Moeda. Esses últimos são abordados no sentido de compilar os trabalhos que descrevem e diferenciam fácies sedimentares dos depósitos terrígenos existentes na porção oeste do QF.

Dorr (1969) cartografa e descreve as unidades mais recentes apresentando as bacias de Fonseca e Gandarela à época já conhecidas (Gorceix, 1884 *in* Dorr, 1969) e, de modo genérico, "*mudstones*". Os chamados *mudstones* são definidos pelo autor como porções de argila maciças, laterizadas e não plásticas associadas a vales elevados. São encontrados preferencialmente na porção oeste do QF, ao longo dos sinclinais Moeda e Dom Bosco. O autor indica que não há transição para material saprolítico, de modo que necessariamente são fruto de transporte superficial, algo corroborado pela presença de lentes de conglomerado basal em alguns locais, e não se apresentam interceptados por rochas intrusivas. Não são observadas estruturas sedimentares primárias, apesar de alguns afloramentos apresentarem juntas. Dorr (1969) destaca a presença de horizontes com manchas amarelas, brancas e vermelhas, predominando as últimas, variação que se deve à lixiviação de óxido de ferro.

Ainda, o autor distingue os materiais de alteração *in situ,* desses, destaca-se a canga. É definida como um tipo de rocha, cuja denominação é exclusividade brasileira e denomina material cimentado, limonitizado e litificado, rico em óxidos e hidróxidos de ferro. O autor reconhece a canga normal, caracterizada por conter fragmentos líticos, em que sua maioria é de hematita e itabirito, mas que pode conter fragmentos de quartzito e filito, cimentados por óxidos e hidróxidos de ferro e alumínio; canga química, pobre em fragmentos líticos, mas rico em limonita; a canga rica, em que os fragmentos são, em grande parte, de hematita e cimentados por matriz limonítica.

Em Lobato *et al.* (2005) se retoma a concepção de que as coberturas sedimentares vão desde o Paleógeno até o Neógeno. Os autores, em grande parte, compilam as ocorrências primeiramente cartografadas pelo mapeamento regional Dorr, (1969). Dentre essas coberturas, os autores indicam a ocorrência de bacias sedimentares intramontanas e tectonicamente controladas, coberturas detrito-lateríticas, sedimentos Plio-Pleistocênicos e Pleito-Holocênicos, representados por terraços, elúvios e colúvios, além de sedimentos aluvionares mais recentes.

Lobato *et al.* (2005) subdividem as coberturas em detrito-lateríticas e sedimentos recentes. As primeiras incluem solo laterítico, colúvios e chapadas de canga, com estruturas limonitizadas e horizontes com concreções ferruginosas que capeiam os topos das serras. Os sedimentos incluem os sedimentos argilosos e arenosos, alúvio e coluvionares do Oligoceno ao recente.

Já em Castro e Varajão (2020), apresentam-se de forma detalhada o registro estratigráfico e evolução geológica das principais unidades correspondentes aos depósitos cenozoicos no QF, correspondente às formações Fonseca, Chapada de Canga, Gandarela e Cata Preta. Além disso, o compilado bibliográfico mais recente já compreende uma subdivisão das unidades de cobertura recente em função da idade (Fig. 4).

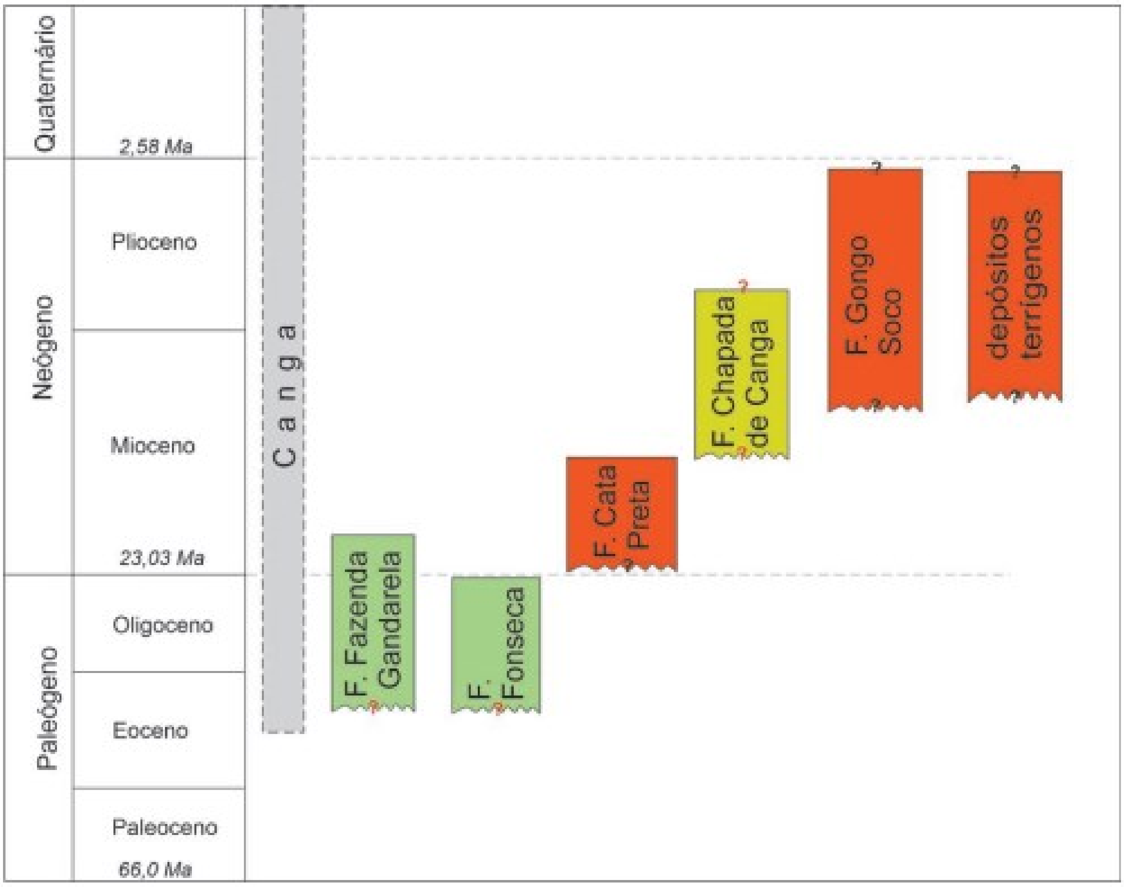

Fig. 4 – Coluna estratigráfica proposta para o Cenozoico do Quadrilátero Ferrífero, conforme apresentado em Castro e Varajão (2020).

Além dos depósitos com boa caracterização litológica e estratigráfica são reconhecidos depósitos recentes não tão bem detalhados, tratados em Castro e Varajão (2020) como registros estratigráficos dispersos. Os autores indicam que o motivo dessa falta de detalhamento é principalmente a falta de boas exposições ou de testemunhos de sondagem.

Quanto às fácies sedimentares, elas foram definidas por Castro e Varajão (*op cit.*) e Varajão *et al.* (2020), como cinco principais, que ocorrem de forma descontínua lateral e/ou verticalmente, e não necessariamente ocorrem todas juntas no mesmo depósito. Sinteticamente se apresenta essas fácies descritas pelos autores:

- Fragmentária (F): sedimentos imaturos de matriz principalmente argilosa, castanho avermelhado a vermelho escuro, que suporta fragmentos angulares de areia média a matacão de filito, quartzito, hematitas e itabiritos.
- Nodular (N): matriz argilo siltosa avermelhada, sem estruturas sedimentar e rico em manchas esbranquiçadas, vermelho, rosa e amarelo, que contém fragmentos líticos e nódulos. Está no topo de fácies fragmentárias e fácies argilo quartzo arenosa.
- Argilosa Quartzo Arenosa (AQA): apresenta cor variada, de vermelho a esbranquiçado, com zoneamentos mosqueados, com matriz argilosa a argilo siltosa. Têm ampla variação de conteúdo de quartzo, mica branca, minerais pesados e fragmentos líticos.
- Argilosa Maciça (AM): apresenta estrutura maciça, contém grãos de quartzo de areia fina a grossa, dispersos em matriz argilosa, com nódulos ferruginosos milimétricos.
- Conglomerado (C): correspondem a paleocanais constituídos principalmente por fragmentos líticos de filito, quartzito ferruginoso, quartzo de veio, com matriz argilo arenosa, ocorrendo geralmente no topo de outras fácies sedimentares.

Algo particularmente interessante a respeito desses materiais sedimentares é trazido por Spier, *et al.* (2018). Em seu trabalho, os autores descrevem e avaliam mineralogia, petrologia, composição química e relação estratigráfica da canga e de um material chamado *brick-red material (brm).* Nesse estudo, a disponibilidade de testemunhos de sondagem, bem como afloramentos na Mina de Águas Claras permitiram identificar dois tipos de canga, um decorrente de laterização *in situ* de formações ferríferas bandadas, e uma segunda decorrente de cimentação de material transportado. O brm, segundo os autores, é uma argila vermelha maciça. Ao microscópio distinguem-se cristais de hematita, bem como de goethita euédricos, com distribuição heterogênea.

Na Mina de Águas Claras, o perfil identificado evidencia canga transportada existente em superfície, recobrindo depósito sedimentar cenozoico de dezenas de metros de espessura, que sobrepõem geração mais antiga de canga transportada sobre canga *in situ*. Esse estudo é interessante, pois com auxílio de informação de subsuperfície foi possível identificar uma relação estratigráfica muito particular, evidenciando a complexa história de processos pedogenéticos e sedimentação recente. Os autores conseguiram datar a canga existente na área estudada, encontrando idades de 41 Ma para a canga da base do perfil e de 26 Ma para a canga no topo do perfil. Esse é um resultado promissor, pois contribui para compreender não apenas quando a canga foi formada e, por conseguinte, os depósitos sedimentares associados, mas também auxilia na correlação com eventos tectônicos e/ou denudacionais estudados para toda a porção sudeste do Cráton São Francisco.

3.2.1. Localização dos Depósitos Conhecidos

Os depósitos cenozoicos conhecidos no Quadrilátero Ferrífero podem ser encontrados em toda a região. Castro e Varajão (2020) e Varajão *et al.* (2020) compilam os depósitos recentes registrados na literatura por localização, que é apresentada na Fig. 5.

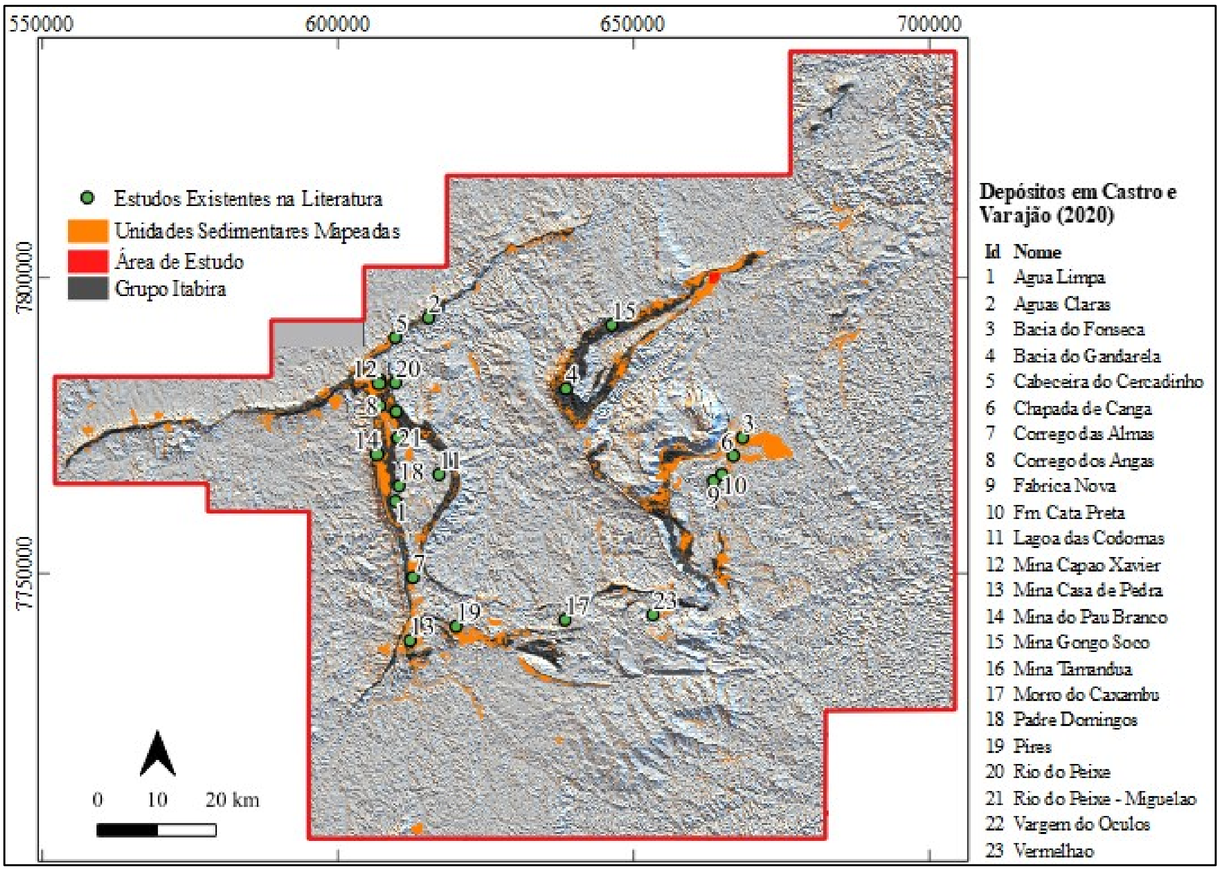

Fig. 5 – Localização dos depósitos sedimentares detalhadamente descritos do Quadrilátero Ferrífero a partir do compilado de Castro e Varajão (2020), com a delimitação das unidades cartografadas evidenciada pelas linhas pretas

É perceptível que existem tantos depósitos documentados, e até mais numerosos, na região oeste do QF. Entretanto, os estudos existentes nas porções leste e sul do QF trazem maior volume de informações descritivas, com definição de fácies e análise dos processos pedogenéticos, apresentando idade por meio de correlação bioestratigráfica, como é o caso das bacias de Gandarela e Fonseca (Maizatto, 2001). Já os estudos existentes na porção oeste são englobados como depósitos terrígenos e idade inferida a partir de correlação com a porção leste. É um denominador comum de todos esses depósitos a ocorrência clara e reconhecida de estruturas rúpteis, que geram o espaço de sedimentação das bacias e, em alguns casos, gera também deformação posterior à sedimentação.

Em termos de registro cartográfico, há uma clara distinção do detalhamento das coberturas recentes entre os mapas produzidos pela integração de dados de Balthazar *et al.* (2005) e pela integração de dados de Endo *et al.* (2019), como apresentado na Fig. 6. O primeiro apresenta menor quantidade, em área, dos depósitos recentes cartografados, perfazendo um total de 330 km². O compilado trazido por Endo *et al.* (2019) apresenta cerca de 347 km² de área de depósitos cenozoicos, trazendo a importante diferenciação de coberturas recentes conforme estratigrafia anteriormente discutida. Em Daher e Amaral (2022) é discutida a relação de área dos depósitos, bem como sua relação com estruturas antrópicas de interesse.

A Fig. 6 evidencia as principais regiões em que há ganho na proporção de área atualmente cartografada como coberturas recentes. Essas áreas, representadas como depósitos terrígenos ou coluvionares, estão principalmente na porção central do Sinclinal Moeda e nas regiões vizinhas à Serra do Curral, em sua porção NW.

É de grande importância a avaliação da distribuição cartográfica desses depósitos. Isso, porque frequentemente esse material é mapeado erroneamente como produto de intemperismo de unidades Paleoproterozoicas. Com isso, a atualização da distribuição dessas unidades permite não somente a correta classificação do material aflorante, mas também permite avançar na pesquisa e diagnóstico das características desses depósitos sedimentares recentes.

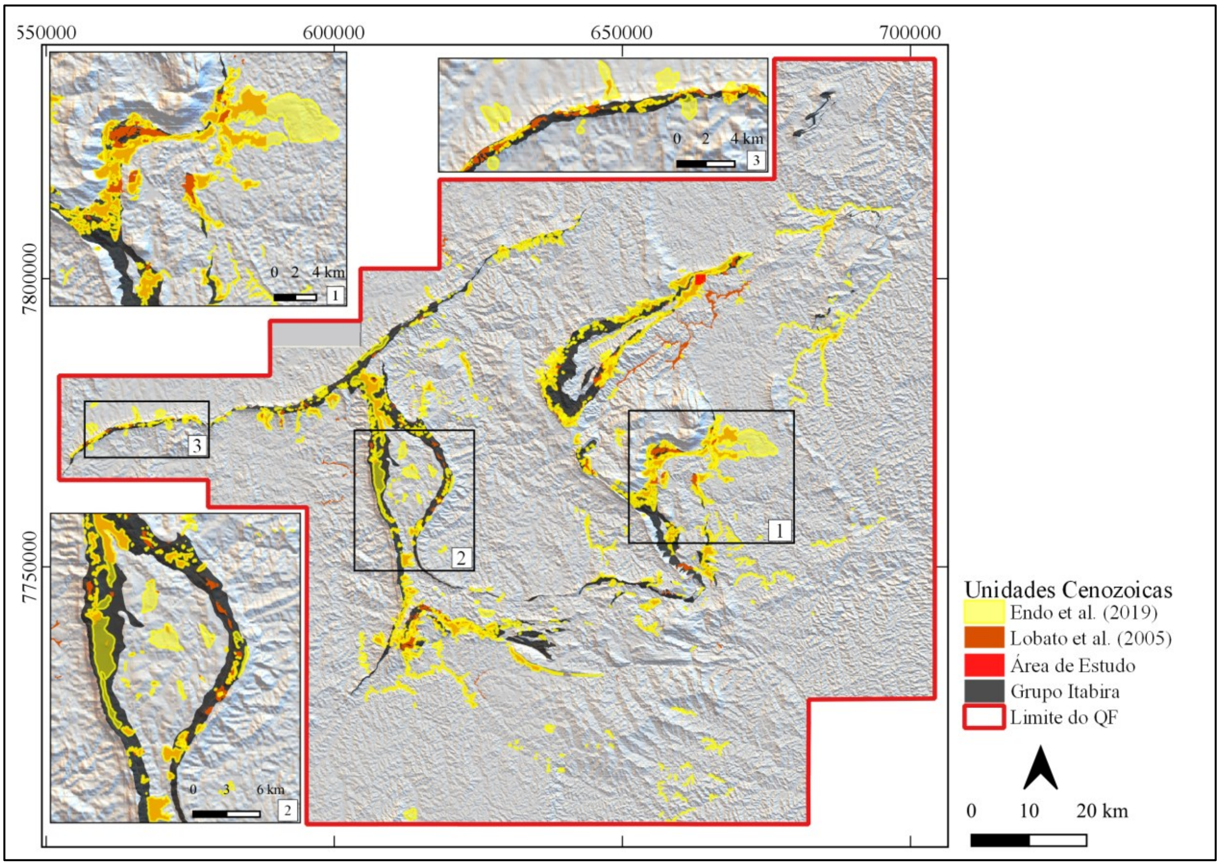

Fig. 6 – Mapa simplificado do Quadrilátero Ferrífero, com destaque para as coberturas recentes cartografadas, em amarelo. A este se sobrepõe apenas as unidades cenozoicas representadas em Lobato *et al.*, 2005 na cor laranja. Modificados de Endo *et al.*, 2019.

3.2.2. Gênese e Evolução dos Depósitos Cenozoicos do QF

Os registros mais antigos dos sedimentos recentes da região são compilados por Dorr (1969), que apresenta múltiplas explicações para a origem dos *mudstones* por vários autores, tais como alteração *in situ* de rochas carbonáticas (Gair, 1957 *in* Dorr, 1969), retrabalhamento de litotipos específicos (Gair, 1962 *in* Dorr, 1969) ou preenchimento de paleocanais e posterior intemperismo e laterização (Wallace, 1965 *in* Dorr, 1969). Entretanto, nenhuma dessas é tomada como final.

Análises químicas realizadas em amostras de *mudstones* indicaram teores anômalos de óxido de titânico, de modo que Dorr (*op cit.*) atribui sua origem a algum tipo de cinza vulcânica. Ele aventa a possibilidade de erupções explosivas ocorridas na porção sudeste do Brasil terem gerado nuvens de cinzas que foram depositadas nos vales existentes à época, já, naturalmente, parcialmente preenchidos com conglomerados decorrentes de processos de vertentes. Mesmo apresentando essa possibilidade, o autor não encerra a questão, mas a apresenta como assunto de interesse futuro.

Castro e Varajão (2020) e Varajão *et al.* (2020) trazem a diferenciação dos depósitos terrígenos como unidades de origem *in situ* e unidades de origem sedimentar. Para os primeiros, retoma-se a ideia de laterização das unidades aflorantes e pequeno transporte de vertente, como indicado em Guild (1957 *in* Castro e Varajão, 2020) e Pomerene (1964, *in* Castro e Varajão, 2020). Para os depósitos resultantes de sedimentação, os autores discutem deposição sobre saprolitos, com base apresentando recorrência de coberturas lateríticas retrabalhadas a partir das vertentes. Eles indicam uma evolução complexa, envolvendo história de deposição e processos pedogenéticos intimamente relacionados ao longo do tempo e do espaço.

A partir desse conhecimento, o atual trabalho parte de um comparativo descritivo das unidades encontradas na agora chamada Bacia Bandeira. Essas unidades serão comparadas, em características e processos genéticos, àquelas já mencionadas nos trabalhos predecessores.

4. ARTIGO 1

Characterization of Bandeira Sedimentary Basin on Serra do Tamanduá, Northeastern Region of Quadrilátero Ferrífero, Minas Gerais, Brazil

Caracterização da Bacia Sedimentar Bandeira na Serra do Tamanduá, Nordeste do Quadrilátero Ferrífero, Minas Gerais, Brasil

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ABSTRACT: This study presents the geological aspects of the sedimentary deposit of the Bandeira Basin, applying a methodology that can be used to characterize other similar sedimentary deposits. A bibliographic review was the first step on this effort, which quickly shows that Cenozoic sedimentary geological units have been widely studied since the 1990s. Its methods to study these sediments inspired some procedures in this work, and based on field data, such as mapping and drillhole core database analysis, three drillhole cores were selected for further investigation and detailed description. Gathering and analyzing this data established the basis for the definition of the Bandeira Basin, subdivided in three units: unit A, which was only found on the southeast area, exclusively from Nova Lima's chlorite schist source; unit B, intermediate, occurs on the central and southeast areas, with possible Rio das Velhas Supergroup as source areas of the sedimentary material; and unit C, superior, occurs extensively in the hole area, coluvionar, sedimented from the Minas Supergroup units. The contact between units is abrupt or erosive, keeping record on successive stages of sediments. The basin becomes thicker on its central and southwest ends, and thinner on the east and north, where part of the basement outcrops. Cenozoic tectonic events were probably active on this area, controlling the sedimentary processes, with the NW-SE and NE-SW morphological lineaments reactivated, triggering the sediment deposition and migration on the deepest spot of the basin. These sediments were tridimensional specialized with a 3D modeler Leapfrog Geo, which allows the user to access the visualization of any region of interest, in the modelled scale. The assertive characterization of the units may allow several other studies and developing better civil projects.

