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**GEOLOGIA E METALOGÊNESE DO DEPÓSITO Au-Ag
(Pb-Zn) DO CORINGA, SUDESTE PROVINCIA MINERAL
TAPAJÓS, PARÁ**

Tese apresentada por:

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Orientador: Prof. Dr. Evandro Luiz Klein (CPRM)

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GEOLOGIA E METALOGÊNESE DO DEPÓSITO Au-Ag (Pb-Zn) DO CORINGA, SUDESTE PROVÍNCIA MINERAL TAPAJÓS, PARÁ

TESE APRESENTADA POR:

STELLA BIJOS GUIMARÃES

Como requisito parcial à obtenção do Grau de Doutor em Ciências na Área de GEOLOGIA, Linha de Pesquisa EVOLUÇÃO CRUSTAL E METALOGÊNESE

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*Dedico este trabalho às
verdadeiras riquezas da Terra,
meus diamantes Lara e Alice!*

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RESUMO

A Província Mineral Tapajós (PMT) está localizada na parte centro-sul do Cráton Amazônico e é considerada uma das principais províncias metalogenéticas do Brasil. Uma parte significativa da província compreende rochas vulcânicas e vulcanoclásticas félsicas e granitos, formados predominantemente em dois intervalos, 2,02 a 1,95 Ga e 1,91 a 1,87 Ga, pertencentes a várias unidades estratigráficas e litodêmicas. A partir de dados obtidos em trabalho de campo, petrografia e geofísica aérea de alta resolução nos permitiram produzir um novo mapa na escala de 1: 100.000 para a porção sudeste da PMT, onde localiza-se o depósito de ouro e prata (Cu-Pb-Zn) Coringa. Identificamos duas novas unidades geológicas: (1) as rochas vulcânicas e piroclásticas da Formação Vila Riozinho, anteriormente atribuídas ao Grupo Iriri, incluindo uma fácies aqui definida dessa formação, que compreende um grupo de rochas com o maior conteúdo magnético da região (Formação Vila Riozinho -fácies piroclástica magnética), e (2) o Feldspato Alcalino Granito Serra (FAGS), que é intrusivo na Formação Vila Riozinho (FVR). Essas unidades representam as rochas hospedeiras do depósito Coringa. As rochas da FVR representam um arco magmático cálcio-alcálico de alto K a shoshoníticas. Existem semelhanças nos padrões de LILE e HFSE e nos diagramas multielementares com as rochas graníticas da Suíte Intrusiva Creporizão (SIC). A contemporaneidade entre essas unidades reforça uma possível correlação petrogenética e converge para a hipótese de fontes semelhantes, de provável refusão de rochas de arco. Os dados isotópicos revelaram comportamento semelhante entre VRF, FAGS e a Suíte Intrusiva Maloquinha e apresentam valores negativos de ϵNd ; no entanto, indica rochas derivadas de fontes enriquecidas (rochas da crosta antiga). Portanto, essas unidades tiveram a mesma fonte durante o ajuste tectônico e a evolução crustal da PMT. Desta forma, representa um estágio pós-colisão transcorrente que se seguiu à colisão do Arco Magmaítico de Cuiú-Cuiú relacionado ao evento vulcano-plutônico Orosiano (2033-2005 Ma). Com base nas informações geocronológicas disponíveis, essas unidades podem ser associadas a um evento vulcano-plutônico que ocorreu no período Orosiriano, a cerca de 1,98 Ga. O depósito de Au-Ag (Cu-Pb-Zn) Coringa ocorre essencialmente em veios que seguem a estruturação regional (NNW-SSE). Hospeda-se nas rochas vulcânicas e piroclásticas das fácies piroclástica magnética da Formação Vila Riozinho (ignimbritos, tufo e brechas) e o Feldspato Alcalino Granito Serra, com predominância das rochas supracrustais. Os processos hidrotermais afetaram todos os litotipos associados à mineralização, produzindo alteração distal