KEYWORDS: Cenozoic; Coluvionar deposits; Gandarela Syncline, neotectonics.

4.1. Introduction

Quadrilátero Ferrífero (QF) is a major interest region due to the world-class deposits of metallic ores, such as gold and iron, located in Minas Gerais State, southeastern Brazil. Due to its importance, extensive research on mineralized rocks and Precambrian host rocks have been performed, providing information on lithostratigraphic, structural, and ore-forming relationships (Dorr 1969, Lobato et al. 2005, Farina et al. 2016).

Although the main focus since the late 60's has been on the ore-forming rocks, Cenozoic sedimentary basins also occurred in the region (Castro and Varajão 2020; Varajão et al. 2020), but haven't been fully characterized, and with some exemption (*e.g.* Gandarela and Fonseca Basins - Maizatto 2001), the Cenozoic basins are usually simply described as lateritic soils or lateritic covers. These units are not only important for the pedogenetic, morphologic, and erosive comprehension of Cenozoic processes, but are also important to constrain the characteristics of these sediments, because roads, civil constructions, and mining infrastructure are often built over these sediments or using them as material source. Therefore, understanding these materials and their characteristics brings scientifical, but also practical benefits.

This paper aims to synthesize the main studies on the Cenozoic deposits of the *Quadrilátero Ferrífero* and to bring detailed and complete description of sedimentary facies, and their contacts, thickness, and 3D arrangement from Bandeira Basin, which is located at Serra do Tamanduá, the northeastern portion of Gandarela Syncline, QF.

4.2. Geological Setting of Quadrilátero Ferrífero

The Quadrilátero Ferrífero (QF) is a 12.000 km² region, on the southeast portion of the São Francisco Craton (Fig. 7; Alkmin 2004; Endo et al. 2020). Its name is referred to one of the most significant iron occurrences in the world. It has been studied since the 1960s and has become one of the most detailed studied regions in Brazil. The scientific research began with a partnership between the United States Geologic Survey and Departamento Nacional da Produção Mineral. The result of this partnership was a study paper that brings a synthesis of the unique and complex lithostructural settings of QF (Dorr 1969).

The basement consists of granite and gneissic rocks, mainly Archean, ranging to Paleoproterozoic, forming a nucleus all over the QF (Farina et al. 2015). Overlaying, in tectonic contact these rocks, the Rio das Velhas Supergroup is an Archean greenstone belt that consists of metasedimentary and metavolcanic rocks and hosts the main gold deposits in the region

(Balthazar and Zuchetti 2007, Balthazar and Lobato 2020).

The Minas Supergroup consists of metasedimentary rocks from Siderian, that recover the greenstone belt. Its base consists of siliciclastic units (Caraça Group - Dorr 1969; Nunes 2016), with quartzites and micaceous phyllites. The intermediate layers (Itabira Group - Dorr 1969) consist mainly of metasedimentary chemical units (dolomitic bodies, ferruginous chert), and schists. Itabira Group hosts almost all the iron deposits of QF. The top of the Minas Supergroup is mainly dominated by siliciclastic units (Dorr 1969, Dutra 2017), intercalated with ferruginous quartzite, carbonaceous and sericite phyllites, micaceous schists, and metabreccias (Piracicaba Group). These are classically interpreted as marine platform environment to marine slopes (Dorr 1969).

The Estrada Real Supergroup (Castro et al. 2020) are Riacian rocks deposited in restricted basins. It is subdivided into Sabará Group (Almeida et al. *2*005) and Itacolomi Group (Machado et al. 1996).

Cenozoic deposits as lateritic and sedimentary covers occur spread in QF, on top of Archean and Proterozoic units. Those were identified with a wide variety of thicknesses and heterogeneous sedimentary records.

The QF has a complex evolution, with multistage sedimentation and deformation processes. The pre-Cambrian geological units and structural records are well documented, as well as the evolution processes that occurred during Archean and Proterozoic (Farina et al. 2016). However, the Cenozoic sedimentary records, its characteristics, and genesis processes are not yet fully understood. The detailed studies were performed relying on good outcrops and, in some cases, drill hole data.

Previous studies focused on Gandarela and Fonseca Basin suggested that the early stages of sedimentary units are lacustrine and fluvial records, and the upper units are the result of debris flow, found to be Eocene to Oligocene in age, based on palynological data (Maizatto 2001). Lipski (2002) findings show the close relationship between the reactivation of pre-Cambrian basement structures to the now-formed basins, presenting active neotectonics activity in Quadrilátero Ferrífero.

Serra do Tamanduá (Fig. 7) consists mainly of the Rio das Velhas Supergroup and the Minas Supergroup lithologies, covered by lateritic deposits spread along the ridge (Lobato et al. 2005, Endo et al. 2019). The focus of this paper is Bandeira Basin, one of these basins along the Serra do Tamanduá.

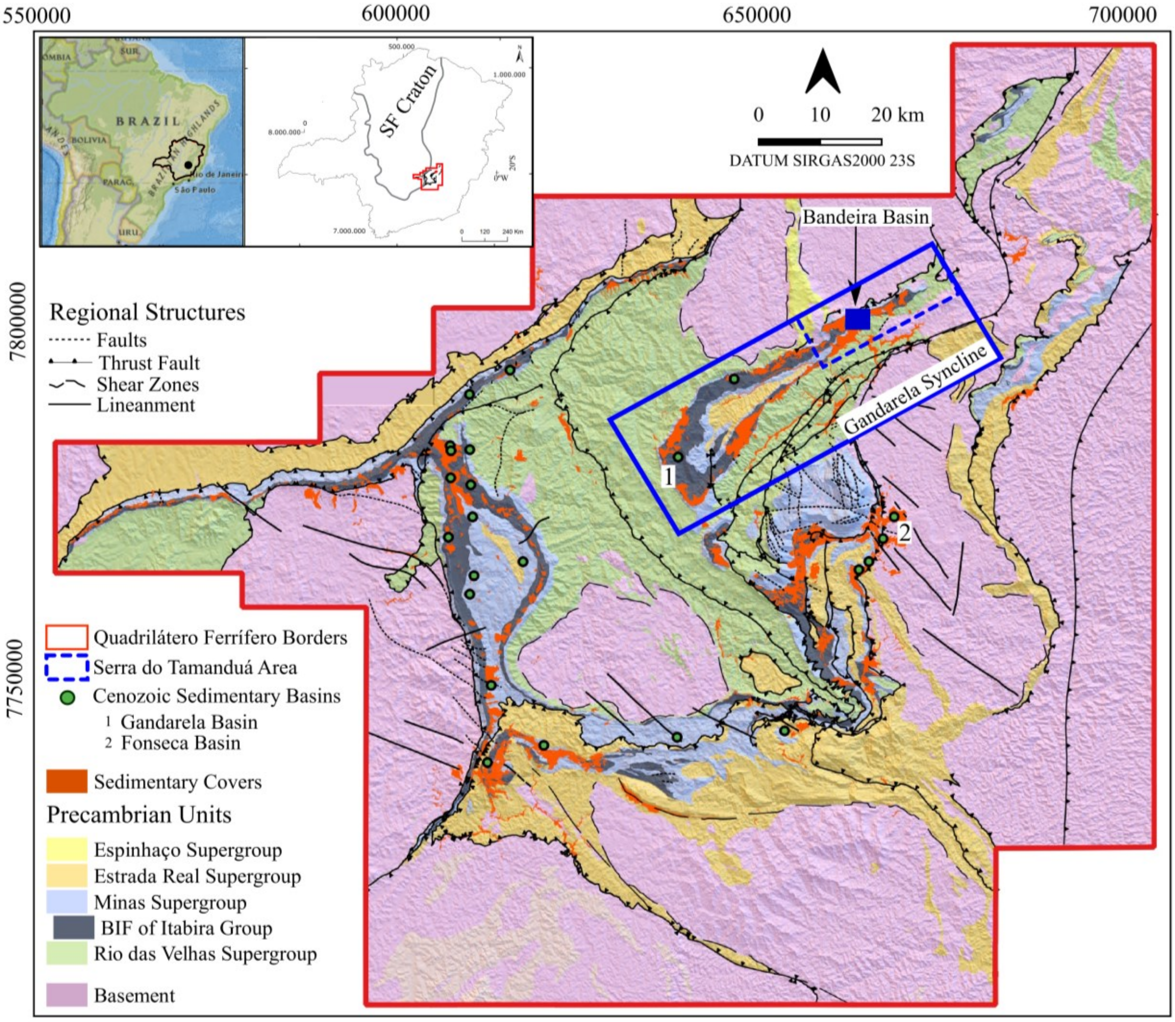

Fig. 7 – Geological map of the main units in Quadrilátero Ferrífero, Minas Gerais, Brazil. Modified from Endo et al. 2019, Castro et al. 2020. SF – São Francisco Craton.

4.3. State-of-art: Cenozoic Sedimentary Basins in Quadrilátero Ferrífero

Dorr (1969) described these recent sedimentary covers as mudstone, laterite, and canga, and their genesis processes. In this paper, Fonseca Basin was briefly described as a sedimentary basin, as previously described by Gorceix (1894 *in* Dorr *op. cit*).

The aspects discussed are mostly regarding the mudstone, often described as a massive clayey material, non-plastic, and associated with the filling of ancient morphological features such as valleys. They are more commonly spotted in the western portion of the QF, on the Moeda e Dom Bosco synclines.

This author discusses some possibilities for the origin of these units. Dorr (1969) highlights that these covers do not have transitional contact with the underlying saprolite material and are not intercepted by younger intrusive rocks, which demonstrates that they are the youngest units in this area. Although some outcrops of the lateritic covers present deformational structures such as joints, few or no sedimentary structures are seen.

Dorr (*op. cit*) emphasizes that horizons with yellow, white, and red colors are the result of iron oxide leaching. In conclusion, the author lists the following possible explanation, although indicates it clearly as an open question:

i. Weathering product of dolomite (Guild 1957 *in* Dorr 1969);
ii. Laterization of siliceous ferruginous dolomite (Pomerene 1964, *in* Dorr 1969);
iii. Reworked ocherous itabirite (Gair 1962 *in* Dorr 1969);
iv. Windblown volcanic ash filling Cenozoic valleys (Dorr 1969).

Dorr (*op. cit*) also distinguishes *in situ* materials, such as duricrusts, mostly known as canga and laterite. The paper indicates that laterite is non cemented material, result of debris, talus, and ferruginous soil of iron formation, while canga cemented material, rich in iron oxides and hydroxides. It is recognized three types of canga:

i. Normal: composed by lithic fragments, such as hematite, itabirite, quartzite and phyllite, cemented by iron an aluminum oxide and hydroxide.
ii. Chemical: poor in lithic fragments but rich in limonite;
iii. Rich: composed by hematite fragments cemented by limonite.

Most recent papers (*e.g.* Spier et al. 2018), treats canga as a rock-like material, since its cemented matrix, usually with ferruginous oxides and hydroxides makes it as resistant as rock material. The occurrence of canga is usually described in surface exposures, but there are some occurrences in subsurface as well, as in the Águas Claras Mine, in the northern part of the Quadrilátero Ferrífero.

This kind of setting is described by Spier et al. (*op. cit*), that shows a canga layering over itabirites, with both *in situ* and normal canga. Overlying this normal canga, it is described a brick-red material, which is a red massive sedimentary clay, with dozens of meters of thickness. This material is covered again by another normal canga layer. These authors investigated the age of these reference units, discovering that the upper layer is 26 Ma and the lower layer is 41 Ma, which is a very important result that indicates a complex history of deposition, pedogenetic and tectonic Cenozoic events.

Papers published since the 1990s described sedimentary basins individually. Using different approaches, they often aim to explain the genesis processes of the geological setting, *e.g.* Morro do Caxambu deposit (Santos and Varajão 2004), Gongo Soco Formation (Saadi et al. 1992), and other examples (Lipski 2002). The most complete studies consist in the characterization of Fonseca and Gandarela's Basin, both located at the eastern portion of QF (Fig. 7). The sedimentary occurrences units range from Paleogene to Neogene (Lobato et al. 2005).

The Fonseca Basin is a 32 km² area with sediments as thick as 35 m, over a granite-gneissic basement. It is completely described from outcropping sediments, with the most outstanding palynological as well as macrofauna records. It consists of two units: Fonseca Formation is mainly fluvial units at the base, and the upper unit is Chapada de Canga Formation, formed by alluvial fan ferruginous cemented conglomerates (Maizzatto 2001, Castro and Varajão 2020).

The Gandarela Basin consists of a 9 km² in area, at least 125 m in thickness characterized by 15 drillhole core descriptions. Seven sedimentary facies with the most complete palynological record of the southeastern continental Brazilian basins were described, and two facies association: the first, lacustrine, partially covered by the second, a debris flow controlled. Its basal contact is not intercepted by the drill hole described, but it is most likely units of the Minas Supergroup (Maizatto 2001, Castro and Varajão 2020).

Castro and Varajão (2020), present one of the most recent papers to address the age of these sediments and establish an age hierarchy among the known recent deposits. The authors suggest that the previously generic terrigenous deposits can be detailed from the sedimentary facies' perspective.

The lack of details for these occurrences can be explained by the shortage of outcrops. Also, the outcrops alone do not always show the accurate dimension of the deposit, which having drill hole information can be very enlightening.

The approach adopted in Castro and Varajão (2020), Varajão et al. (2020), and previously in Santos e Varajão (2004) is based on the macro and micro characteristics of the sediments. The more recent work shows five main facies, that do not necessarily occur in all the recent deposits and are discontinuous both laterally and vertically. The facies are as follows:

- Fragmentary facies (F): immature sediments in a clayey matrix, reddish brown to dark red, composed by angular to sub-rounded lithic fragments of phyllite, quartzite, hematite and itabirite, that ranges from millimeters to decimeters in diameter.

- Nodular facies (N): massive sediments in a silt clay red matrix, and rich in yellow, white, red, pink stains, lithic fragments, and nodules. Commonly occurs associated with other sedimentary facies such as fragmentary and quartz sand clay facies.
- Quartz sand clay (AQA): the sediments are in a variety of colors such as red to white, with a clayey to silty matrix. It has a high percentage of quartz, white mica, heavy minerals, and lithic fragments.
- Massive clay (AM): massive, rich in fine to coarse-grained quartz and ferruginous millimetric nodules.
- Conglomerate (C): sediments are composed of lithic fragments of phyllite, ferruginous quartzite, and vein quartz, sub-angled to sub-rounded, in a clay sandy matrix, that generally occurs overlying other sedimentary facies, suggesting paleochannel records.

These Cenozoic sedimentary units are closely related to graben and horst structures, caused by late tectonics in South American passive margin (Varajão et al. 2020). These authors resume the perspective presented in Lipski (2002) and show further details of five selected sedimentary deposits in Moeda Syncline.

The Cenozoic strain state in South America is mainly responsible for generating or reactivating structures of the basement, triggering sedimentary processes (Lipski 2002). Therefore, graben-like features caused sediments to be concentrated in basins. Those unconsolidated sediments were later deformed by brittle processes. Small-scale faults and fracturing surfaces are formed due to compressional and extensional punctual strain. The sedimentary features described by Lipski (*op cit.*), focusing on structural analysis, show the close relationship between the reactivation of pre-Cambrian basement structures to the now-formed basins.

4.4.Methods

For the description of Bandeira Basin it was used a multistage method, with bibliographic research, field mapping, and *in situ* investigation. The macro characteristics of the sediments are presented with a synthesis of the field observations, showing the map and the main features of key samples.

This investigation initiated with an extensive bibliographic study, using local and regional maps such as Lobato et al. (2005, 1:50.000) e Endo et al. (2019, 1:150.000), highlighting differences and similarities in the contacts and description of the sediments. It was used as a base for a field survey made to check the units that outcrop in the study area, which resulted in a local detailed field map.

A total of 320 m of drill holes were described and they are identified as MAD-FSE0001, MAD-FSE0002, and MAD-FSE0003. The profile of these drill holes is shown in Fig. 14. The drill holes samples set the pattern to lithofacies references and codes that is used from this point on.

A database of 35 drill holes, in a total of 4,250 m of core samples was provided and analyzed, in addition to the three drill holes described. All data were carefully checked in the way that it was possible to use this information afterward in tridimensional software. The database was uneven, due to multiple drill hole surveys and descriptions of samples through time. It identified the need to have a unified assignment to all the drill hole descriptions, so this work also adapted the descriptions given so they would match all databases available.

In synthesis, it was used a database of 38 drill holes, in total. Three of these were described in detail by the authors, while the rest had their descriptions given by the mining company and had its data compiled and treated using the three detailed drill holes as reference.

The following steps have been performed:

i. Assign classification to each described interval;
ii. Reclassification of selected intervals to bring compatibility to all the databases;
iii. Comparison between the database and drill hole photos;
iv. Final validation and creation of the database in the format of importing to the tridimensional modeling.

The sedimentary facies classification was done with a modified classification from Castro and Varajão (2020). Considering the three cores described, an individual profile of each drill hole was drawn, so the material found could be grouped on sedimentary facies, using nomenclature based on Miall (1978) and illustrated, showing a correlation in depth and lateral placement. The names of the facies are explained in their descriptions. For those drill holes, samples for petrographic analysis were selected, and described under optic microscope.

All the drill hole data was used to build the tridimensional model with the software Leapfrog Geo 2022.1, with the mapping results and structural information. To model the basement of the basin, besides the drill hole database, surface and regional mapping provided the necessary information. The format of the basin was modeled considering that:

- The drill hole information provides unique and punctual information, that, when accessed from the tridimensional point of view, can enlighten significant lateral and vertical distribution of the units;
- Although difficult to track on drill hole samples, the contact relations of the sediments can be modeled from the features that could be described and considering basic sedimentary principles;

The basin geometry can be inferred using information first of the sediments described, but also considering the concept of accommodation space for these sediments. This reference comes from other sedimentary deposits known in Quadrilátero Ferrífero.

4.5.Results

The Bandeira Basin is a sedimentary deposit found in northeastern Serra do Tamanduá (Fig. 7). Its sediments lie over Archean (outcropping in part of the study area) and Proterozoic weathered rock. The sediments of the Bandeira Basin occur over a large area in the Serra do Tamanduá, outcropping in railway, road cuts, and as crusts on the floor. It is composed of multiple clayey to sandy sediments, many of which are interbedded with gravel-rich sediments. The simplified geologic map, as well as the location of the drillholes, are displayed in Fig. 8.

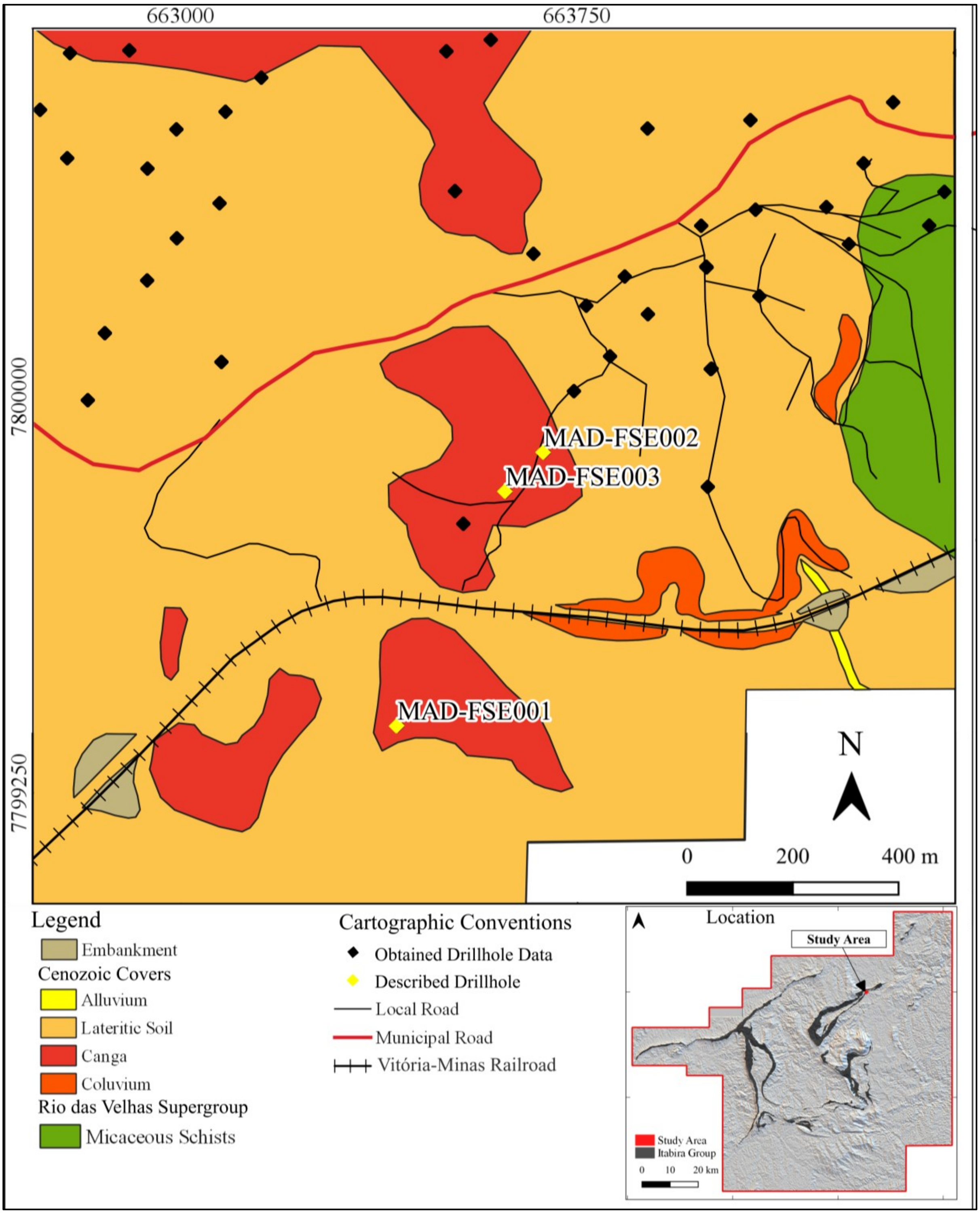

Fig. 8 – Simplified geological map of the Bandeira basin area highlighting the drill hole database.

4.5.1. Bandeira Basin

The sediments outcropping are shown in Fig. 8, as well as part of its basement. The characteristics of every material will be described in stratigraphic order.

4.5.1.1. Mica phyllite and quartz mica phyllite

In the study area it is identified altered mica phyllite (red, purple to light yellow saprolite), with no or few schistosity that are parallel to steeply dipping. It has white mica, chlorite, and quartz that vary its content. They are identified as phyllite from the Nova Lima Group, outcropping only in the northeastern portion of the area. Its contact with the Minas Supergroup does not outcrop, although it can be seen as an abrupt contact in some drill hole samples.

4.5.1.2. Gravel with Rounded Clasts (Grc)

Sediments similar to conglomerate were found in the drill hole MAD-FSE0001, and it is clast supported. The lithic fragments are green, yellow, and black, showing high sphericity and rounded to angular shape. It was not observed clast orientation. Its matrix is sandy-silty with clay, with fine to medium-grained sand (Fig. 9 E) Quartz fragments are present in the matrix. The clasts are surrounded by a ferruginous cortex. At the base, it shows a sharp contact with mica phyllite saprolite, while towards the top, the matrix proportion increase, progressively turning into a diamict-like sediment.

4.5.1.3. Organic mud (Mo)

Organic mud occurs around 75 m in depth. It is composed of black clayey sediment with kaolinite spheres. The top and bottom contact is abrupt. It may have a role as a stratigraphic marker, with the potential to pollen and microfossil content, which further investigation in the thin section shall reveal.

4.5.1.4. Gravel with angular clasts (Gac)

Only in drill hole MAD-FSE0001 gravel deposit with about 7 m thick lies over the organic soil and under a horizon of white sediment. It is composed by a clayey matrix with boulders, cobbles, and gravels of sericite phyllite, quartz sericite schist, and quartz vein fragments, white to beige. The clasts are mostly angular to subangular, some smaller are rounded. These fragments within these deposits show similarities with the weathered mica phyllite (belonging probably to the Rio das Velhas Supergroup) described at the northeastern part of the studied area (Fig. 8).

4.5.1.5. Clayey and Sandy Quartzose Sediments

These units are heterogeneous interbedded massive clay (Cm) and quartzose sand (Sq) sediments, in which might occur quartzose gravel (Gq). These sediments do not outcrop in the area, but they are described in all three of the drill holes sampled. In the drillhole database provided they are often simply described as siltstone, with no further details. They have a maximum thickness of 36 m and are thicker on the west and south portions of the study area.

For the most part, it is white, clayey, light, and rich in kaolinite, as shown in Fig. 9 A. The claystone is always massive, white to yellow or yellow with white nodules. Locally, nodules are pink and red, as shown in Fig. 9 B. In these parts, one might find some gravel or coarse quartzose sand content in sparse points. The grains are high in sphericity, angular to rounded, and immersed in a clayey matrix with few mica grains.

In some depths the drill hole intercepts layers of massive, light pink, lilac, and purple clayey sediments with white nodules (Fig. 9 C). It overlies the rich organic layers at the bottom of this sequence and was only seen in MAD-FSE0001 with 1 m in thickness.

There are several portions in which sandy sediments are found. These are usually 10 cm to a few meters thick, usually white, massive and quartzose. Locally, a few lithic fragments of ferruginous quartzite and quartz vein may be present. These sandy sediments present some levels with a kaolinite matrix with fine-grained quartz and sparse pebbles of quartzite. This sediment can contain some kaolinitic clay, with medium to coarse grains and some laminae rich in manganese oxide. In the thin section (Fig. 10) these sandy sediments show up to 35% of the clayey matrix, with much of the grains being angular in shape, with magnetite, zircon, and hematite as accessory minerals.

There are some remarkable portions of white to beige clayey sediment rich in manganese oxides. The manganese oxides can be both nodules and filling extensive fractures, millimetric thick, with no structural pattern, although they may often occur parallel to the drill hole axis, as shown in Fig. 9 D. These manganese-rich sediments are identified mostly on the bottom of the clayey and sandy sediments, sometimes being a challenge on how to distinguish it from the underlying weathered bedrock. These manganese oxides are more clearly and regularly aligned in millimetric features in a matrix that is rich in iron oxide and hydroxide.

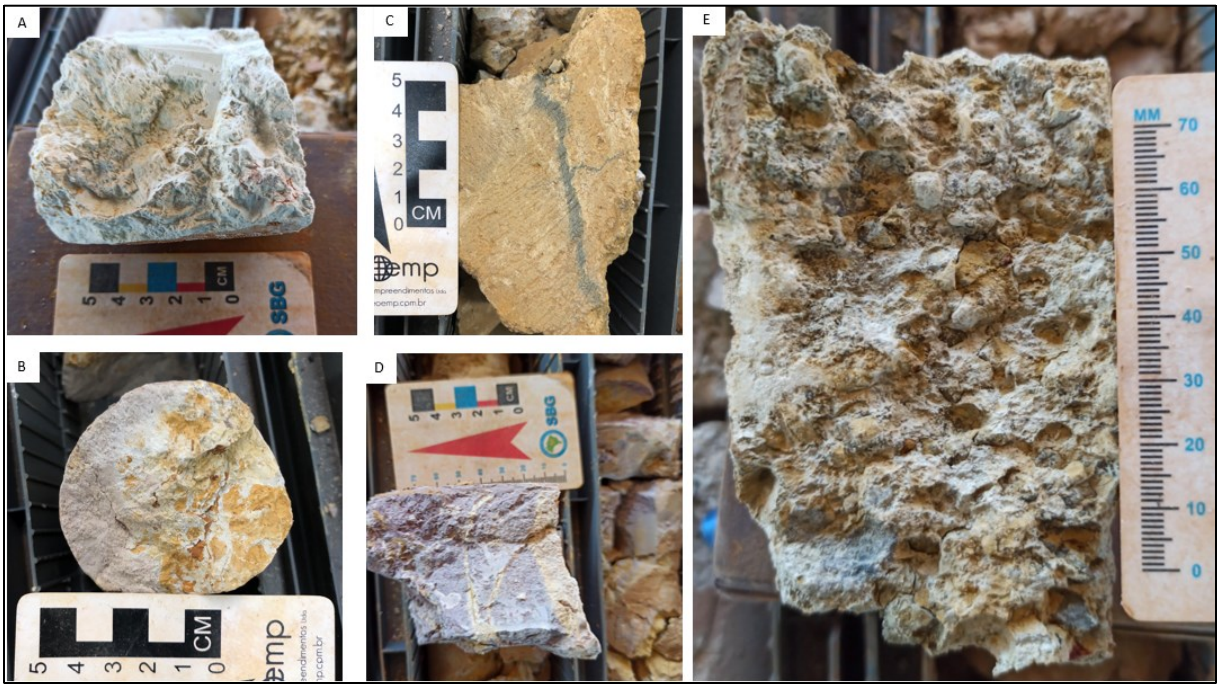

Fig. 9 – A) White clay, massive; B) clay with white and ochre massive portions and quartz pebble in small proportion; C) material with manganesiferous vein; D) pink clay; and E) rounded pebble and cobble conglomerate, of mica schist and lateritic material.

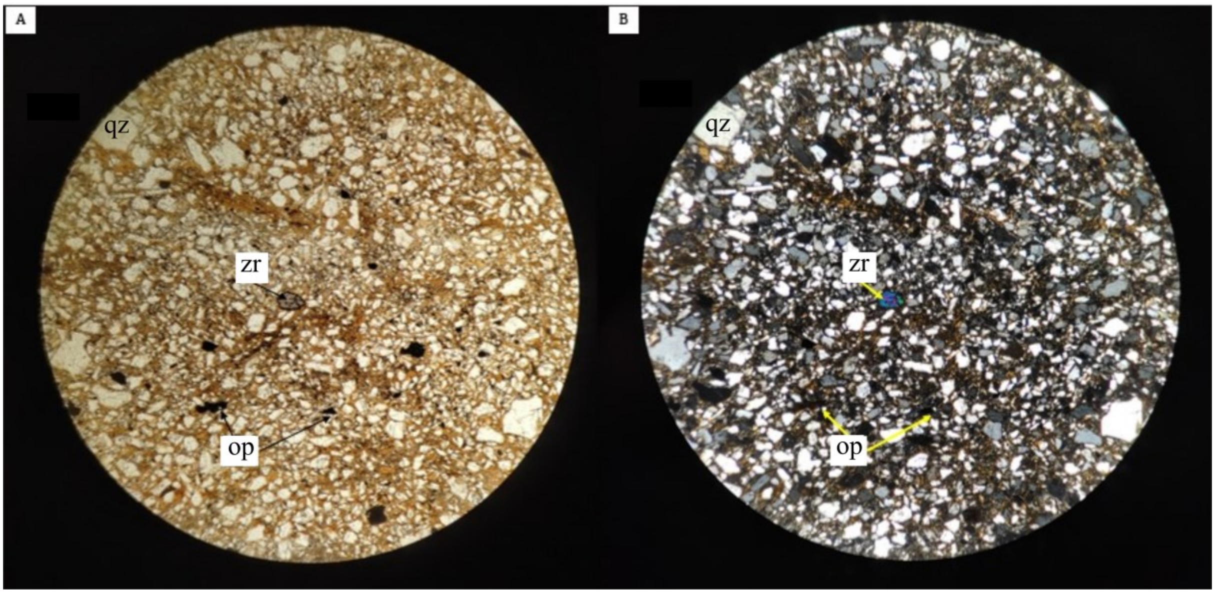

Fig. 10 – Microphotography of thin section, 10x magnification, of the immature sandy quartzose sediments from MAD-FSE003 (71m), rich in angular quartz grain (qz), some opaque minerals (op) and rare zircon (zr) A) under plane-pollarized light and B) under crossed-pollarized light.

4.5.1.6. Clay to Gravel Sediments

This is the most common unit of Bandeira Basin, outcropping in the study area. It can reach 37 m in thickness. It outcrops aside the Vitória-Mina's railroad tracks as a dark brown material with pebble and cobble-sized clasts of itabirite, hematite and canga immersed in a sandy to clayey matrix. It overlies both the Archean units and the Minas Supergroup, with erosive contact. These sediments form a complex and heterogeneous unit. Its identified facies are:

- Cgshem – Massive, dark brown sediment, with a clay (C) matrix in which there are fine sand (s) to sparse pebble-sized (g) clasts of quartz and hematite (hem). The clasts have low sphericity, and some coarse-sized specular iron oxide grain occurs, as shown in Fig. 11 A.
- Cgslith – Sediment rich in clayey to sandy matrix, often red. The clasts are pebble and sparse cobble-sized, with high sphericity, of mica phyllite (gray or silver), itabirite (mostly with low sphericity), hematite, milky quartz to crystalline quartz vein (Fig. 11 B);
- Cslam – Sediment with interbedded levels of laminated clayey to sandy (s) and clayey (C) massive material. The layers that present parallel bedding structures, as in Fig. 11 D, have laminae (lam) of black, sandy, and silty hematite and quartzose grains, laminae of red clayey with high plasticity, and yellow and gray quartzose and micaceous sand. Some of these layers present erosive contact with the other layers.
- Csglim - Yellow to brown material, in which matrix is clay (C) silty to clayey sand, with some massive sandy (s) layers composed by specularite and magnetite (Fig. 11 C), with moderate plasticity. This material contains granule to pebble-sized (g) clasts of quartz and lithic fragments, some of them surrounded in goethite or limonite (lim). There are few fragments bigger than 5 cm. Most of the clasts are rounded to subangular, with high sphericity.

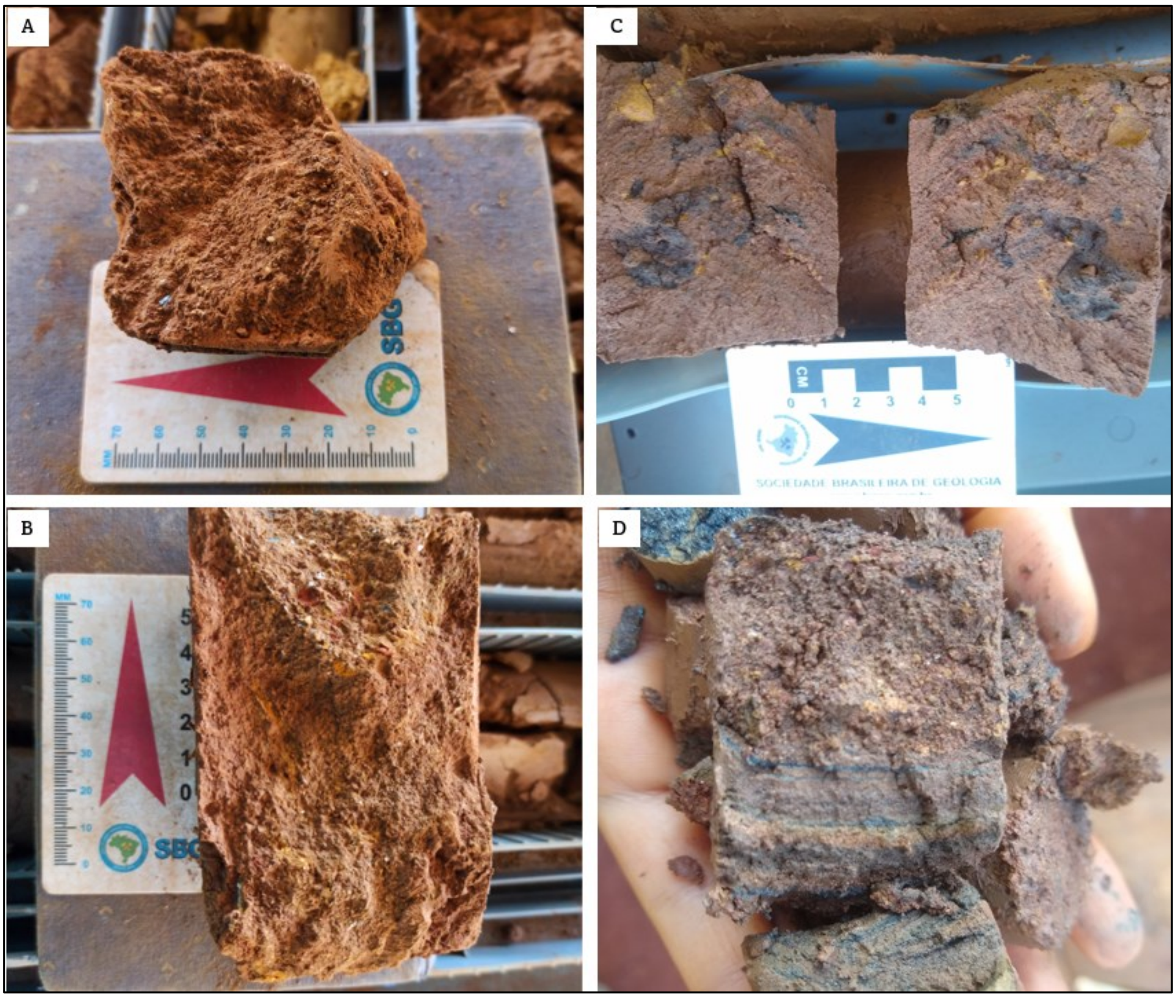

Fig. 11 – A) sand clayey matrix, with pebbles of canga and laterite; B) CGSLith massive clayey matrix, with quartzose and lithic fragments; C) CGSLim massive colluvium with clay to silty matrix, pebble-sized grain surrounded by goethite and some hematite silt widespread; D) colluvium with planar bedding, with massive and laminated strata, rich in manganese, hematite and quartz sand sized grain and a few lithic fragments.

4.5.1.7. Residual Soil (RS)

It is found in some specific depths a yellow to ocher clayey material (Fig. 12 B, C), that has a transitional contact to the clay to gravel sediments layers in the bottom and an erosive contact to the material often overlying it. For this contact with the sediments, the soil is originated from the sediments themselves. These layers are up to 5 m in thickness and occur in all three drill holes, near 15 m (MAD-FSE003), 22 m (MAD-FSE001), and 35 m (MAD-FSE002). It has clayey, with sparse fine- to medium-grained sand content, with cobbles and some black manganese nodules. These nodules increase in content toward the top, as well as some thin roots and wood small fragments (Fig. 12 A).

Fig. 12 – A) Material rich in thin roots and organic remains; B) Ochre material with pebble sized manganesiferous nodules; C) material rich in kaolinitic portions in and with thin roots.

4.5.1.8. Canga (CG)

The canga is a clast rich, rock-like ferruginous material (Fig. 13 A), with few or no ferruginous matrix. The fragments are usually between 0,5 cm to 15cm in diameter, angular to subangular, with low degree of sphericity, often surrounded by a botryoidal goethite concentric layer. In some outcrops canga can have (Fig. 13 B) some matrix content, with up to 10 cm clasts of itabirite and canga or limonitic material. The matrix is dark brown, sand clayey, with fine to coarse-grained quartzose sand.

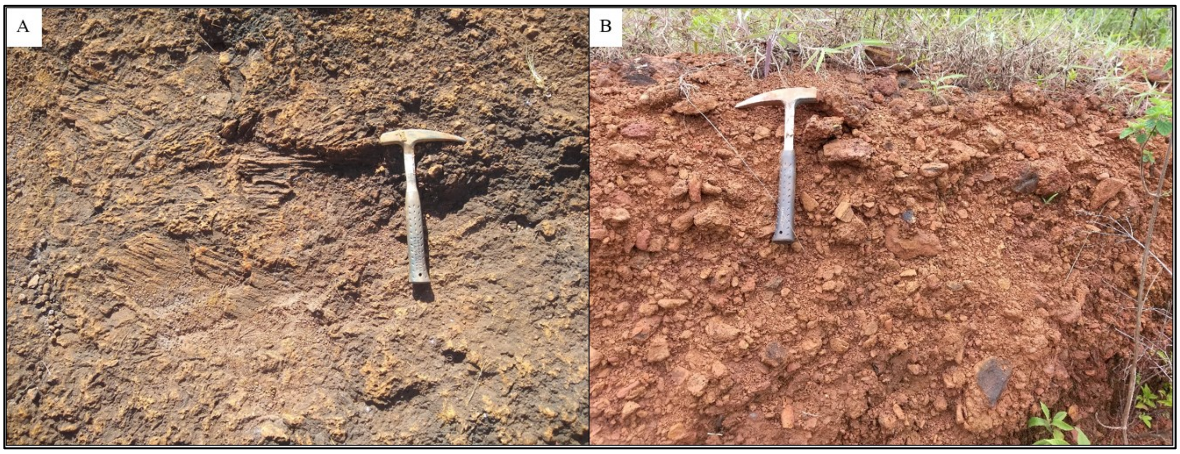

Fig. 13 – Canga occurrences outcropping as crusts on the floor. A) Poor in matrix; B) or rich in matrix.

4.5.1.9. Lateritic Soil (LS)

This soil-like material is red to reddish brown and overlies mostly of the sedimentary units. It is sand clayey to sand silty clayey, rich in pebble to cobble-sized hematite, canga and limonitic material matrix supported. Roots and wood-like fragments occurs, mainly in the shallow levels. It has transitional contact increasing cementation downwards to canga or increasing the pebble content to clay silt sandy sediments.

4.5.2. Stratigraphic Units of Bandeira Basin

Based on the spatial associations in the drill holes, this paper proposes the categorization of Unit A, Unit B, and Unit C, as shown in Fig. 14. The units may be synthesized as follows:

- Unit A: consists in the gravel and diamict-like sediments, including sandy materials and the black organic sediments. It is the bottom-most interval and occurs only in the MAD-FSE001 drillhole core in southwest.
- Unit B: comprehend the facies with clay and sandy sediments interbedded with gravels. Transport reworking is low as seen by the angular fragments. This unit is found only in-depth, with variable thickness in the three drill holes described and in other drill holes, from the database, located in the central to the western portion of the area.
- Unit C: reunite facies with clay, silt, and sandy sediments, which correspond to a colluvionar material affected by pedogenesis in different moments. There is some

transport reworking, as shown by the rounded fragments. It is widely spread and is the most extensive in-depth unit, which can be found in every drill hole core.

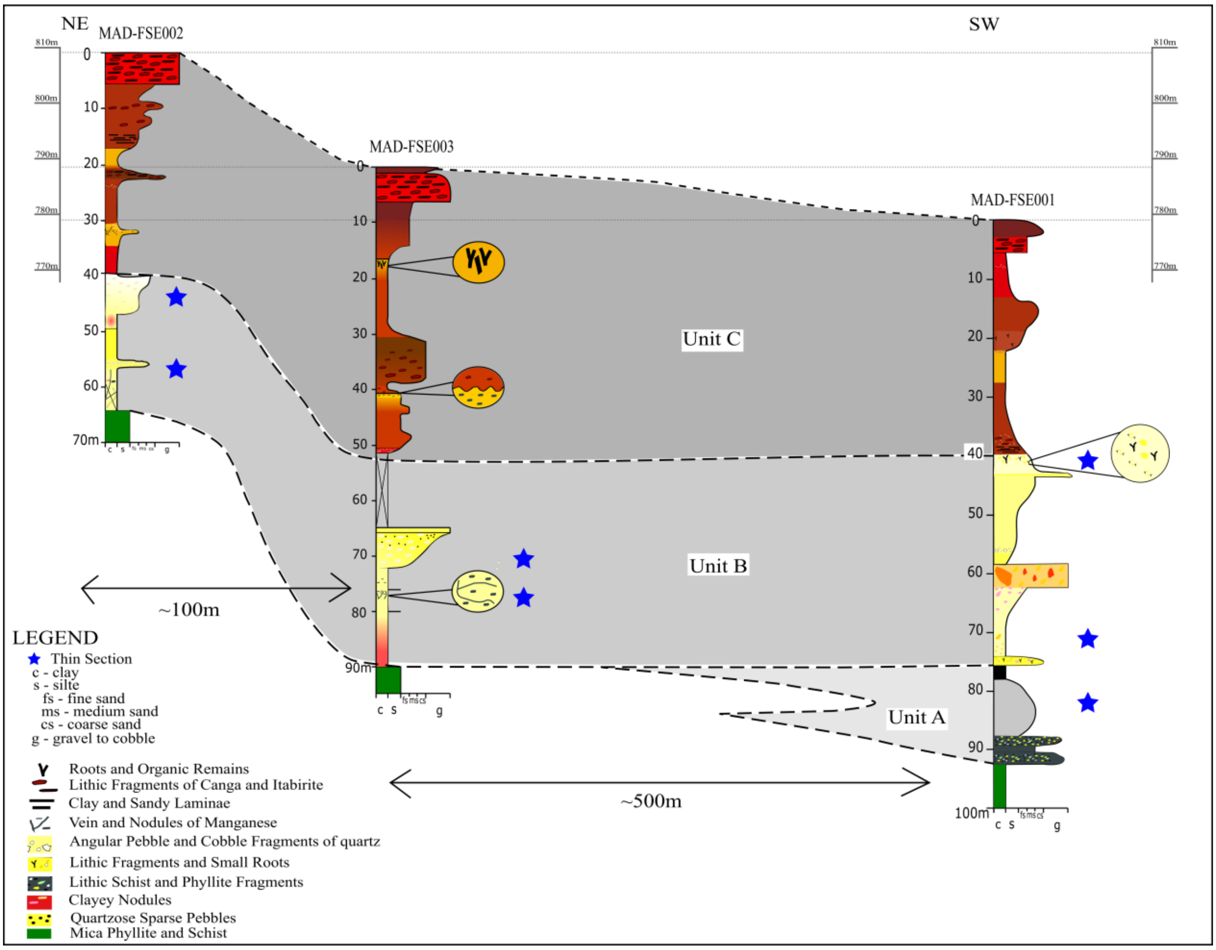

Fig. 14 – Drillhole profile description for MAD-FSE001, MAD-FSE002 and MAD-FSE003. Drillhole profiles with the individualized intervals, some remarkable features, and their correlations. The colors used are as similar as possible from the real core sample.