(carbonato-clorita-epidoto), alteração intermediária-proximal (sericita-pirita) e alteração proximal (clorita-hematita). Os veios mineralizados são geralmente compostos por quartzo + pirita + calcopirita + galena + esfalerita + electrum + clorita + sericita. Os grãos de ouro ocorrem como inclusões ou preenchendo fraturas na pirita. Os fluidos apresentam baixa salinidade, rico em H₂O e pobre em CO₂, com evidência de mistura (magmática-meteórica), e a presença de adulária e Mn-calcita são características diagnósticas desse depósito. Todas as características convergem para confirmar um depósito epitermal de intermediária sulfetação como modelo genético para o depósito Coringa.

Palavras-chave: Ouro. Epitermal. Coringa. Tapajós.

ABSTRACT

The Tapajós Mineral Province (TMP) is located in the south-central portion of the Amazonian Craton and is considered one of the main metallogenic provinces of Brazil. A significant part of the province comprises felsic volcanic and volcanoclastic rocks and granites, which formed predominantly in two intervals, 2.02 to 1.95 Ga and 1.91 to 1.87 Ga, belonging to several stratigraphic and lithodemic units. Fieldwork, petrography, and high-resolution airborne geophysics allowed us to produce a new map at the 1:100,000 scale for the southeastern portion of the TMP, where the gold and silver (Cu-Pb-Zn) Coringa deposit is located. We identified two new geological units: (1) the volcanic and pyroclastic rocks of the Vila Riozinho Formation, previously attributed to the Iriri Group, including a facies defined here of this formation, which comprises a group of rocks with the largest magnetic content in the region (Vila Riozinho Formation - magnetic pyroclastic facies), and (2) the Serra Alkali Feldspar Granite, which intruded into the Vila Riozinho Formation (VRF). These units are the host rocks of Coringa deposit. The FVR rocks represent a magmatic arc with high K calc-alkaline to shoshonitic affinities. There are similarities in the patterns of LILE and HFSE and the multielementary diagrams with the granitic rocks from Creporizão Intrusive Suite (CIS). The contemporaneity between these units reinforces a possible petrogenetic correlation and converge to the hypothesis of similar sources, of probable remelting of arc rocks. Isotopic data revealed similar behavior between VRF, SAFG and Maloquinha Intrusive Suite expose similar behavior and present negative ϵ_{Nd} values; however, it indicates rocks derived from enriched sources (ancient crustal rocks). Therefore these units had the same source during tectonic setting and crustal evolution of TMP. It is a transcurrent post-collisional stage that followed the collision of the Cuiú-Cuiú Magmatic Arc related to the Orosian volcano-plutonic event (2033-2005 Ma). Based on available geochronological information these units can be associated with a volcano-plutonic event that occurred in the Orosirian period, at about 1.98 Ga. The Au-Ag (Cu-Pb-Zn) Coringa deposit, occurs essentially in veins and veinlets whose match the regional trend (NNW-SSE). The host rocks are volcanic and pyroclastic rocks of the Magnetic Pyroclastic Facies (MPF) from the Vila Riozinho Formation (ignimbrites, tuffs, and breccia), and the Serra Alkali Feldspar Granite, with a predominance of the supracrustal rocks. The hydrothermal processes affected all lithotypes associated with mineralization, producing distal alteration (carbonate-chlorite-epidote), intermediate-proximal alteration (sericite-pyrite) and proximal alteration (chlorite-hematite). The mineralized veins are

generally composed of quartz + pyrite + chalcopyrite + galena + sphalerite + electrum + chlorite + sericite. Gold grains occur as inclusions or fractures in pyrite. The fluids presents low salinity, rich in H₂O and poor in CO₂, with evidence of mixing (magmatic-meteoric), and the presence of adularia and Mn-carbonate are outstanding features of this deposit. All characteristic converge to confirm an intermediate- sulfidation epithermal deposit as a genetic model to Coringa deposit.

Keywords: Gold. Epithermal. Coringa. Tapajós.