4.6. Discussion

4.6.1. Processes Interpreted for the Bandeira Basin Facies

The mapping data, as well as the drilling information, show that the basement of the Bandeira Basin consists of weathered rocks of the Minas and Rio das Velhas supergroups, in the depositional setting presented as shown in Fig. 15. The sediments are located at Serra do Tamanduá, NE-SW oriented and at the easternmost part of the Gandarela Syncline. The slope decreases from north to south of the ridge. The sedimentary basin is located on the southern side of the ridge, suggesting that the area may have experienced material gravity reworking from the north on its natural slopes.

Drill hole information indicates that the sediment layers are thicker where they are on top of the Rio das Velhas Supergroup than when they are overlying the Minas Supergroup. The oldest sediments are grouped in this paper under the name of Unit A, with conglomeratic, sandy, and clayey sediments that were only noticed on the southwest portion of the Bandeira Basin, around 75 m in depth in MAD-FSE001. These sediments have fragments of chlorite schist and quartz, that are consistent with a provenance from the weathered rocks of Rio das Velhas Supergroup (Nova Lima Group). The fragments are often rounded and have high sphericity, suggesting a reworking process by sedimentary transport, possibly with the influence of water. The proportion of fragments decreases upwards in gradational contacts, punctually erosive, especially where the sediments are richer in fragments.

This sedimentary record could be interpreted as a first pulse of basin filling, rich in coarse material, with its source area probably near the depositional site. These sediments were only found in one drill core and it may implicate in a local process, where the basin just started to form. The fragments themselves might have been formed after reworking of weathered outcropping material, as they often show a layer of ferruginous cortex outside the fragments. The weathered mica phyllites of Rio das Velhas Supergroup were eroded, transported, and then deposited in an incipiently formed Bandeira Basin. Although the process that triggered the sedimentation is not yet clear, especially considering this one drill hole, it is interpreted as a fan delta debris, with fluvial influence (Fig. 15 1).

The upper limit of facies association A is marked by an organic-rich layer with 1.35 m thick of black clayey material. This represents a shift in the sedimentation process and perhaps the involvement of a water body, such as a lake.

Unit A is overlain by interbedded clayey and sandy sediments, which are found throughout the southern and central areas of the Bandeira Basin. The contact between the black organic material from Unit A and the base of Unit B is abrupt. This might mean a lack of stratigraphic record, suggesting that the organic-rich material could be thicker and that the process and environment responsible for the deposition of such sediment might have lasted more than its actual thickness suggests.

Unit B occurs from depths around 35 to 75 m. These sediments are mostly massive, kaolinite rich, light in density, and greasy to the touch, where the argillaceous sediments are predominant. The contact relation is difficult to classify on the drill hole samples, but the interleaving is frequently locally erosive. In the clayey sediments is frequent to identify sparse coarse sand grain, granule, and pebble, high in sphericity and angular. The sediments might have been transported by cohesive (muddy-rich) debris flow, as exemplified in Fig. 15 2. In some parts, this unit can be classified as diamict-like sediments, due to the increase in size and quantity of clasts. The occurrence of manganese vein and nodules can be associated to the groundwater level and oxidation processes during subaerial exposure.

In the southern portion of the area, also in the drill hole MAD-FSE001, besides those sediments, a talus-like material is found in the middle of the clayey and sandy sediments, or as named Unit B, different from all the described facies. This suggests an episodic deposition of non-cohesive (granular or clay-poor) flow. The boulders are sericite phyllite consistent with the one found outcropping in the study area, around the Vitória-Minas' railroad. This indicates that the basement of the basin, the weathered rocks of the Nova Lima Group, are the source area to these sediments. The high content of kaolinite endorses this interpretation.

The other drill holes described, along with the database provided by the mining company, do not show any evidence of this kind of material. Unit B often shows interbedded conglomeratic sediments with massive clayey and sandy ones. However, it does not show any talus-like sediments but in the MAD-FSE001 drill hole. The talus-like occurrence, as shown in Fig. 15, is noteworthy not only because shows a different sedimentation process, but it can also represent a topographic break nearby the point surveyed. This might suggest the simultaneous influence of tectonic processes influencing sedimentation. It is not clear which unity in Rio das Velhas Supergroup could provide the amount of quartz content found in these sediments.

The upper layer of sediments is Unit C, and outcrops all over the study area, (Fig. 15 3). These sediments are thicker in the central and southwestern portion of the area, ranging from 9 m to 35 m-thick (average of 20 m). The basal contact is abrupt, with successive layers of colluvial sediments and some erosive contact. The sediments have fragments with different angularity, sphericity, and composition, as once described, that indicates a different source area when compared to Unit B. Unlike units B e A, this unit is richer in sedimentary structures, such as massive sediments intercalated with bedded and laminated ones. Once the lithic fragments are mostly itabirite, ferruginous quartzite and canga, it is most likely that the source area for these sediments is the Minas Supergroup, probably Itabira and Piracicaba groups.

The sediments are poorly sorted and show a diversity of clast lithotypes in most of the described layers, suggesting low-sorting capacity deposition processes and multiple source areas. This unit is interpreted as formed by coluvionar processes along the southern slopes of the Serra do Tamanduá.

The clear layering structures in these sediments, with evidence of erosive contacts between some of them, might indicate that at least part of the sediments experienced a longer transport and perhaps an underwater deposition. These sediments might represent the distal part of the flow since they represent a non-cohesive mass flow.

Other distinct feature identified in Unit C is the presence of ochre horizons, rich in manganese nodules, wood fragments and small roots. These horizons are at maximum 5 m thick and has basal gradational contact and upper abrupt contact. They have been interpreted as residual soils of the colluvium, indicating that these sediments have been exposed to pedogenetic processes, with phreatic influence.

If these soil-like horizons occur in depth, such as described in 5.1.7, it indicates that it was later buried by distinct debris flow. The material that buries these colluvium residual soils is richer in granule and pebble-sized clasts of hematite, itabirite and lateritic material in greater amounts than the sediments in depth. It is also clearly richer in sandy matrix, with quartz and Fe-oxide composition.

These last, most superficial layers are the subject of a recent, yet different, pedogenetic process that resulted in the cementation of the sediments, leading to the formation of canga. In some areas, these canga layers are overlaid by a lateritic soil material, that is different from the canga exactly because it is not yet cemented. The lateritic soil means the canga layers suffered weathering that broke the cemented matrix. The characteristics of canga and the lateritic soil are very similar, being the cementation grade the one distinctive factor. This probably means that the process that once resulted in the canga, might be overturned by a process that weathers the canga and produces its chemical fragmentation.

The terrain morphology probably had a massive influence on the distribution of the sediments, since the thickness of the sediments in relation to the basin basement is clearly variable. The east and southeast parts of the Bandeira Basin are 2 to 10 times thinner than the central and northwestern portions of the basin. All the southern part of the study area's basement is composed of the Rio das Velhas Supergroup.

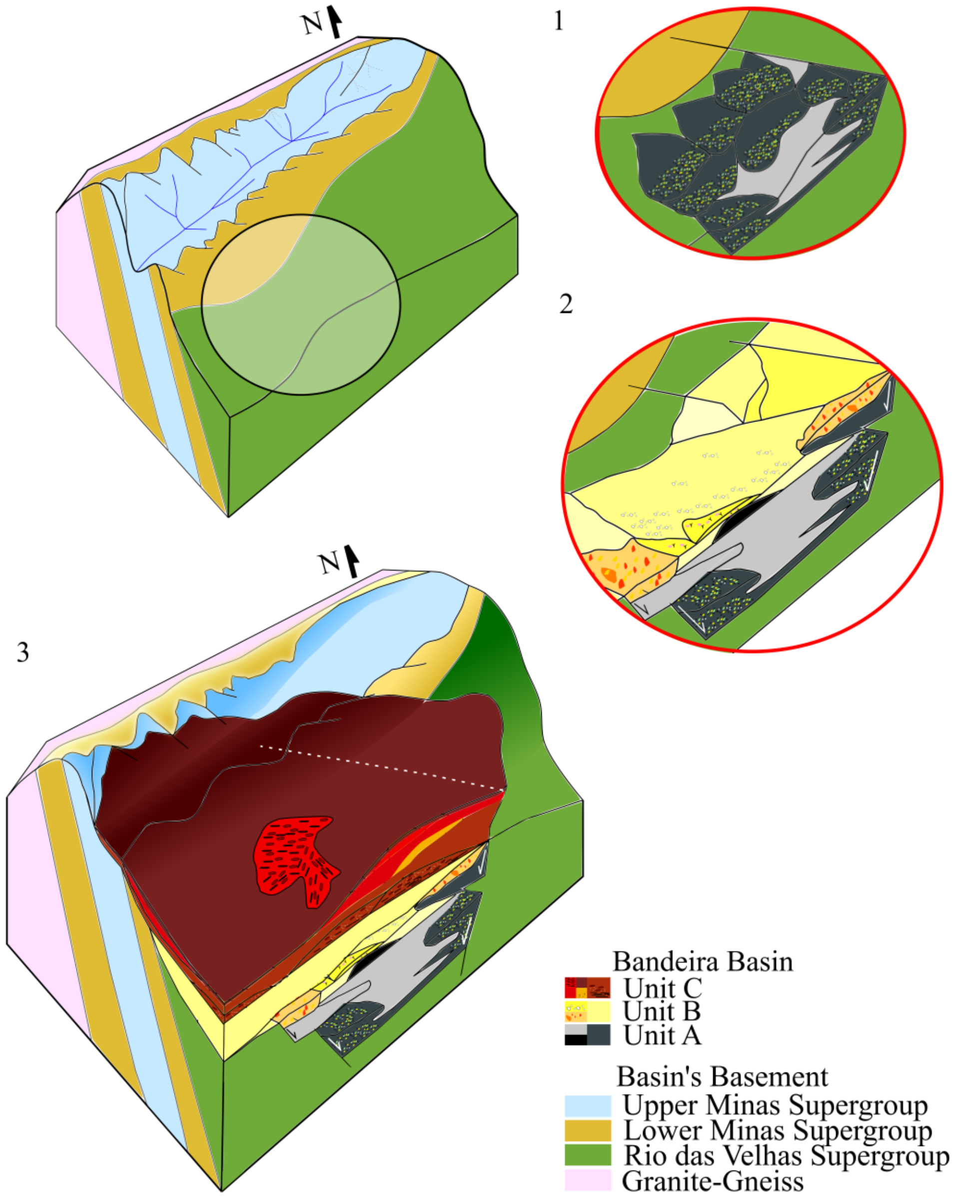

Fig. 15 – Geological arrangements in a 3D representative model.

4.6.2. Comparison and Basin Correlation

Multiple well-known papers bring attempted explanation on the origin of the recent sediments found in Quadrilátero Ferrífero (Maizatto 2001, Spier et al. 2018, Varajão et al. 2020). For the allochthone units, the genesis is explained with depositional history and pedogenetic processes related to time and basin geometry complexities.

It is suggested for the Bandeira Basin a clear contribution of slope erosional and transport processes that reworked both the Rio das Velhas and Minas Supergroup in different times and spaces. The upper unit, here classified as Unit C, is probably the result of reworking of the Minas Supergroup. Below it, the units B and A (Fig. 14) forming clay, sandy and gravely sediments, possibly represent the reworking of the Archean units of the Nova Lima Group from Rio das Velhas Supergroup.

The changing in source areas, from base to top in the Bandeira Basin, (i.e., from the Archean Nova Lima Group to the Paleoproterozoic Minas Supergroup), is probably a function of the evolving Bandeira Basin that slowly covered the Archean source areas with sediments due to its lateral expansion. Also, it might have some influence on neotectonics' movements that uplifted Paleoproterozoic rocks exposing them to a faster erosion rate.

The sedimentary model presented for Gandarela and Fonseca basins (Castro and Varajão 2020 and Varajão et al. 2020) is similar to the ones that occur in Bandeira Basin and can be correlated (Fig. 16).

In facies association A, the gravel facies from Bandeira Basin are very similar to the Conglomerate facies, as well as it correlates with channel fluvial sediments, present in Facies Association A of Fonseca Basin (Maizatto 2001). Part of the intervals described in facies association B is associated with the Massive Clay facies from Castro and Varajão (*op cit.*). The Fragmentary and Quartz Sand Clay facies from Castro and Varajão (2020) can be related to layers found in the facies association C (Fig. 16), as well as the canga layers.

The Bandeira Basin shows only one canga layer, different from the situation in Águas Claras Mine (Spier et al. 2018). Also, the Nodular Facies (Castro and Varajão 2020, Varajão et al. 2020) do not have an equivalent in Bandeira Basin. However, many of the layers here described do not have correlation nor similar descriptions in the literature up to now, thus enriching the collection of sedimentary facies and processes known for the Cenozoic basins in the Quadrilátero Ferrífero.

Fig. 16 shows the drill hole profile MAD-FSE001, its described lithofacies, and processes. It shows also the stratigraphic units proposed, and the comparison with the literature.

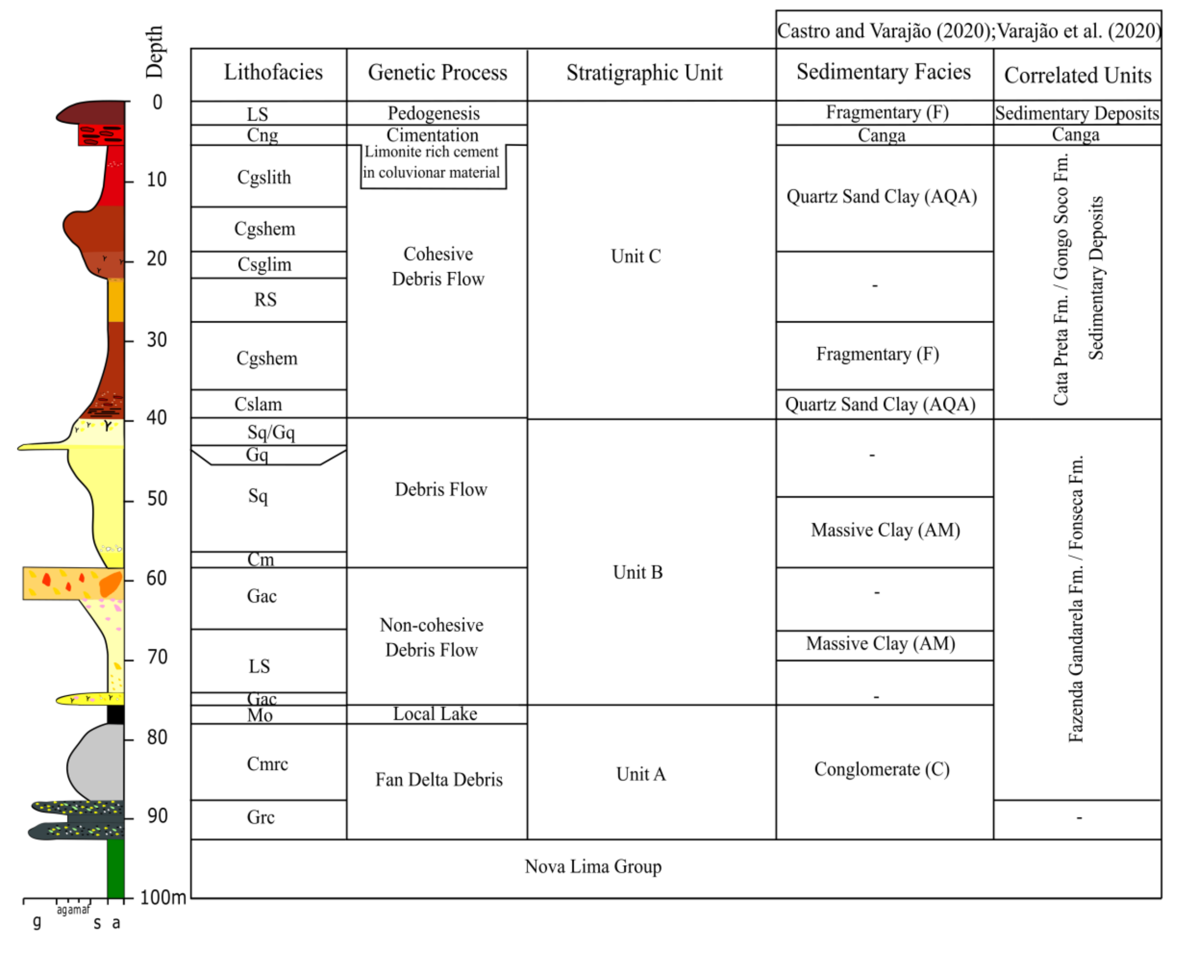

Fig. 16 – Drillhole profile MAD-FSE001, indicating proposed lithofacies units and processes interpreted for the Bandeira Basin, as well as a comparison with the sedimentary facies and geological units (Castro and Varajão 2020; Varajão et al. 2020).

4.6.3. Geometry of the Bandeira Basin

The difference in thickness along the Bandeira Basin is a distinct feature of the shape of the basin, as it might have relation to how the neotectonics affected the Quadrilátero Ferrífero and had impact in both sedimentation and accommodation process of the recent sediments.

It is possible to simulate three-dimensional environment of the probable setting for the Bandeira Basin. Considering other examples in literature, Lipski (2002) and Varajão et al. (2020), these sedimentary basins tend to be formed by i) fault activity, where the blocks shift relative to others, whether along existing structures or forming new ones, generating space for sedimentation; ii) progressive infilling of paleo relief along the slope where the sediments were transported.

Software Leapfrog Geo 2022.1 was used to generate a model interpretation (Fig. 17).

The model consistent with the information analyzed was made considering the main role of fault-controlled basement displacement. The Fig. 17 shows this scenario, that combines the idea of tectonic controlled erosion and deposition. This potential setting can be found in Bandeira Basin especially if considered the great increase in thickness of the sediments in the central portion of the area. Varajão et al. (2020) show that the space of accommodation can be associated with erosional processes, always associated with faulting system. The fault-controlled basin was conceived considering the geomorphological lineaments mapped in regional scale, from today setting.

According to Lipski (2002), the basement can provide direct information for the format of the basin. Hence, the model was drown considering that the thicker portions of the sediments are aligned to the NW-SE orientation. In this scenario, most of the units B and A has the Rio das Velhas Supergroup as basement and source area. This is consistent with the gravel and talus facies containing clasts of phyllites and schists only. The Rio das Velhas Supergroup is also a more probable source area for the argillaceous white massive clay found in these units. In fact, the main thickness of the sediments, represented by units B and A, generated in a context of tectonically active landscapes. Both of those units correspond to the central and southwestern portions of the basin. The contours representative of the contact between units B and A were modeled and presented in Fig. 17 1.

Differently from units B and A, the unit C (contact between units B and C indicated in Fig. 17 2) can be related to the predominant erosional process, that has been acting on the Minas Supergroup as a source area. The facies that comprehend the unit C are widely spread and clearly more extensive than the other two units. There are some points where the thickness laterally varies suddenly, but those sediments are always occurring on the surface all over the area. That suggests that even if the sediments suffered some tectonic influence, this is no longer the case, at least for the upper part of the sedimentary sequence.

The outcropping units, lateritic soil and canga, are outcropping in almost all the area of the basin. Both were modeled and presented in Fig. 17 3 and 4, respectively. The lateritic soil is almost homogeneous in thickness, but the canga unit consists of local occurrences, with thin thickness.

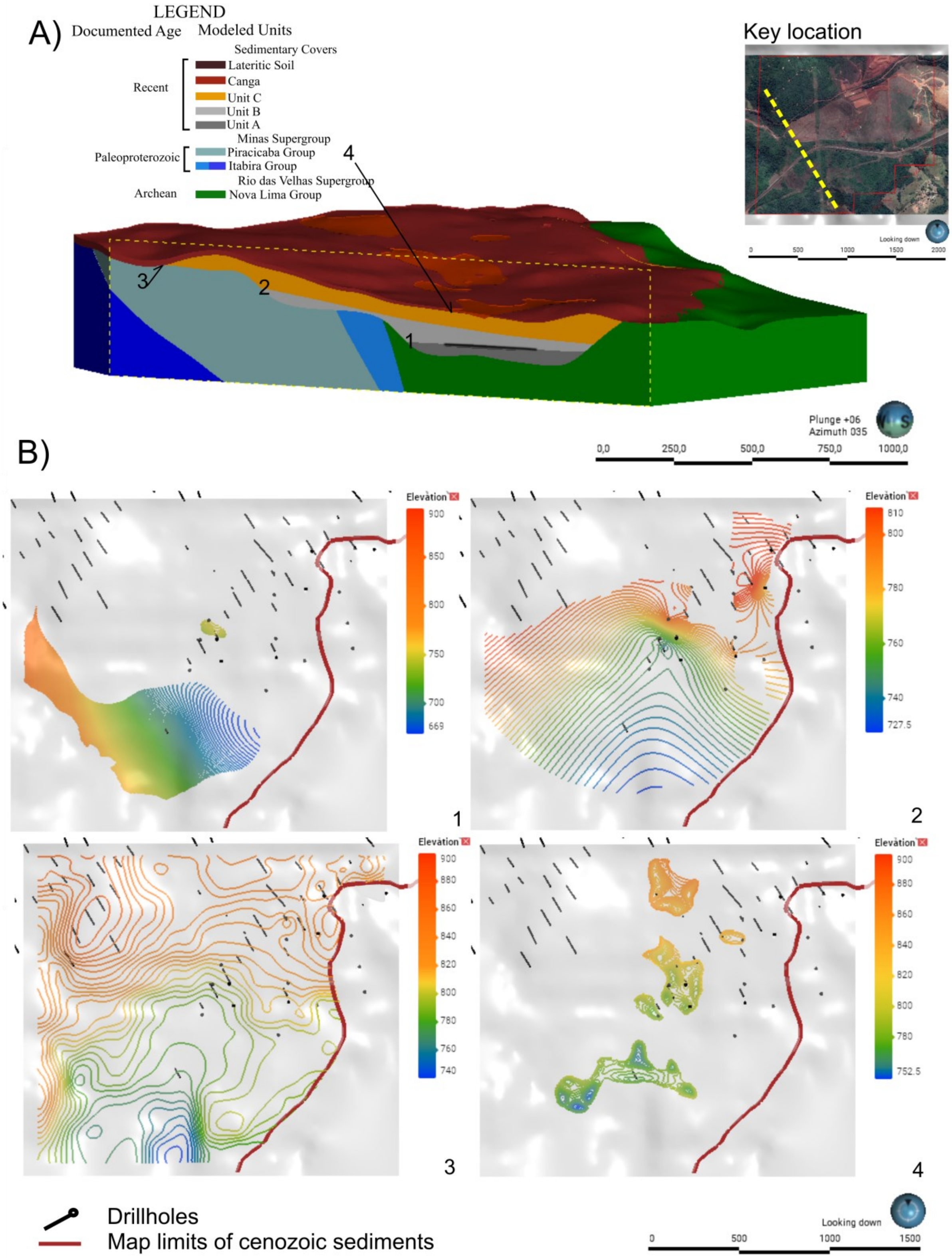

Fig. 17 – Modelled simulations of the Bandeira Basin. A) Section of the geological model, considering the criteria and interpretation presented in this chapter; B) contour map of the contact of the main sedimentary units identified in Bandeira Basin, presenting the contact between units A and B in B1; contact between units B and C in B2; contact of lateritic soil in B3 and contact of canga units in B4.