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1. INTRODUÇÃO

1.1 APRESENTAÇÃO

O Cráton Amazônico representa uma grande placa litosférica continental que possui características litológicas e estruturais heterogêneas. O conhecimento sobre sua evolução avançou muito nas últimas décadas, contudo com propostas de compartimentação tectônica com base em dados geocronológicos e isotópicos.

Segundo abordagem de alguns autores (Santos 2003, Tassinari & Macambira 2004, Vasquez *et al.* 2008), as grandes províncias geocronológicas são definidas em razão de seus padrões geocronológicos, assembleias litológicas, orientações estruturais e histórias evolutivas individuais e distintas em relação às províncias adjacentes. Embora possuam divergências, ambas se assemelham ao admitir que a evolução do Cráton Amazônico seja resultante de sucessivos episódios de acreção crustal durante o Paleo-Mesoproterozoico, em volta de um núcleo mais antigo, estabilizado no fim do Arqueano.

Juliani *et al.* (2013) questionaram os modelos acrecionários, sugerindo que estruturas regionais orientadas segundo a direção E-W seriam contínuas desde o leste do Cráton Amazônico (região de Carajás) até a região da Província Mineral do Tapajós (PMT) e, portanto, incompatíveis com o modelo acrecionário de sudoeste para nordeste.

Pesquisas mais recentes (Fraga *et al.* 2017, Klein *et al.* 2017, Kroonenberg *et al.* 2016, Vasquez *et al.* 2017) tem considerado a distribuição das rochas do Cráton Amazônico de forma mais abrangente e integrada, observando similaridades tectônicas e geológicas, e propondo utilização do conceito de domínios.

Na porção centro-sul do Cráton Amazônico localiza-se a Província Mineral Tapajós - PMT (ou Domínio Tapajós) e é considerada uma das principais províncias metalogenéticas do Brasil, com destaque para mineralizações de ouro. Uma parte significativa da província compreende rochas graníticas, vulcânicas e vulcanoclásticas félsicas, que se formaram predominantemente em dois intervalos de tempo, 2,02 a 1,95 Ga e 1,91 a 1,87 Ga e estão agrupados em várias unidades estratigráficas e litodêmicas (Vasquez *et al.* 2017) (**Fig. 1.1**).

Os primeiros registros da atividade garimpeira na PMT datam do fim da década de 1950, com desenvolvimento de garimpos nas proximidades dos rios nos depósitos secundários, e posteriormente o ouro passou a ser extraído também em depósitos primários. A expressiva produção de ouro rendeu a Província Mineral Tapajós o título de maior produtora

deste bem mineral entre as décadas de 1970 a 1990. Com isso, tornou-se um grande foco das mineradoras em períodos alternados durante as duas últimas décadas.

Ainda que avanços no conhecimento geológico sobre a PMT sejam considerados, os modelos geotectônicos discutidos atualmente, a petrologia das rochas e os modelos genéticos das mineralizações não são consensuais. Levantamentos cartográficos de maior detalhe e estudos geoquímicos e geocronológicos mais aprofundados e integrados são imprescindíveis para que se possa compreender a evolução geotectônica da área e sua relação com as mineralizações existentes. Estudos de caráter local visando à caracterização dos inúmeros depósitos existentes também são fundamentais para que se possa, através da integração desses dados, entender o contexto metalogenético da província.

A presente tese aborda, em parte, esses problemas e teve como objeto de estudo a porção sudeste da PMT, e o sistema hidrotermal do depósito polimetálico (Au e Ag $\pm$ Cu-Pb-Zn) Coringa, que no início deste trabalho tinha os direitos minerários em titularidade da empresa *Magellan Minerals*, atualmente da *Serabi Minerals*. No mesmo contexto ocorre o prospecto Mato Velho de titularidade da mesma empresa. A área do depósito localiza-se no sudoeste do Estado do Pará (**Fig. 1.2**), e sudeste da TMP (**Fig. 1.1**), entre as duas drenagens principais da região, os rios Jamanxim, a oeste e Curuá, a leste, próximo ao limite entre os municípios de Novo Progresso e Altamira (**Fig. 1.2**).