4.6.4. Evolutionary Model for Bandeira Basin

The Bandeira Basin has a complex sedimentation history. The ancient landscape consists in the units of Minas e Rio das Velhas Supergroup outcropping and forming the Serra do Tamanduá. Those consists in the basement, which suffered effect of tectonic activity. This started a process of modification on the relief existing by the time, allowing the deposition of the oldest unit investigated, Unit A, only occurring in the southernmost part of the area. At this point, probably only the Rio das Velhas Supergroup were sourcing sediments, as shown by the composition of the fragments found. What started as a debris predominant forming process, has its upper layer dominated by lacustrine deposition, forming an organic-rich clayey layer.

The Bandeira Basin might have started as a local sedimentation, probably evolving into a wider area for a sedimentation area, represented by Unit B. The talus-like sediments and their interbedded feature with clay-rich material from Unit B both show that the source area was presumably the Rio das Velhas Supergroup, and that the basement of the basin was still influenced by tectonic normal fault activity. At this point it is not possible to know whether this activity was continuous or episodic, although its geological record tends to show that at least some episodic sedimentation occurred.

Given that normal faulting influenced sedimentation (mainly in units A and B), it is likely that the main mechanism of subsidence is mechanical subsidence. Further basin analysis studies are needed to better enlighten his subject.

Unit C sets the start of the contribution of the Minas Supergroup as the source area for the basin. The material probably was transported by successive debris flow processes. It is likely that these flows could have been spaced in time, suffering some aerial exposure, due to the soil-like material found interbedded with colluvium in this unit. The presence of manganese nodules, clay nodules and small roots, and organic material endorse this hypothesis. The uppermost and outcropping lithotypes correspond to the canga and lateritic soil, which are the result of pedogenesis on the coluvionar material from Unit C previously deposited.

4.7. Conclusion

Although the focus on the QF was the host-rock of the world class iron and gold deposits, in the last years the knowledge of the recent sedimentary deposits is evolving. The occurrence of sedimentary basis is known since the late 19th, but it lacks further studies.

In this context, this paper brings a characterization of the sedimentary deposit now named Bandeira Basin, found in Serra do Tamanduá. The description of the deposit was based in geological mapping, drillhole samples as well as thin section, to comprehend the stratigraphic variation of the lithotypes, its distribution and its relationship with the basement rocks. Some of the conclusions are:

- The sedimentary deposits can be divided in at least three units of distinct lithotypes;
- These lithotypes are different in composition, granular sizes and contact relation, resulted of association of different sedimentary processes, morphology of the terrain, and, probably, tectonic processes;
- Drillhole data is essential to define and to understand vertical and lateral distribution of the Bandeira Basin units. With only the mapping data, most of the features and processes interpreted would not be possible;
- The units described can be correlated to other sedimentary basins of Quadrilátero Ferrífero, although Bandeira Basin has a predominance of debris flow processes for the sediment's deposition, which does not occur in other basins analyzed.

The detailed characterization on these sediments was inspired from advances in scientific knowledge, but it is clearly relevant to other fields of study. The methods applied in this paper are mostly simple, low cost and bring a relatively quick answers on the type of material found in the samples analyzed. It is important to constrain and characterized this material since it is used as material for building, *e.g.,* local roads, but also for civil infrastructures that are built over these materials. Therefore, the knowledge of the physical characteristics of the material will provide a better understanding of its behavior under different circumstances.

Bandeira Basin can be compare with other known sedimentary deposits in furthers studies in QF, providing a better understanding of local and regional recent sedimentary and tectonic processes.

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5. ARTIGO 2

A new Paleogene palynological record of the Quadrilátero Ferrífero (Minas Gerais, Brazil): age and paleoenvironment of the basal portion of the Bandeira Basin - Serra do Tamanduá

Um novo registro palinológico do Paleógeno no Quadrilátero Ferrífero (Minas Gerais, Brasil): idade e paleoambiente da porção basal da Bacia Bandeira na Serra do Tamanduá

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ABSTRACT: The sedimentary units of Quadrilátero Ferrífero have been widely studied thru the 2000's. There are different approaches to focus on these kinds of sediments, but in the eastern portion of this area, research have shown the importance of organic-rich among the sediments. Studying those units enabled dating those sediments using palynological data. This paper brings the recognition of a so far unknown organic-rich layer in Serra do Tamanduá. The authors described and identified the existing species of preserved in this organic matter. Using these references, the age could be stablished for this stratum of the deposit. A correlation of these findings with the known basins in the eastern portion of Quadrilátero Ferrífero was performed, indicating the differences and similarities between them. It was found to be remarkable the presence of angiosperms pollen, specially poricostatus and Rhoipites., other than spores, algae, and gymnosperm pollen. A bio stratigraphical age of late Eocene was indicaten and it is consistent with the ages of Gandarela's and Fonseca's basins. There is significant thickness of material overlying the specific organic-rich layer, certainly younger, although it is not clear to indicate an accurate age for those.

Palavras-Chave: Palynomorphs; Eocene; Bandeira Basin.

RESUMO: As unidades sedimentares do Quadrilátero Ferrífero têm sido estudadas mais amplamente ao longo dos anos 2000. Os depósitos que ocorrem na porção leste dessa região comumente possuem intervalos ricos em matéria orgânica. O estudo dessas unidades tem permitido atribuir idade por meio das assembleias de palinomorfos caracterizadas nesses sedimentos. Esse trabalho, de forma inédita, apresenta a identificação de sedimentos recentes ricos em matéria orgânica na Serra do Tamanduá. Foi realizada a caracterização das espécies existentes e identificadas nessa unidade, com a descrição e identificação da matéria orgânica preservada. A partir disso, foi estabelecida uma correlação entre os sedimentos já descritos na porção leste do Quadrilátero Ferrífero, a fim de identificar as principais diferenças entre essas unidades e entre a assembleia de palinomorfos descritos. É notável a presença de pólen de angiospermas, em especial de poricostatus e de Rhoipites. além de esporos, algas e, em menor escala, pólen de gimnospermas. Uma idade bioestratigráfica desse estrato do depósito foi definida como Eoceno tardio, que é correlata àquela conhecida para as bacias do Gandarela e Fonseca. Há uma coluna de material sedimentar significativa sobreposta às unidades ricas em matéria orgânica datadas, que certamente são mais jovens, mesmo que não seja possível, até agora, indicar a idade dessas unidades de forma mais acurada.

Palavras-Chave: Palinomorfos; Eoceno; Bacia Bandeira.

5.1.Introduction

The Quadrilátero Ferrífero (QF) is a major interest region due to the world class deposits of metallic ores, such as gold and iron. It comprehends a greenstone belt and tectonic controlled sedimentary succession of Paleoproterozoic and Archean units, that suffered multi-stage deformation and ore forming processes. For that interest, there are extensive research on the mineralized rocks, as well as its host rocks, all Precambrian in age (Dorr, 1969, Lobato *et al.*, 2005, Farina *et al.*, 2016), that provide information on lithostratigraphic, structural and ore forming relations. The Serra do Tamanduá is part of the northeastern end of the Gandarela Syncline, eastern border of the QF, and is a result of folding processes of the Proterozoic units, forming a NE-SW oriented ridge (Figure 1).

Although there are multiple research subjects on these ancient units, the knowledge about the recent sediments that outcrop all over the QF is restricted. These sedimentary units currently have generic descriptions, in most cases as lateritic soils or canga covers and are often misconceived as in situ weathered material. This subject has called attention in publications that aims to synthesize, systematize, and present the knowledge on these sedimentary basins (Castro e Varajão, 2020; Varajão *et al.* 2020). On the other hand, there are a few well-documented sedimentary basins, with geological, biostratigraphic and structural features surveyed and described, notably the Cenozoic Gandarela and Fonseca basins (Maizatto, 2001).

The Bandeira Basin is a sedimentary basin located in Serra do Tamanduá, in which is found sediments with few meters to approximately 90 m in thickness. The sediments were studied in the paper of Daher *et al.* (*in prelo*), consisting in a tectonic influenced influx of sediments originated in weathered rocks of Rio das Velhas and Minas Supergroup. In this paper, we present palynological and palynofacies analyses that allowed the first assessment of the age and paleoenvironment of the basal portion of the Bandeira Basin. These analyses are used to discuss the geological evolution of this sedimentary basin and to test part of the genesis processes interpreted in Daher *et al.* (*op cit.*).

This study is not only important for the pedogenetic, morphologic and erosive understanding of Cenozoic processes, but also to provide correlation on a regional basis of the sedimentary mechanism of eastern part of Quadrilátero Ferrífero. It also endorses the successful application of palynological techniques to better understand the local context of organic-rich sedimentary layers in Cenozoic deposits.

5.2. Geological Setting

The QF is a 12.000 km² region located on the southeastern portion of the São Francisco Craton (Fig. 18; Endo *et al.,* 2020). The Quadrilátero Ferrífero name stems from hosting one of the biggest occurrences of iron ore in the world, which was researched in the 1960's in a partnership between USGS-DNPM. This initial research is synthesized in Dorr (1969), which was the first paper to acknowledge the geological aspects of the region. The QF has a unique and complex lithostructural history, with units ranging from the Archean to the Phanerozoic (Figure 1, modified from Castro *et al.* (2020)), and is today one of the most detailed studied regions in Brazil.

The basement of the QF is composed of granite and gnaissic rocks, dating from Archean to Paleoproterozoic, and forming nuclei all over the QF (Farina, 2015). These units underlie the Archean greenstone metasedimentary and volcanic gold-bearing units (Baltazar e Zuchetti, 2007), known as Rio das Velhas Supergroup. The metasedimentary Proterozoic rocks of the Minas Supergroup overlap both the Rio das Velhas Supergroup and the granitic units (Dorr, 1969). All these rocks suffered complex sedimentary and multistage deformation processes, synthesized in Farina *et al.* (2016).

The recent sedimentary units in the QF are known since the work of Dorr (1969), which highlights the sedimentary basins that were known by that time, the Fonseca and Gandarela basins (Gorceix, 1884 in Dorr, 1969). The author also acknowledges multiple small sedimentary accumulation all over the western part of QF in the Moeda e Dom Bosco synclines, often described as mudstones. Those are defined as massive, lateritic clay, non-plastic, and have its deposition originated possibly by erosion of Precambrian rocks. Dorr (1969) points out that the saprolite of Archean and Proterozoic units does not have transitional contact to these recent sediments and that the last are not intercepted by intrusive rocks. Although some outcrops presented deformational structures such as joints and small-scale faults, few or no sedimentary structures are seen. Dorr (1969) also emphasizes the presence of horizons characterized by yellow, white, and red colors, that result from iron oxide leaching.

Additionally, *in situ* material, known as canga, a rock-like cemented material, rich in iron oxides and hydroxides, are also widespread in the QF.

These sedimentary covers range from Paleogene to Neogene (Lobato *et al.*, 2005). The vast advances in the study of these deposits, gathered between 1990 e 2001, were synthetized by Castro e Varajão (2020), which tries to establish correlations between these recent deposits. The age of these units is essentially based on palynological data.

The main geological record which provides chronologic data is the Gandarela basin, in which the Fazenda do Gandarela Formation is the most complete continental stratigraphic record of Cenozoic sediments of the southeastern Brazil, according to Castro and Varajão (*op cit.*). It has linhite layers ranging from 0.2 to 21 m in thickness, laminated or massive, as indicate Maizatto (2001). In those layers were found paleontological records from Neoecoen to Lower Miocen, that are pteridophytes spores, angiosperms, and gymnosperms pollen, besides icnofossils.

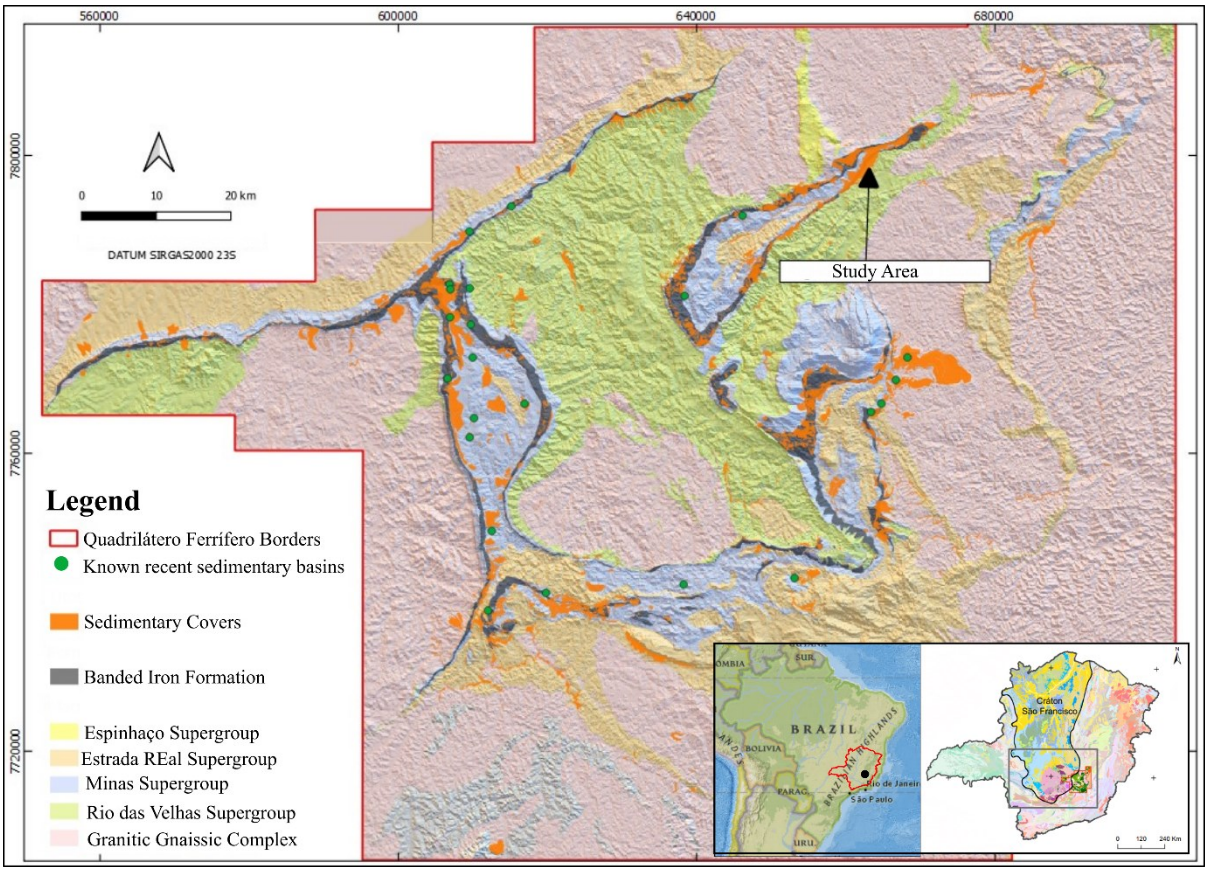

Fig. 18 – Geological map of the main units in Quadrilátero Ferrífero. Modified from Endo *et al.*, 2019, using reference of location of known sedimentary basins as in and Endo *et al.*, 2020.

5.2.1. Bandeira Basin Setting

The Bandeira Basin is in the Serra do Tamanduá (Figure 1), an area historically known for the occurrence of the Rio das Velhas and Minas supergroups covered by lateritic crusts. These laterites were found to be more intriguing than previously thought and were described in detail by Daher *et al.* (*in prelo*). In this study, three different sedimentary units were described for the Bandeira Basin. The unit A is the only one that outcrops along the roads and railroads of the area (Fig. 19) and the other two units are only known due to drillhole investigations executed all over the study area.

In synthesis, from upper to basal units:

- Unit A: includes most superficial covers and consists of lateritic soil, canga, a few portions of alluvium and widely spread and thick colluvial material. The colluvium is highly variable both vertically and laterally, comprising clayey-rich matrix with few clasts and sandy clayey matrix with diverse clast content and composition. There are also several layers of massive clay, some of them containing small roots and manganese nodules. This unit is interpreted as the result of episodic sedimentation, with reworking by transport, and having the Minas Supergroup as source area. Several layers of colluvium and lateritic soil were identified at different depths, which suggests that the sediments resulted from different events of debris flow through time. After each deposition, it is interpreted a time gap before the next flow, since ancient lateritic soils, with concretions and woody-like organic matter are present. Some erosive contacts can also be identified in between the intervals.

- Unit B: comprehend the facies with clay and sandy sediments interbedded with gravels. Transport reworking is low as seen by the angular fragments. This unit is found only in depth, with variable thickness, located in the central to western portion of the area. The origin of this material is not clear, but it is interpreted as episodic sedimentation, mostly with low transport reworking, having the Rio das Velhas Supergroup as source area.
- Unit C: corresponds to gravel and diamict-like sediments, including sandy material and black clay organic-rich sediments that are the object of this study. It is the bottom-most interval and occurs only in the MAD-FSE001 drillhole core in southwest. This unit constitutes the start of the basin deposition, with the Rio das Velhas Supergroup as source area.

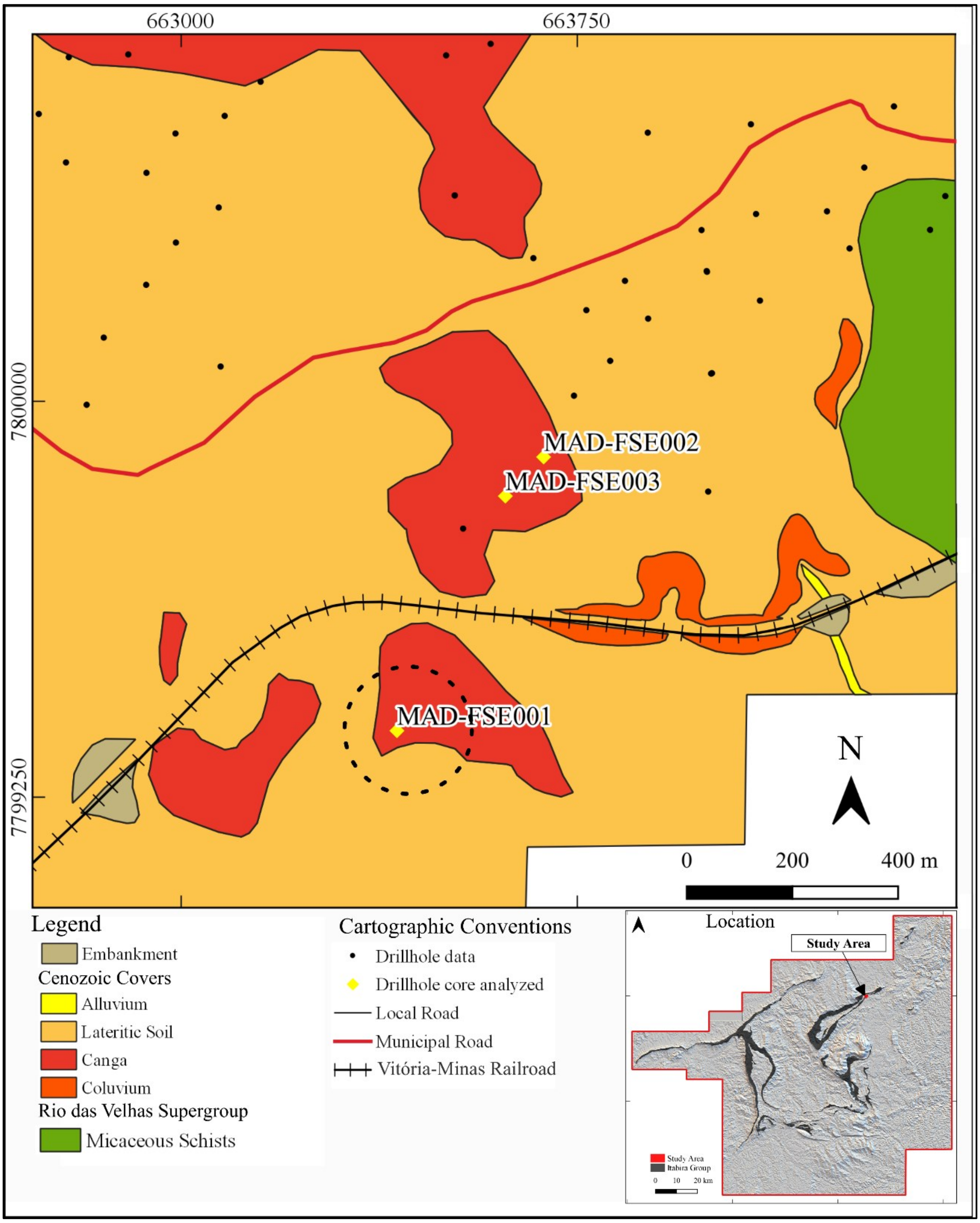

Fig. 19 – Local map of the Bandeira Basin. The dashed lined black circle indicates the drillhole focused on this study. Modified from Daher *et al.*, *in prelo*.

5.2.2. Organic-rich layer

The drillhole MAD-FSE001 provided the most complete profile for the Bandeira Basin (Fig. 20). It shows the units A, B and C characterized in Daher *et al.* (*in prelo*), with approximately

92 m of Cenozoic sediments, overlying in an erosive contact the lithotypes of the Nova Lima Group (Rio das Velhas Supergroup). In the uppermost Unit C, between depths of 75.75 and 78.20 m, there is a black, clay to silty, organic-rich layer. This unit initiates with gravel sediments, grading to a diamict-like interval and massive sandy material. Above, the contact with the organic-rich interval is sharp.