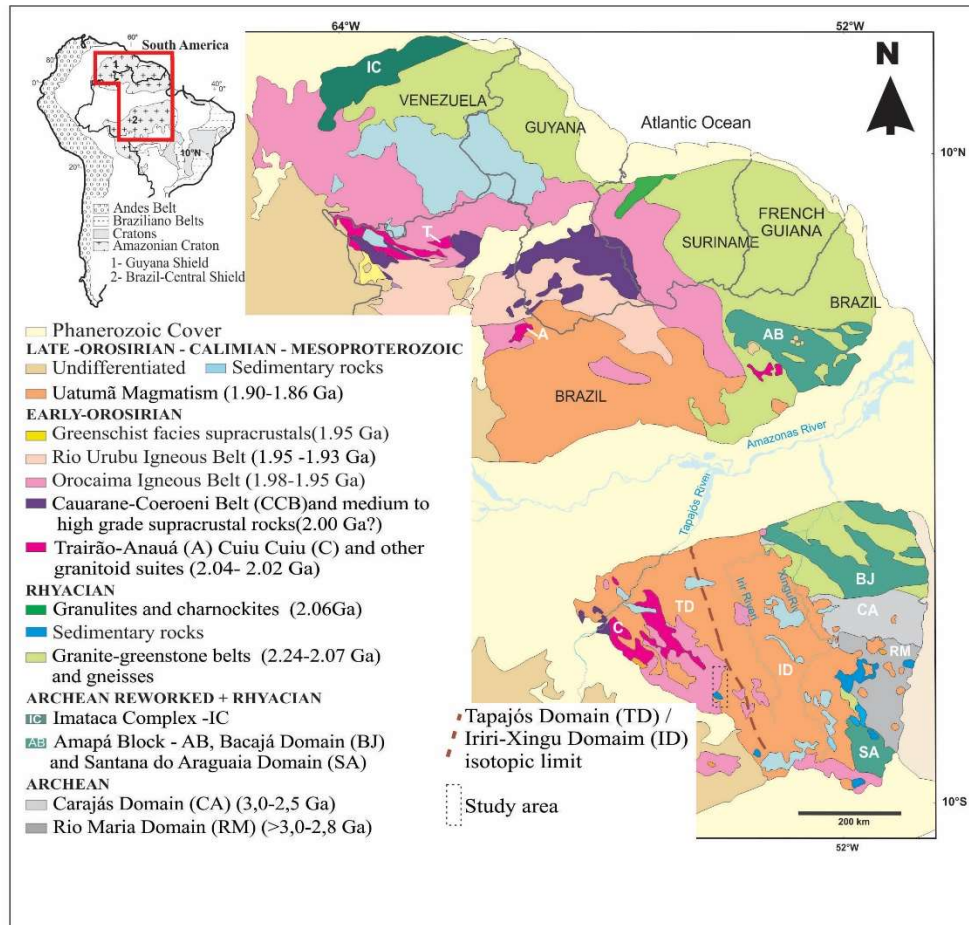


Fig. 1.1 - Esboço geológico do Escudo Brasil Central (sul) e Escudo da Guiana (norte) que formam o Cráton Amazônico, com localização da área de estudo. Fonte: Modificado por Fraga *et al.* (2017).

1.2 ESTRUTURA DA TESE

Esta Tese de doutorado é composta de três artigos científicos, em conformidade com o regimento do Programa de Pós-Graduação em Geologia e Geoquímica (PPGG) da Universidade Federal do Pará (UFPA). A introdução da Tese (Capítulo 1) é composta pelos seguintes itens: *1.1 Apresentação, 1.2. Estrutura da Tese, 1.3. Problemáticas abordadas, 1.4. Objetivos e justificativas, 1.5. Materiais e métodos, 1.6 Geologia Regional.*