This is the only occurrence of this sediment type in all other drillhole accessed, with good potential for preservation of organic matter remains. This layer thus offered a unique opportunity to obtain fossil data that could be used to assign a biostratigraphic position for this basal portion of the Bandeira Basin. Another important fact is that in some similar basins studied in eastern QF, for example Gandarela and Fonseca basins (Maizatto, 2001), organic-rich sediments are well known and described. This provides a recognized regional database, which provides comparison ground to those sediments.

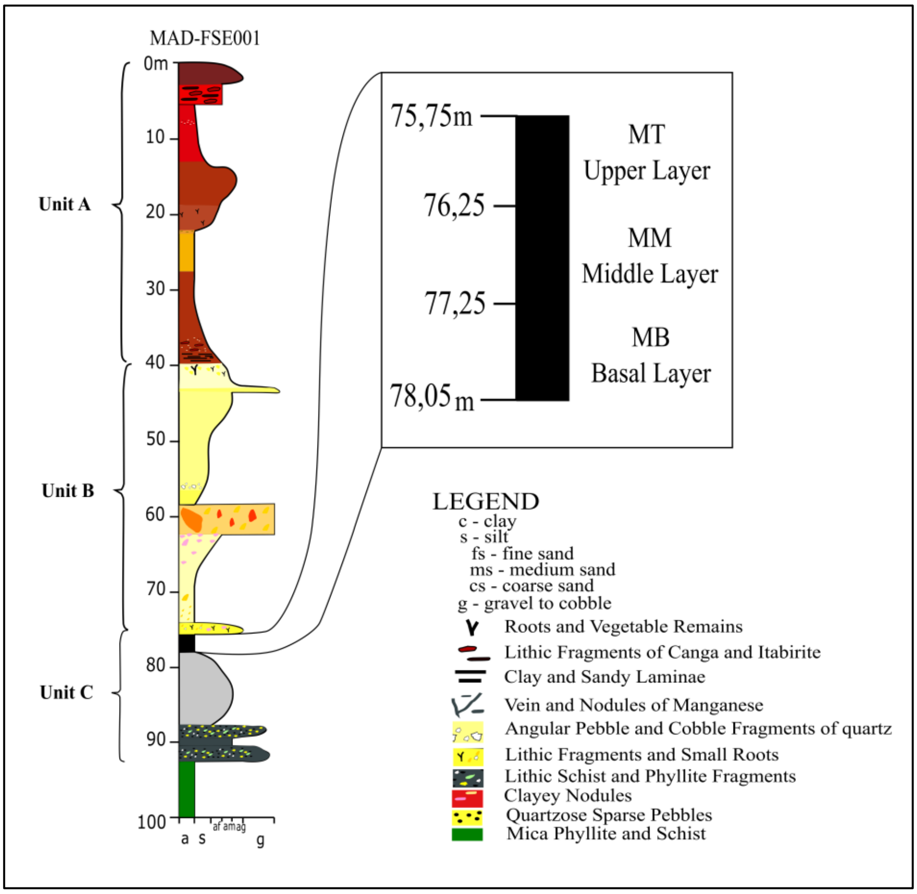

Fig. 20 – Drillhole profile and nomenclature of organic rich material of Bandeira Basin. Modified from Daher et al (*in prelo*). The colors aim to represent the original color of the sediments.

5.3.Methods

The 2.45 m layer of black organic material of the drillhole MAD-FSE001 was collected in three sections of equal thickness (Figure 3) since there was no textural variability along the layer, and one sample representative of each section was collected. Samples were carefully macerated and homogenized, and then subsamples of 2 cm^3 were collected for palynological and palynofacies analyzes.

For palynological analysis, samples were treated with HCl- 10%, HF-40%, and KOH-10%. For each sample, three slides were mounted with glycerin. For palynofacies analysis, only HCl-10% and HF-40% were used, with no centrifugation, and slides were mounted in glycerin jelly.

5.4.Results

5.4.1. Palynology

The three sections of the organic layer yielded well-preserved palynomorph assemblages. A total of 1,526 palynomorphs were counted (Fig. 21) and 52 pollen and spore taxa were recorded (8 pteridophytes, 1 lycophyte, three gymnosperms, and 40 angiosperms); three freshwater algal remains were also recorded (Fig. 22 and Fig. 23). The top sample (MT) had the highest concentration with 734,600 palynomorphs/cm^3 and the highest taxa diversity (43 taxa). MB and MM had total concentrations around 180,000 palynomorphs/cm^3 and 25 and 27 taxa, respectively.

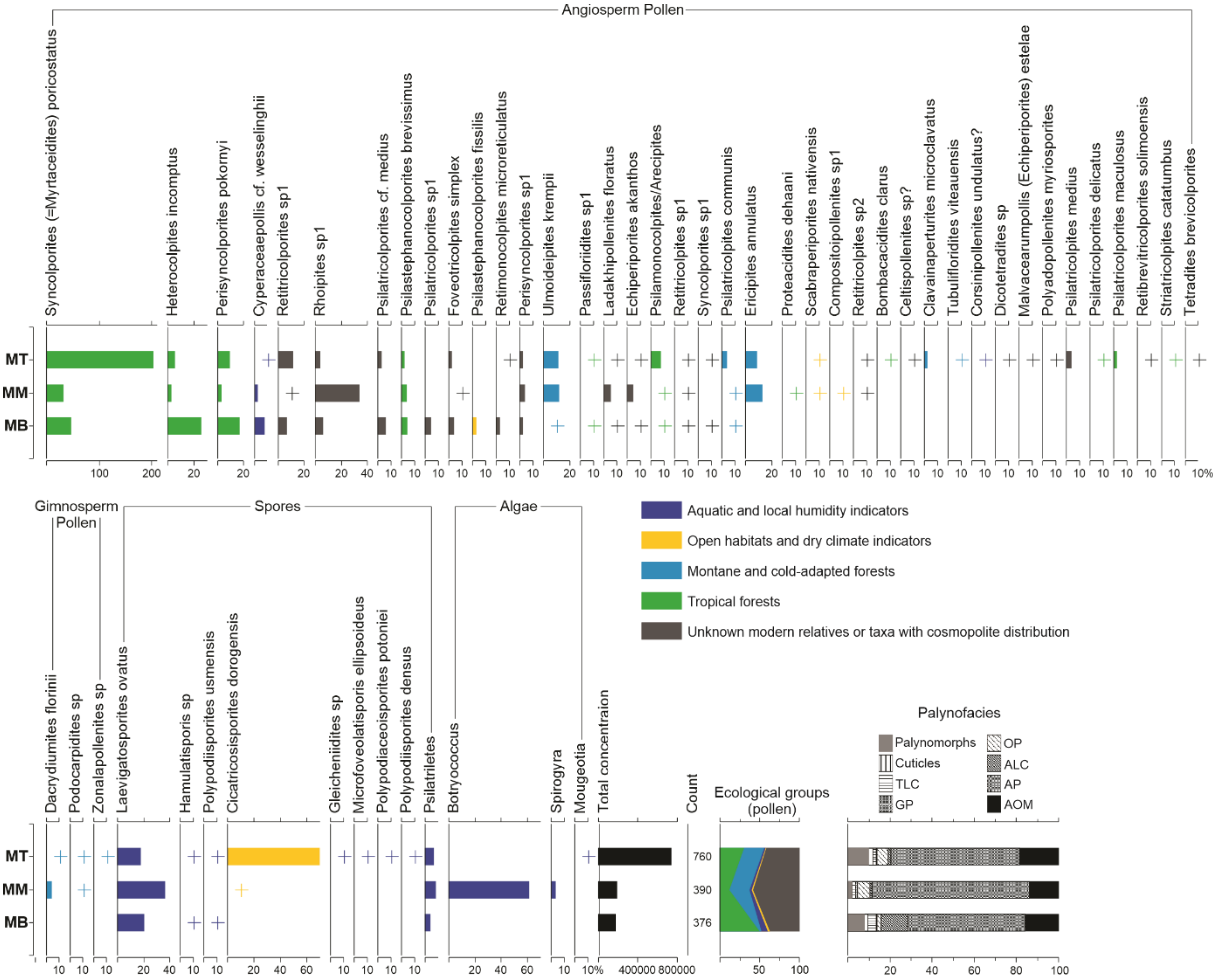

Fig. 21 – Synthesis of palynomorph data gathered after analysis of the three samples obtained from the drillhole MAD-FSE001, from Bandeira Basin: percentage diagram of palynomorphs, total concentration, and palynofacies data.

The basal sample assemblage is dominated by three taxa presented in Fig. 22 and Fig. 23: *Syncolporites poricostatus* (Myrtaceae), *Heterocolpites incomptus* (Melastomataceae) and *Perisyncolporites pokornyi* (Malpighiaceae). Gimnosperm pollen are absent in this basal sample. The middle sample assemblage is dominated by *Rhoipites* sp1, *Syncolporites poricostatus* (Myrtaceae), *Ericipites annulatus* (Ericaceae), and *Ulmoideipites krempii* (*Ulmus*). The middle sample has the highest proportion of gimnosperm pollen (*Dacrydiumites florinii* (*Dacrydium*) and *Podocarpidites* sp (*Podocarpus*)) and is also characterized by the presence of abundant remains of *Botryococcus braunii* colonies. In the top sample, most frequent angiosperm taxa are *Syncolporites poricostatus* (Myrtaceae), *Retitricolporites* sp1, *Ulmoideipites krempii* (*Ulmus*), *Perysincolporites pokornii* (Malpighiaceae), *Ericipites annulatus* (Ericaceae), and *Psilamonocolpites* (Arecaceae). Three gymnosperm pollen were present on the top sample, with low frequencies ((*Dacrydiumites florinii* (*Dacrydium*), *Podocarpidites* sp. (*Podocarpus*), and *Zonalapollenites* sp. (*Tsuga*)). This sample has the most diverse assemblage of spores and is characterized by high frequency of *Cicatricosisporites dorogensis* (*Anemia*). The monolete spore *Laevigatosporites ovatus* (Polypodiaceae) is frequent in all three samples.

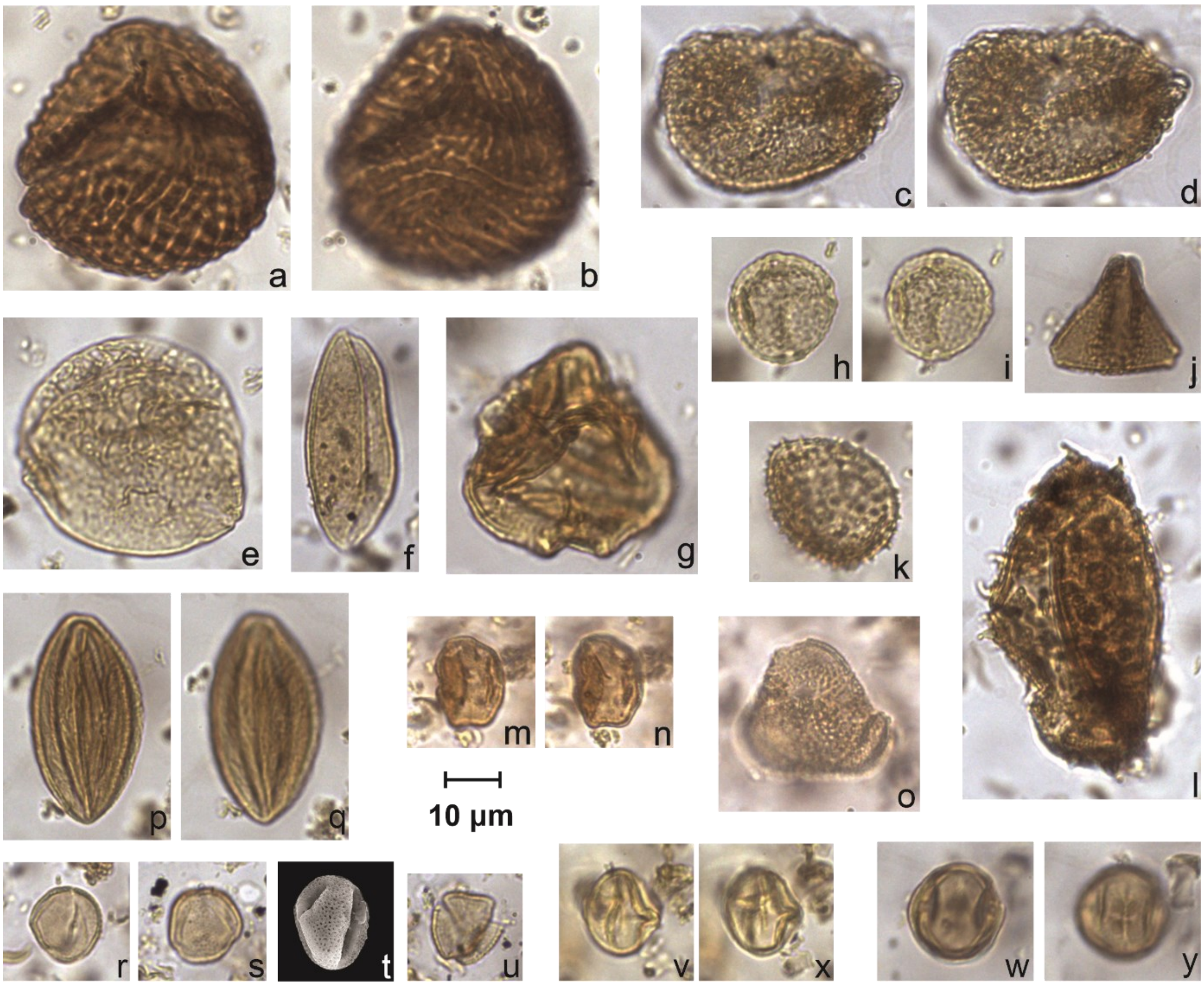

Fig. 22 – Selected palynomorphs from the organic-rich layer of the Bandeira Basin. a-b: *Cicatricosisporites dorogensis* Potonié & Gelletich, 1933; c-d*: Dacrydiumites florinii* (Cookson & Pike, 1953) emend Harris, 1965; e: *Podocarpidites* Cookson, 1947 ex Cooper, 1947 ex Cooper, 1953; f: *Psilamonocolpites* van der Hammen & Mutis, 1965; g: *Corsinipollenites undulatus* (Gonzalez) Lima & Salard-Cheboldaeff, 1981; h-i: *Ulmoideipites krempii* Anderson, 1960 emend Elsik, 1968; j: *Proteacidites dehaani* Germeraad, Hopping & Muller, 1968; k: *Echiperiporites akanthos* van der Hammen & Wymstra, 1964; l: *Malvacearumpollis estelae* (Germeraad, Hopping & Muller, 1968) Hekel, 1972; m-n: *Scabraperiporites nativensis* Regali, Uesugui & Santos, 1974; o: *Bombacacidites clarus* Sah, 1967; p-q: *Striatricolpites catatumbus* Gonzalez, 1967; r-u: Rhoipites sp1; v-x: *Psilatricolporites delicatus* Maizatto, 1997; w-y: *Psilatricolporites maculosus* Regali, Uesugui & Santos, 1974.

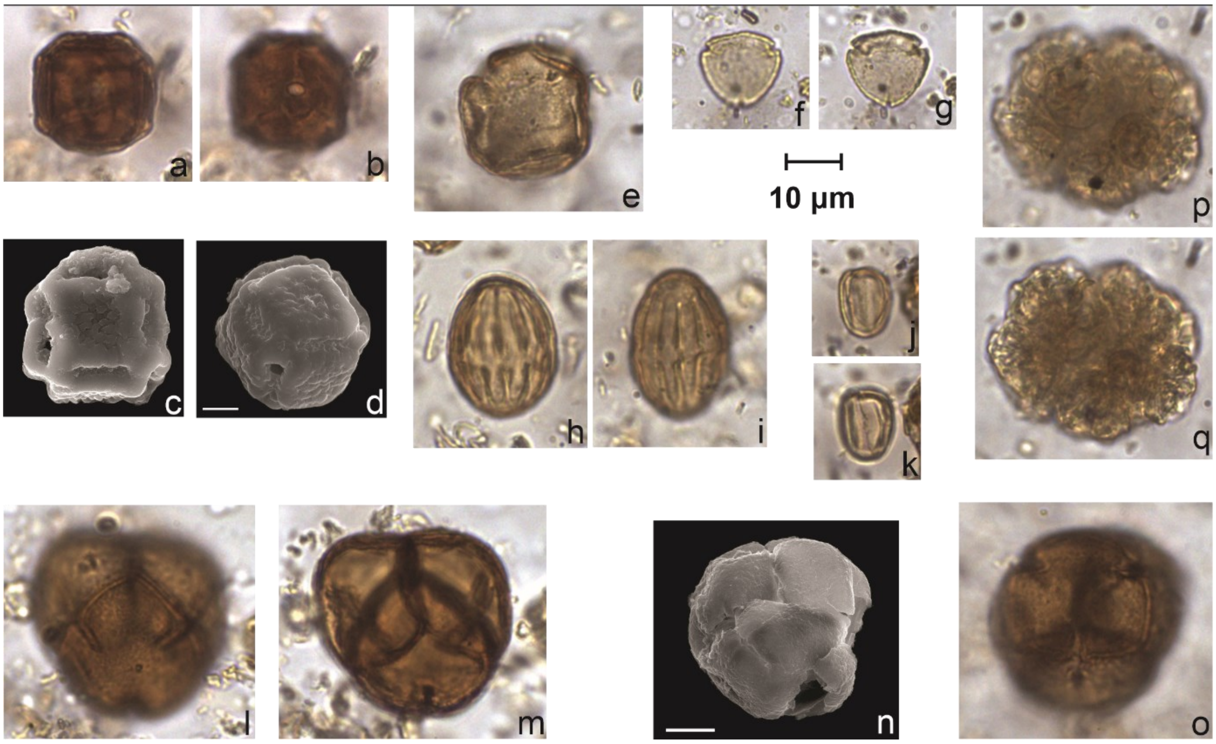

Fig. 23 – Selected palynomorphs from the organic-rich layer of the Bandeira Basin (cont.). a-d: *Perisyncolporites pokornyi* Germeraad, Hopping & Muller, 1968; e: *Perisyncolporites* sp1; f-g: *Syncolporites poricostatus* van der Hoeken-Klinkenberg, 1966; h-i: *Psilastephanocolporites fissilis* Leidelmeyer, 1966; j-k: *Heterocolpites incomptus* Van der Hammen, 1956 ex Hoorn, 1993; l-o: *Ericipites annulatus* González-Guzmán, 1967; p-q: *Botryococcus braunii* Kützing, 1849.

5.4.2. Palynofacies

Samples MB, MM, and MT presented similar assemblages of organic constituents. In all samples, amorphous particles (AP, Fig. 24) were the predominant type, followed by amorphous organic matter (AOM). The basal sample presented a larger contribution of altered fragments (ALC, Fig. 24) and transparent fragments (TLC). The amorphized particles are likely the product of degradation of terrestrial phytoclasts, hence their predominance indicates a high degree of transformation of the particulate organic matter. This might reflect a shallow depositional environment, subject to oxidization; for instance, Sebag *et al.* (2006) observed high proportions of AP in peaty deposits. Alternatively, the organic matter assemblages of samples MB, MM and MT might reflect a lacustrine deposition in which forest organic soils were a primary sediment source. In fact, AP and ALC are the dominant palynofacies constituents in organic soils (Sebag *et al.*, 2006).

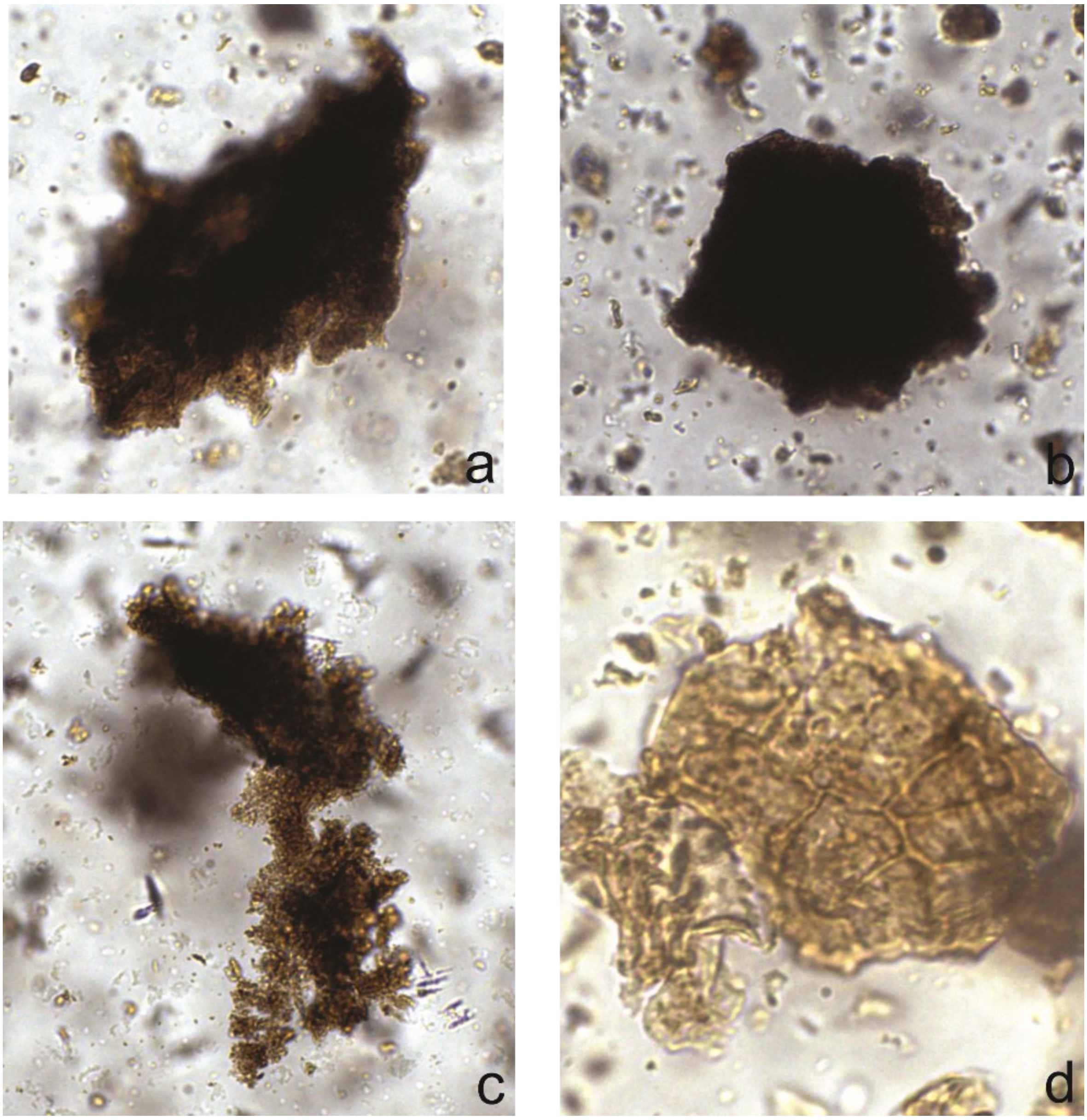

Fig. 24 – Main categories of particulate organic matter from the organic-rich layer of the Bandeira Basin. a: Altered fragment (ALC); b) Amorphized particle (AP); c: Amorphous organic matter (AOM); d: cuticle.

5.5.Discussion

The palynomorph assemblages were found in a very specific layer of the Bandeira Basin, which corresponds to the uppermost Unit C, as proposed by Daher *et al.* (*in prelo*). The analyzed data brings to knowledge a possible age for deposition of the basal sediments of the basin. Although the biostratigraphic data is limited to this specific layer, they have value to discuss the meaning of the palynomorph assemblages in terms of paleontology and sedimentology and to suggest an age definition for the Bandeira basin.

5.5.1. Age Discussions and Regional Correlation

The presence of *Cicatricosisporites dorogensis*, *Dacrydiumites florinii*, *Ulmoideipites krempii*, *Scabraperiporites nativensis* and *Bombacacites clarus* situates the deposition of the Bandeira organic layer in the middle Eocene/Oligocene. In Brazilian deposits, *C. dorogensis* occurs from the early Eocene to the end of the Oligocene; *D. florinii* (= '*Parvisaccites*?') occurs from the middle Eocene to the end of the Oligocene; *U. krempii* from the late Cretaceous to the end of the Oligocene; *S. nativensis* from the middle Eocene to the early/middle Oligocene; and *B. clarus* from the middle Eocene to the early Miocene (Regali *et al.*, 1974a,b; Maizatto, 2001; Santos *et al.*, 2010).

Considering the presence of the up-cited species, along with *Proteacidites dehaani*, *Striatricolpites catatumbus*, *Psilastephanocolporites fissilis*, *Perisyncolporites pokornyi*, *Syncolporites poricostatus*, *Psilatricolporites maculosus*, and *Echiperiporites estelae*, the organic layer of the Bandeira Basin could be correlated to the Zone PE-50-*Retibrevitricolpites triangulatus* (late Eocene) or to the Zone PO-10-*Scabraperiporites nativensis* (early/middle Oligocene) of the Brazilian platform (Regali *et al.*, 1974a).

In the QF, Maizatto (2001) defined two biozones from the palynomorph assemblages of the Fonseca and Gandarela basins: Zone *Retibrevitricolpites triangulatus* (late Eocene) and Zone *Dacrydiumites florinii* (Oligocene). The following taxa from the Bandeira Basin organic layer are present in both *R. triangulatus* and *D. florinii* zones of Maizatto (2001): *Cicatricosisporites dorogensis*, *Polypodiaceoisporites potoniei*, *Polypodiisporites* (=*Verrucatosporites*) *usmensis*, *Laevigatosporites ovatus*, *Psilastephanocolporites fissilis*, *Corsinipollenites undulatus*, *Echiperiporites akanthos*, *Perisyncolporites pokornyi*, *Proteacidites dehaani*, *Ulmoideipites krempii*, *Psilatricolporites delicatus*, *Polyadopollenites myriosporites*, *Bombacacidites clarus*, *Syncolporites poricostatus*, *Dacrydiumites florinii*. In the Gandarela and Fonseca basins, this last species, *D. florinii*, occurs only from the topmost *R. triangulatus* Zone (i.e., from the final late Eocene) and is characteristic of the Oligocene zone it gives name to, however, this species is known to occur in older Eocene deposits from southeast Brazil (Santos *et al.*, 2010).

Although none of the taxa described from the Bandeira Basin is exclusive from either the late Eocene or the Oligocene zones, the overall characteristics of the Bandeira assemblage is more consistent with a late Eocene age. In fact, a characteristic feature of the Oligocene deposits of southeast Brazil is the quantitative superiority of gymnosperm pollen in relation to angiosperms.

In both Gandarela and Fonseca basins, the Oligocene is marked by high frequencies of gymnosperm pollen (*D. florinii* and *Podocarpidites* spp.), a feature that is associated to the global cooling that marks the onset of the Oligocene (Maizatto, 2001). The disappearance of palm pollen is another characteristic of the Gandarela and Fonseca Oligocene assemblages that would also have been a consequence of cooler climate. The predominance of gymnosperm pollen is also observed in other Oligocene deposits of southeast Brazil: at the São Paulo Basin, Santos *et al.* (2010) described a sharp increase of gymnosperm pollen, reaching more than 50%, that marks the onset of the Oligocene. In the Taubaté Basin, the Oligocene is also recognized from very high frequencies (50 to 70%) of gymnosperm pollen (Lima *et al.,* 1985 a,b).

In contrast, at the Bandeira organic layer, although present, gymnosperm pollen reached a maximum frequency of 4% of the pollen sum. The flora is dominated by angiosperms and palm pollen are abundant in the top sample. Due to these aspects, the data presented here suggests that the deposition of the Bandeira organic layer is more likely correlated to the late Eocene *Retibrevitricolpites triangulatus* Zone of Regali *et al.* (1974) and Maizatto (2001).

As described earlier, the Bandeira palynomorph assemblage shares several taxa with the late Eocene/Oligocene assemblages of the Fonseca and Gandarela basins, however, there are some notable differences between the Bandeira and the other two Cenozoic basins of the QF. In fact, the Bandeira samples contain significant presence of the following taxa that were not observed in the Gandarela and Fonseca assemblages: *Heterocolpites incomptus*, *Rhoipites* sp1, *Perisyncolporites* sp1, and *Ericipites annulatus*.

Rhoipites sp1 and *Perisyncolporites* sp1 are very common in the Bandeira assemblages but equivalent pollen-types were not identified in other Cenozoic deposits of southeast Brazil, and neither could they be assigned with confidence to modern pollen taxa. As for *H. incomptus* (Melastomataceae), although this pollen type was not observed in the Gandarela and Fonseca palynofloras, macrofossils of *Tibouchina*-like leaves were described from Eocene-Oligocene deposits of the Fonseca Formation (Duarte, 1956; Carvalho *et al.*, 2021), which attests the presence of Melastomataceae in the QF during the Paleogene. Further, in the Itaquaquecetuba Formation of the São Paulo Basin, Santos (2008) found significant frequencies (close to 10%) of *H. incomptus* in some samples from the late Eocene section, while one foliar impression of *Leandra* is described by Biagolini *et al.* (2013) in this same formation.

Carvalho *et al.* (2021) also presented evidence of the presence of Melastomataceae as part of the tropical rain forest assemblage from the middle-late Paleocene in the Neotropics. Regarding *E. annulatus*, the high frequency of Ericaceae pollen found in the Bandeira organic layer has no correspondence in other Cenozoic deposits of southeast Brazil; the only mention of Ericaceae pollen is found in Santos (2008) that cites the presence of *Ericipites* spp. in the work of Yamamoto (1995) on the Itaquaquecetuba Formation. Pollen of Ericaceae was otherwise described in the Eocene of Colombia (Gonzaléz-Guzmán, 1967) and in the late Paleocene of North Dakota (USA) (Zetter *et al.*, 2011), as well as in younger Miocene deposits of the Amazonia Basin (D'Apolito *et al.*, 2021).

It is noteworthy though that Southeastern Brazil is recognized as one of the five biogeographic regions of greater Ericaceae diversity in the Neotropics (Luteyn, 2002) and that the Espinhaço Range, adjacent to the QF, is considered the center of diversity of the two greatest genera of the family in the Brazilian flora (*Agarista* and *Gaylussacia*) - both presenting pollen-types similar to the one found in the Bandeira assemblage (Cruz *et al.*, 1980).

Finally, another particularity of the Bandeira assemblage is the very high frequency of *Syncolporites poricostatus* (Myrtaceae). This taxon is present in the Gandarela and Fonseca Oligocene assemblages, however, in these basins, it is not as dominant as it is the case in the Bandeira assemblage. High frequencies of Myrtaceae pollen are found in the late Eocene assemblage of the Itaquaquecetuba Formation of the São Paulo Basin, in which Myrtaceae is one of the dominant taxa, reaching frequencies close to 30% in several samples (Santos, 2008). In this assemblage, high frequency of Myrtaceae pollen is associated with high frequencies of *Ulmoideipites krempii* and *Perisyncolporites pokornyi*, an association that is also seen in the top sample of the Bandeira organic layer.

In synthesis, a late Eocene age is indicated for the organic-rich layer found in Bandeira Basin. Considering the Gandarela's Basin as the most continuous biostratigraphic record of QF, one can correlate the layer in question Fig. 25 B, to the Fazenda Gandarela Formation, as illustrated in Fig. 25 C.

The lithofacies descriptions in Maizatto (2001) are consistent with the descriptions for part of the unit C of Bandeira Basin. In Fazenda Gandarela Fm., the facies I, corresponding to lacustrine sediments, comprehend mostly of the middle to upper sediments, overlapping the so-called facies II, which are debris flow sediments. The author identifies Eocene and Oligocene ages for almost all samples analyzed in the basin, regardless the sedimentary facies.

The Unit C of Bandeira Basin has very similar lithofacies with facies II of Maizatto (*op cit.*.). The difference relies on the fact that the geological record of Unit C of Bandeira Basin finishes in the organic-rich layer analyzed. In Fazenda Gandarela Fm. it was established that the facies I corresponds to the organic bearing predominant horizon, interpreted as lacustrine sediments (Fig. 25 C). In Bandeira Basin, no lacustrine, other than the organic-rich layer record can be interpreted from the facies described. This specific horizon is the one consistent with facies I described by Maizatto (*op cit.*.) and the only remains of such a geological condition in this basin. This is the biggest difference between those two sequences.

Although in Gandarela Basin a talus-like sediment was not identified, the clay, sandy and gravel sediments in Unit B are like the easternmost portion of the Gandarela Basin. It is unclear if this portion of the Gandarela Basin is still considered part of the facies I, but the drillholes “f10” and “f14” in Maizatto (2001) have some correlation with the Unit B found in Bandeira Basin, with the only exception being the organic layers found in different depths.

In the eastern portion of the Gandarela’s Basin, only drillhole presented to register sediments with Miocene age is the “f’4”. In the central and western parts of the area, the samples shows a decrease in the thickness of the sediments with Oligocene register. Even if the Bandeira Basin has until now one register of Eocene horizon, it is fair to suppose that the upper units might be correlated with the upper units of Gandarela Basin.

The southern portion of the Serra do Tamanduá has low density in drillhole data, which may explain why these organic layers were not found until now. Regardless of that, it is possible that the lacustrine geological record has been partially eroded or was small and localized. The sediments that overlap this specific horizon has sedimentation mechanisms that could indicate partial removal of the previous setting.

This was the only stratigraphic horizon in Bandeira Basin that could have its age established using biostratigraphic tool. The overlapping units are, surely younger, although it is not possible to determine how younger they are.

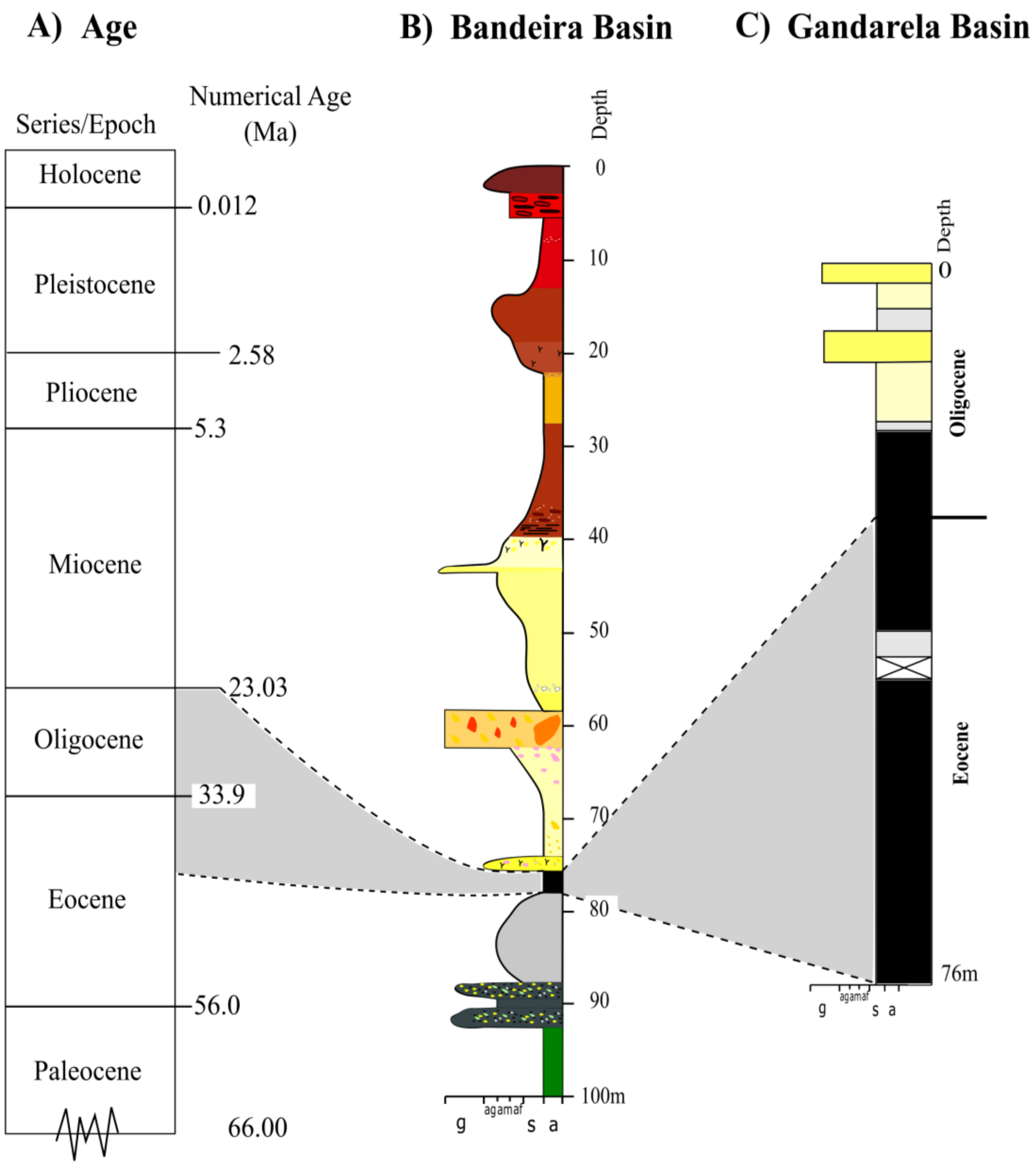

Fig. 25 – Illustration of the age obtained for the organic-rich layer of Bandeira Basin. A) presents a section of the Internaetional Stratigraphic Chart; B) profile of drillhole MAD-FSE001 and C) profile of drillhole f10, reproduced from Maizatto (2001).

5.5.2. Paleoenvironmental and paleoclimate implications

The pollen assemblage of the Bandeira organic layer is composed predominantly of tree taxa and presents a mixture of tropical lowland taxa and montane/cool-adapted taxa (Table 1, Supplementary Materials). This suggests the presence of a landscape occupied by forest formations under a tropical to subtropical climate. The middle and top sample contain higher proportions of montane/cool-adapted taxa, which indicates a cooling trend during the deposition of the organic layer. As a suggestion, it may have links to the Antarctic glaciation across the Eocene-Oligocene that impacted atmospheric and oceanic temperatures (e.g., Kennedy *et al.*, 2015). The top layer is also characterized by a high frequency of *Cicatricosisporites dorogensis* (Anemia), a fern that is associated to open, well-drained habitats (Kennedy *op cit.*.). Maizatto (2001) associates peaks of *C. dorogensis* in the Gandarela Basin to the occurrence of dry events. A drier and cooler climate is thus suggested for the top sample.

5.5.3. Open Questions

The upper units of Bandeira Basin have not yet clear ages of units B and A for Bandeira Basin. Because a gap may exist between units B and C, the authors can only correlate those units to the ones in which similar processes occurred. For that, units B and A for Bandeira Basin might have been deposited from late Miocene, as the top of Fazenda Gandarela Fm. to middle and upper Miocene, as Cata Preta and the bottom of Gongo Soco Fm. (Castro and Varajão, 2020). For this, it is recommended that there is further investigation to achieve those ages in more accurate ways than facies correlation.

Although other horizons were found in units B and A in which it was identified small roots and manganese nodules, that were interpreted in Daher et al (*in prelo*) as residual soil of coluvionar sediments. It is a possible approach try to analyze those horizons searching for preserved palynomorph content. It surely will not have the appropriate concentration of palynomorphs, as one organic-rich layer has, but it might have enough record to comparison to other continental or marginal sedimentary basins in South America.

There is no mention of similar organic-rich layer in any other deposit in wester or southern parts of QF so far.

5.6.Conclusion

This research applies a consolidated method of biostratigraphy for dating of organic rich. It was determined with a reliable basis that the upper Unit C, defined in Daher et al (*in prelo*) corresponds to a late Eocene geological record. It means that these sediments can be directly related to both Gandarela and Fonseca Basins in time.

The studies shows that a thick column of sediments overlies this specific horizon, and it is not possible to establish their ages other than correlating the facies with other known deposits, such as Fazenda Gandarela Fm, Cata Preta Fm. and Gongo Soco Fm. This means the continuous processes of sedimentation occurred over time and this may explain some differences of the geological record on these basins.

Even though the nature and characteristics of these sediments changes drastically, stablishing the age of the organic-rich layer contributes to the general figure of sedimentological, and environmental conditions of the eastern region of Quadrilátero Ferrífero during Cenozoic.

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Supplementary Material

Table 1:

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Spores								
Monolete Spores								
Laevigatosporites ovatus	*Laevigatosporites ovatus* Wilson & Webster, 1946	Pteridophyte - Polypodiaceae	Fern	Tropical, forests and other habitats. Typically epiphytic, less commonly rupicolous or terrestrial.	**X**	**X**	**X**	upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - lower Miocene of the Gandarela Basin (Maizatto, 1997); Oligocene of the Taubaté Basin (Lima *et al.* 1985a,b); Oligocene of the Resende Basin (Lima & Melo, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene of the Bonfim Basin (Lima & Dino, 1984); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021); and others
Microfoveolatosporis ellipsoideus	*Microfoveolatosporis ellipsoideus* (Plufg, 1953) Krutzsch, 1967	Pteridophyte - (Schizeaceae - Dettman, 1963)	Fern	Tropical, temperate. Terrestrial, rupicolous.			**X**	Oligocene of the Taubaté Basin (Lima *et al.*, 1985b); upper Eocene of the Gandarela basin (Maizatto, 1997)
Polypodiisporites densus	*Polypodiisporites densus* D'Apolito, Jaramillo & Harrington, 2021	Pteridophyte - Polypodiaceae - *Polypodium*	Fern	Tropical, forests and other habitats. Typically epiphytic, less commonly rupicolous or terrestrial.			**X**	Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Polypodiisporites usmensis	*Polypodiisporites usmensis* (van der Hammen, 1956) Khan & Martin, 1972	Pteridophyte - Polypodiaceae	Fern	Tropical, forests and other habitats. Typically epiphytic, less commonly rupicolous or terrestrial.	**X**		**X**	(= *Verrucatisporites usmensis*) Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - lower Miocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Miocene of the Amapá, Pará, Maranhão, Sergipe, Rio de Janeiro and Paraná continental platforms and of the Cumuruxatiba and Espírito Santo basins (Regali *et al.* 1974a, b); upper Eocene of the São Paulo basin (Santos *et al.*, 2010); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Trilete Spores								
Cicatricosisporites dorogensis	*Cicatricosisporites dorogensis* Potonié & Gelletich, 1933	Pteridophyte - Anemiaceae - *Anemia*	Fern	Tropical, open well-drained habitats. Terrestrial, rupicolous.		**X**	**X**	middle Eocene - Oligocene of the Brazilian continental platform (Regali *et al.*, 1974); Eocene of the Fonseca Basin (Lima & Salard-Cheboldaeff, 1981); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - Oligocene of the Gandarela Basin (Maizatto, 1997); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Oligocene of the

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
								Resende Basin (Lima & Melo, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); Eocene of the Bonfim basin (Lima & Dino, 1984); Oligocene of the Taubaté Basin (Lima *et al.*, 1985a,b)
Gleicheniidites sp	*Gleicheniidites* Dettmann, 1963	Pteridophyte - Gleicheniaceae - *Gleichenia*	Fern	Tropical. Rupicolous, terrestrial.			**X**	Oligocene of the Taubaté Basin (Lima *et al.*, 1985a); Eocene of the Bonfim basin (Lima & Dino, 1984)
Hamulatisporis sp	*Hamulatisporis* Krutzsch, 1959	Lycophyte - Lycopodiaceae - *Lycopodium*	Fern	Tropical and subtropical, comon in wet montane forests. Terrestrial.	**X**		**X**	upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Oligocene of the Taubaté Basin (Lima *et al.*, 1985b); Eocene of the Bonfim basin (Lima & Dino, 1984)
Polypodiaceoisporites potoniei	*Polypodiaceoisporites potoniei* Kedves, 1961	Pteridophyte - Polypodiaceae	Fern	Tropical, forests and other habitats. Typically epiphytic, less commonly rupicolous or terrestrial.			**X**	upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - lower Miocene of the Gandarela Basin (Maizatto, 1997); Oligocene of the Resende Basin (Lima & Melo, 1994); Oligocene of the Taubaté Basin (Lima *et al.*, 1985b); Campanian - Miocene of the Brazilian continental platform (Regali *et al.*, 1974); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Oligocene of the São Paulo Basin (Lima *et al.*, 1991)

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Psilatriletes	*Psilatriletes* van der Hammen, 1954, ex Potonié, 1956	Pteridophyte	Fern	-	**X**	**X**	**X**	Miocene of the Solimões Formation (Silva, 2008; D'Apolito *et al.*, 2021)
Pollen								
Gimnosperm pollen								
Vesiculate (Classe Vesiculatae)								
Dacrydiumites florinii	*Dacrydiumites florinii* (Cookson & Pike, 1953) emend Harris, 1965	Podocarpaceae - *Dacrydium*	Tree	Montane and lowland, wet climate		**X**	**X**	(=Parvisaccites? sp; = Sciadopityspollenites quintus) Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - Oligocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Rio de Janeiro, São Paulo and Paraná continental plataforms (Regali *et al.,* 1974a); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Oligocene of the Taubaté Basin (Lima *et al.*, 1985a,b); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994)
Podocarpidites sp	*Podocarpidites* Cookson, 1947 ex Cooper, 1953	Podocarpaceae - *Podocarpus*	Tree	Montane and lowland, wet climate		**X**	**X**	upper Eocene - Oligocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - Oligocene of the Rio de Janeiro, São Paulo and Paraná continental platforms (Regali *et al.*, 1974); Eocene of the Gandarela Basin (Lima & Salard-Cheboldaeff, 1981);

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
								Oligocene of the São Paulo Basin (Lima *et al.*, 1991); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Oligocene of the Resende Basin (Lima & Melo, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); Eocene of the Bonfim basin (Lima & Dino, 1984); Oligocene of the Taubaté Basin (Lima *et al.*, 1985a,b); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Zonalapollenites sp	*Zonalapollenites* Pflug, 1953	Pinaceae - *Tsuga*	Tree	Temperate forests, wet climate			X	Oligocene of the Taubaté Basin (Lima *et al.*, 1985b)
Angiosperm pollen								
Inaperturate (Classe Inaperturate)								
Clavainaperturites microclavatus	*Clavainaperturites microclavatus* Hoorn, 1994 emend Martínez *et al.*, 2013	Chloranthaceae - *Hedyosmum*	Shrub, tree	wet habitats of cool montane cloud forest			X	Miocene of the Solimões Formation (Silva, 2008; D'Apolito *et al.*, 2021)
Monosulcate (Classe Monocolpatae)								
Psilamonocolpites/Arecipites	*Psilamonocolpites* van der Hammen & Mutis, 1965	Arecaceae	Tree, shrub	Tropical and subtropical regions	X	X	X	upper Eocene of the Fonseca Basin (Maizatto, 2001); upper Eocene of the Gandarela Basin (Lima & Salard-Cheboldaeff, 1981; Maizatto, 1997); Oligocene of the São Paulo Basin

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
								(Lima *et al.*, 1991); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); Oligocene of the Resende Basin (Lima & Melo, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Retimonocolpites microreticulatus	*Retimonocolpites microreticulatus* van der Hammen & Mutis, 1966	Arecaceae?	-	-	**X**		**X**	Paleocene of Colombia (van der Hammen & Mutis, 1966); upper Paleocene - lower Eocene of Colombia (Gonzales-Guzman, 1967); Eocene of the Gandarela Basin (*Retimonocolpites* sp. - Lima & Salard-Cheboldaeff, 1981)
Porate								
Triporate (Classe Triporatae)								
Corsinipollenites undulatus?	*Corsinipollenites undulatus* (Gonzalez) Lima & Salard-Cheboldaeff, 1981	Onagraceae - *Ludwigia*	Herb, shrub	mainly wetlands			**X**	upper Eocene of the Gandarela Basin (Lima & Salard-Cheboldaeff, 1981); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); Oligocene of the Taubaté Basin (Lima *et al.*, 1985b); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene of the

Palynomorphs	NAME	Botanical affinity	Life form	Distribution/Ecology (nearest modern taxon)	Samples			Occurrences - Cenozoic Basins
					MB	MM	MT	
								Bonfim basin (Lima & Dino, 1984); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - Oligocene of the Gandarela Basin (Maizatto, 1997)
Proteacidites dehaani	*Proteacidites dehaani* Germeraad, Hopping & Muller, 1968	Proteaceae	Tree, shrub	Tropical and subtropical regions		**X**		Oligocene of the Taubaté Basin (Lima *et al.*, 1985a,b); Eocene of the Bonfim basin (Lima & Dino, 1984); Oligocene of the Resende Basin (Lima & Melo, 1994); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Maastrichtian - Oligocene of the Pará, Maranhão, Sergipe and Rio de Janeiro continental platforms and of the Sergipe/Alagoas Basin (Regali *et al.*, 1974); upper Eocene of the Fonseca Basin (Maizatto, 2001)
Stephanoporate (Classe Stephanoporatae)								
Celtipollenites sp?	*Celtipollenites* Nagy, 1969	Ulmaceae - *Celtis*	Shrub, tree	temperate to tropical			**X**	Cenozoic of Europe and China (e.g. Shatilova *et al.*, 2018)
Ulmoideipites krempii	*Ulmoideipites krempii* Anderson, 1960 emend Elsik, 1968	Ulmaceae - *Ulmus*	Tree	temperate, cool wet forests	**X**	**X**	**X**	Maastrichtian - Oligocene of the Brazilian continental platform and of the Sergipe/Alagoas and Espírito Santo basins (Regali *et al.*, 1974); upper Eocene - Oligocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); Oligocene of the São Paulo Basin (Lima *et al.*, 1991);

<table>
<tr><th rowspan="2">Palynomorphs</th><th rowspan="2">NAME</th><th rowspan="2">Botanical affinity</th><th rowspan="2">Life form</th><th rowspan="2">Distribution/Ecology (nearest modern taxon)</th><th colspan="3">Samples</th><th rowspan="2">Occurrences - Cenozoic Basins</th></tr>
<tr><th>MB</th><th>MM</th><th>MT</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Eocene - Oligocene of the Guanabara Rift (Lima <i>et al.</i>, 1996); Paleogene of the Tanque Basin (Garcia <i>et al.</i>, 2008); upper Eocene of the São Paulo Basin (Santos <i>et al.</i>, 2010); Oligocene of the Resende Basin (Lima & Melo, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene - Oligocene of the Casa de Pedra Graben (Lima <i>et al.</i>, 1994); Eocene of the Bonfim basin (Lima & Dino, 1984); Oligocene of the Taubaté Basin (Lima <i>et al.</i>, 1985a,b)</td></tr>
<tr><td colspan="9">Periporate</td></tr>
<tr><td>Cyperaceaepollis cf. wesselinghii</td><td><i>Cyperaceaepollis</i> cf. <i>wesselinghii</i> D'Apolito, Jaramillo & Harrington, 2021</td><td>Cyperaceae</td><td>Herb, shrub</td><td>mainly wetlands</td><td>X</td><td>X</td><td>X</td><td>Miocene of the Solimões Formation (D'Apolito <i>et al.</i>, 2021)</td></tr>
<tr><td>Malvacearumpollis (Echiperiporites) estelae</td><td><i>Malvacearumpollis estelae</i> (Germeraad, Hopping & Muller, 1968) Hekel, 1972 = <i>Echiperiporites estelae</i> Germeraad, Hopping & Muller, 1968</td><td>Malvaceae</td><td>Tree, shrub, liana, herb</td><td>cosmopolitan</td><td></td><td></td><td>X</td><td>Paleogene of the Tanque Basin (Garcia <i>et al.</i>, 2008); upper Eocene of the Resende Basin (Lima & Amador, 1985); upper Eocene - Miocene of the Amapá, Pará, Maranhão, Sergipe, Paraná and Rio de Janeiro continental platforms (Regali <i>et al.,</i> 1974); upper Eocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); Miocene of the Solimões Formation (D'Apolito <i>et al.</i>, 2021)</td></tr>
</table>

Palynomorphs	NAME	Botanical affinity	Life form	Distribution/Ecology (nearest modern taxon)	Samples			Occurrences - Cenozoic Basins
					MB	MM	MT	
Echiperiporites akanthos	*Echiperiporites akanthos* van der Hammen & Wymstra, 1964	Dicotyledonae	-	-	**X**	**X**	**X**	lower Eocene - Miocene of the Brazilian continental platform and of the Sergipe/Alagoas and Espírito Santo basins (Regali *et al.*, 1974); Oligocene of the Resende Basin (Lima & Melo, 1994); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); upper Eocene - lower Miocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001)
Scabraperiporites nativensis	*Scabraperiporites nativensis* Regali, Uesugui & Santos, 1974	Chenopodiaceae (Amaranthaceae)	Herb, subshrub	cosmopolitan, aquatic or terrestrial herbs		**X**	**X**	middle Eocene - Oligocene of the Brazilian continental platform and of the Espírito Santo Basin (Regali *et al.*, 1974); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010)
Colpate								
Tricolpate (Classe Tricolpatae)								

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Foveotricolpites simplex	*Foveotricolpites simplex* (González-Guzmán, 1967) D'Apolito, Jaramillo & Harrington, 2021	Euphorbiaceae?	-	-	**X**	**X**	**X**	Miocene of the Solimões Formation (D'Apolito *et al.*, 2021); similar to *Foveotricolpites* sp. from the upper Eocene of the Gandarela Basin (Maizatto, 1997); to *Foveotricolpites* sp.1 from the Paleogene of the Tanque Basin (Garcia *et al.*, 2008); to *Retitricolpites* sp. from the upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001) and from the Oligocene of the Taubaté Basin (Lima *et al.*, 1985a); to *Retitricolpites antonii* from the Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); to *Retitricolpites simplex* from the Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994) and from the Neogene of the Maranon Basin (Parra *et al.*, 2019)
Ladakhipollenites floratus	*Ladakhipollenites floratus* Silva-Caminha, Jaramillo & Absy, 2010	Bignoniaceae?	-	-	**X**	**X**	**X**	Miocene - Pliocene of the Solimões Formation (Silva-Caminha, 2010); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Psilatricolpites communis	*Psilatricolpites communis* Archangelsky 1973	Cunoniaceae	Tree, shrub	Tropical, montane forest	**X**	**X**	**X**	Paleocene of Chubut/Argentina (Archangelsky, 1973); Paleocene of the Faja Gris/Argentina (Quatroccchio *et al.*, 1997); upper Oligocene - Middle Miocene of the Cullen Formation, Tierra del Fuego/Argentina (Zamaloa, 2000)

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Psilatricolpites medius	*Psilatricolpites medius* Sah	Dicotyledonae	-	-			**X**	Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994)
Retitricolpites sp1	*Retitricolpites* van der Hammen, 1956 ex van der Hamen & Wymstra, 1964	Dicotyledonae	-	-	**X**	**X**	**X**	
Retitricolpites sp2	*Retitricolpites* van der Hammen, 1956 ex van der Hamen & Wymstra, 1964	Dicotyledonae	-	-		**X**	**X**	
Striatricolpites catatumbus	*Striatricolpites catatumbus* Gonzalez, 1967 =*Striatopollis catatumbus* (González-Guzmán) Ward, 1986	Fabaceae - *Crudia*	Tree	Tropical, lowland rainforest			**X**	upper Eocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); lower Eoceno - Oligocene of the Amapá, Pará, Maranhão, Sergipe and Espírito Santo continental platforms (Regali *et al.*, 1974); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Colporate								
Tricolporate (Classe Tricolporatae)								
Bombacacidites clarus	*Bombacacidites clarus* Sah, 1967	Bombacaceae	Tree	Tropical			**X**	upper Ecene of the Fonseca Basin (Maizatto, 2001); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010)

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Compositoipollenites sp1	*Compositoipollenites* Potonié, 1951 ex Potonié, 1960 =*Echtricolporites* van der Hammnen ex Germeraad, Hopping & Muller, 1968	Asteraceae	Herb, shrub, tree	Cosmopolitan, open habitats		X		upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); similar to *Echitricolporites minutus* from the Oligocene of the Taubaté Basin (Lima *et al.*, 1985a) and from Miocene - Pliocene of the Brazilian platform (Regali *et al.*, 1974)
Tubulifloridites viteauensis	*Tubulifloridites viteauensis* Barreda, 1993	Asteraceae - *Mutisia*	Liana	Wet forests, montane grassland			X	upper Eocene of the São Paulo Basin (Santos *et al.*, 2010)
Psilatricolporites cf. medius	*Psilatricolporites medius* Gonzalez, 1966	Elaeocarpaceae?	-	-	X		X	Eocene of Colombia (Gonzalez, 1966); Eocene of Nigeria (van Hoeken-Klinkenberg, 1966)
Psilatricolporites delicatus	*Psilatricolporites delicatus* Maizatto, 1997	Solanaceae - *Solanum*	Shrub, tree, herb, liana, subshrub	Tropical			X	upper Eocene - Oligocene of the Gandarela Basin (Maizatto, 1997); upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001);
Psilatricolporites maculosus	*Psilatricolporites maculosus* Regali, Uesugui & Santos, 1974	Sapotaceae	Tree, shrub	Tropical			X	Eocene - Miocene of the Amapá, Pará, Alagoas, Sergipe, Espírito Santo and Rio de Janeiro continental platforms (Regali *et al.*,1974); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); lower Miocene of the Maracaibo basin/Venezuela (Rull, 2001)

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Psilatricolporites sp1	*Psilatricolporites* van der Hammen, 1956 ex Pierce, 1961		-	-	**X**			similar to *Psilatricolporites* sp2 from the upper Eocene of the Gandarela Basin (Maizatto, 1997)
Retibrevitricolporites solimoensis	*Retibrevitricolporites solimoensis* Hoorn, 1993 (D'Apolito, Jaramillo & Harrington, 2021)	Malpighiaceae - *Byrsonima*?	-	-			**X**	Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Retitricolporites sp1 (Retitricolpites ovalis?)	*Retitricolpites ovalis* van der Hammen & Wymstra, 1964	Dicotyledonae			**X**	**X**	**X**	
Rhoipites sp1	*Rhoipites* Wodehouse, 1933	Rhamnaceae?	-	-	**X**	**X**	**X**	*Rhoipites* Wodehouse, 1933 accommodates tricolporate pollen grains that are reticulate–pitted, prolate, with marginate/costate colpi.
Syncolporate (Classe Syncolporatae)								
Syncolporites (=Myrtaceidites) poricostatus	*Syncolporites poricostatus* van der Hoeken-Klinkenberg, 1966	Myrtaceae	Tree, shrub	Tropical	**X**	**X**	**X**	upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - lower Miocene of the Gandarela Basin (Maizatto, 1997); middle Eocene - Miocene of the Brazilian continental platform and of the Sergipe/Alagoas, Cumuruxatiba and Espírito Santo basins (Regali *et al.* 1974); Oligocene of the Resende Basin (Lima & Melo, 1994); Eocene of the Bonfim Basin (Lima & Dino, 1984); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Miocene of the Amazon Basin (Hoorn, 1993)

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
Syncolporites sp1	*Syncolporites* van der Hammen, 1954	Sapindaceae?	-	-	**X**		**X**	similar to *Syncolporites* sp from the upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001)
Perisyncolporites pokornyi	*Perisyncolporites pokornyi* Germeraad, Hopping & Muller, 1968	Malpighiaceae - *Banisteropsis*-type	Shrub, tree, liana	Tropical forest	**X**	**X**	**X**	upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); middle Eocene - Miocene of the Brazilian continental platform and of the Sergipe/Alagoas, Jequitinhonha, Cumuruxatiba and Espírito Santo basins (Regali *et al.*, 1974); Eocene of the Gandarela Basin (Lima & Salard-Cheboldaeff, 1981); Oligocene of the São Paulo Basin (Lima *et al.*, 1991); Eocene - Oligocene of the Guanabara Rift (Lima *et al.*, 1996); Paleogene of the Tanque Basin (Garcia *et al.*, 2008); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010); Oligocene of the Resende Basin (Lima & Melo, 1994); upper Eocene of the Resende Basin (Lima & Amador, 1985); Eocene of the Bonfim basin (Lima & Dino, 1984); Oligocene of the Taubaté Basin (Lima *et al.*, 1985b); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Perisyncolporites sp1	*Perisyncolporites* Germeraad, Hopping & Muller, 1968	Malpighiaceae?	-	-	**X**	**X**	**X**	
Stephanocolporate								

Palynomorphs	NAME	Botanical affinity	Life form	Distribution/Ecology (nearest modern taxon)	Samples			Occurrences - Cenozoic Basins
					MB	MM	MT	
Passifloriidites sp1	*Passifloriidites* D'Apolito, Jaramillo & Harrington, 2021	Passifloraceae - *Passiflora*	Liana, subsrub	Neotropical	X		X	*Passifloriidites* is erected to accommodate pollen with the combination of geminicolpi, pseudoperculum/pontoperculum, and reticulate exine of the Passifloraceae type (D'Apolito *et al.*, 2021). The species is different from those described from the Miocene of the Solimões Formation (D'Apolito *et al.*, 2021)
Psilastephanocolporites brevissimus	*Psilastephanocolporites brevissimus* D'Apolito *et al.*, 2019	Myrsinaceae - *Myrsine*	Shrub, tree	Tropical and subtropical regions, forest	X	X	X	Pliocene - Pleistocene of the Negro River (D'Apolito *et al.*, 2019); *Myrsine braziliana* macrofossils were described from the Eocene - Oligocene of the Fonseca Basin (Lima & Salard-Cheboldaeff, 1981)
Psilastephanocolporites fissilis	*Psilastephanocolporites fissilis* Leidelmeyer, 1966	Polygalaceae - *Polygala*	Shrub, herb, liana, subshrub	Tropical to temperate	X			upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); upper Eocene - lower Miocene of the Gandarela Basin (Maizatto, 1997); Eocene - Miocene of the Brazilian continental platform (Regali *et al.*, 1974); Oligocene of the Resende Basin (Lima & Melo, 1994); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021); Eocene of the Fonseca and Gandarela basins (Lima & Salard-Cheboldaeff, 1981); Miocene of the Amazon Basin (Hoorn, 1993); Eocene of the British Guiana (van der Hammen & Wymstra, 1964); Paleogene of the

Palynomorphs	NAME	Botanical affinity	Life form	Distribution/Ecology (nearest modern taxon)	Samples			Occurrences - Cenozoic Basins
					MB	MM	MT	
								Tanque Basin (Garcia *et al.*, 2008); Eocene - Oligocene of the Casa de Pedra Graben (Lima *et al.*, 1994); upper Eocene of the São Paulo Basin (Santos *et al.*, 2010)
Heterocolpate								
Heterocolpites incomptus	*Heterocolpites incomptus* Van der Hammen, 1956 ex Hoorn, 1993	Melastomataceae	Tree, shrub, liana, herb	Tropical, common in tropical-montane environments, often heliophytic plants	X	X	X	Miocene of the Amazon Basin (Hoorn, 1993); upper Miocene - Pliocene of the Tanque Basin (Garcia *et al.*, 2008); according to Biagolini *et al.* (2013) Melastomataceae pollen grains were recorded on the upper Eocene to Oligocene of Brazil (Itaquaquecetuba Formation, São Paulo Basin)
Dicotetradites sp	*Dicotetradites* Couper 1953	Fabaceae - Mimosoideae?	-	-			X	upper Eocene of the Gandarela Basin (Maizatto, 1997); Oligocene of the Taubaté Basin (Lima *et al.*, 1985a)
Ericipites annulatus	*Ericipites annulatus* González-Guzmán, 1967	Ericaceae - *Gaylussacia*-*Agarista*-*Gaultheria*-type	tree, shrub, sunshrub	moist, open, cool montane environments (Luteyn, 2002)		X	X	upper Eocene - middle Eocene of Colombia (González-Guzmán, 1967); Miocene of the Solimões Formation (D'Apolito *et al.*, 2021); Pliocene - Pleistocene of the Negro River (D'Apolito *et al.*, 2019)
Tetradites brevicolporites sp. nov.	*Tetradites brevicolporites* sp. nov.	Dicotyledonae	-	-			X	
Polyad								
Polyadopollenites myriosporites	*Polyadopollenites myriosporites* (Cookson, 1959) Lima, Salard-	Dicotyledonae	-	-			X	upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001); Oligocene of the Gandarela Basin

Palynomorphs	**NAME**	**Botanical affinity**	**Life form**	**Distribution/Ecology (nearest modern taxon)**	**Samples**			**Occurrences - Cenozoic Basins**
					MB	**MM**	**MT**	
	Cheboldaeff & Suguio, 1985							(Maizatto, 1997); Oligocene of the Taubaté Basin (Lima *et al.*, 1985a)
Algae								
Botryococcus braunii	*Botryococcus braunii* Kützing, 1849	Algae Botryococcaceae				**X**		upper Eocene - Oligocene of the Fonseca Basin (Maizatto, 2001)
Mougeotia	*Mougeotia* Agardh, 1824	Algae Zygnemataceae					**X**	middle Paleogene of Colombia (Jaramillo, 1999); late Oligocene - middle Miocene of the Cullen Formation/Argentina (Zamaloa, 2000)
Spirogyra	*Spirogyra* Link, 1820	Algae Zygnemataceae				**X**		late Oligocene - middle Miocene of the Cullen Formation/Argentina (Zamaloa, 2000)

6. CONCLUSÕES

A aplicação de técnicas de descrição de geologia básica como mapeamento, análise de testemunhos de sondagem e avaliação de lâminas delgadas, com o olhar atento aos detalhes, traz, além de diagnóstico, compreensão de processos no registro geológico. A descrição dos sedimentos recentes encontrados na Serra do Tamanduá e chamada Bacia Bandeira tem função de registro do conhecimento geológico de forma pública e consistente. Com esse processo, conclui-se:

- A Bacia Bandeira compreende um conjunto de sedimentos provenientes de unidades Proterozoicas e Arqueanas do Quadrilátero Ferrífero;
- Esses sedimentos foram formados em contexto de processos erosivos desencadeados e influenciados por tectônica ativa, com pulsos de geração e acomodação de material no tempo e no espaço;
- Há a identificação de processos pedogenéticos em profundidade, o que evidencia momentos de hiato registrados nas porções em que foram descritos solos residuais;
- A porção basal dos sedimentos foi depositada no Eoceno tardio identificado por meio do registro bioestratigrafico. As unidades sobrejacentes foram correlacionadas com outras conhecidas no Quadrilátero. A possibilidade de datar as porções superiores dos sedimentos existe, visto a existência de estratos com restos vegetais e pode ser uma possibilidade para o futuro;
- É possível detalhar melhor a distribuição dos sedimentos na região mediante análise dos dados de campo, se houver;
- Ainda há amplas e diversas possibilidades de estudar os numerosos depósitos sedimentares recentes existentes no Quadrilátero Ferrífero, utilizando as descrições e observações de campo, aplicando técnicas investigativas diversas.

7. PERSPECTIVAS DE NOVOS TRABALHOS

O estudo da Bacia Bandeira e a ampliação do conhecimento das bacias Cenozoicas já descritas do Quadrilátero trouxe informações novas, como litofácies sedimentares únicas e a identificação de idade da deposição em porções inferiores da sequência sedimentar. Entretanto, ainda é possível explorar alguns aspectos geológicos e geotécnicos dos sedimentos encontrados. Assim, registra-se a sugestão de algumas linhas de pesquisa, como ramificações da análise da Bacia Bandeira:

- Estudo por meio de geoprocessamento do potencial de estudo das bacias sedimentares cenozoicas ainda não estudadas, cruzando geograficamente as condições que são favoráveis para o estudo dessas bacias;
- Busca por palinomorfos em porções mais recentes da Bacia Bandeira, considerando os estratos em que foram encontrados raízes e nódulos;
- Definir e comparar a composição do material argiloso de diferentes estratos da Bacia Bandeira, buscando entender se:
    - Há diferença composicional entre a matriz argilosa do material das unidades B e C?
    - É possível identificar evidências de processos pedogenéticos por meio da análise da composição das argilas do material da matriz desses sedimentos?
    - Há a possibilidade de identificar algum processo de diagênese, mesmo que incipiente nas porções mais profundas?
- Definir as regiões que podem representar solos nos furos de pesquisa que serão feitos no futuro, na tentativa de delimitar uma paleosuperfície na morfologia do depósito;
- Indicar se existe uma correlação direta entre as características desses sedimentos e a capacidade de transmitir água e influenciar o nível freático local.

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