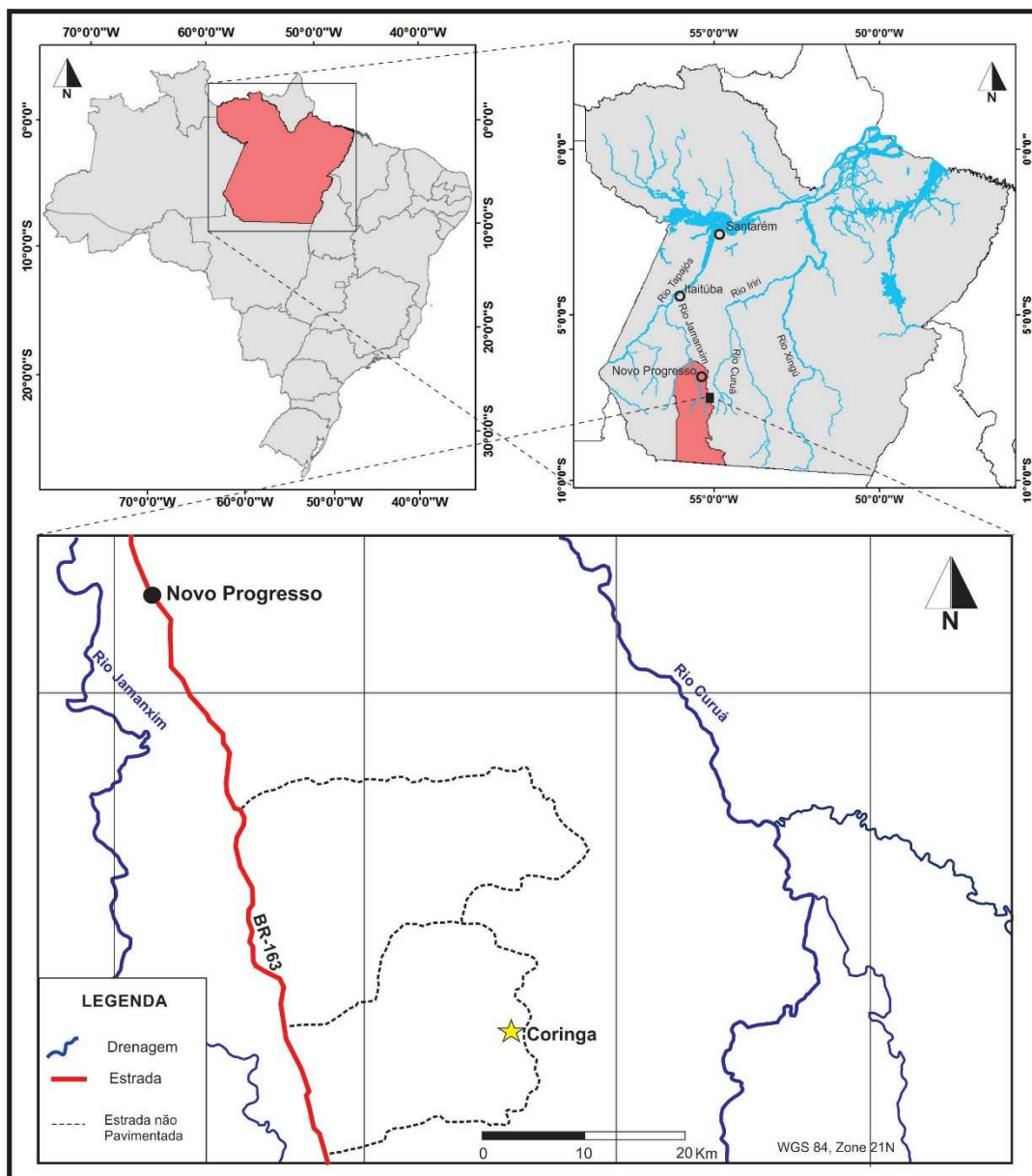


Fig. 1.2 - Mapa de localização e acesso à área do depósito Coringa.

O corpo principal da Tese constitui-se de um artigo publicado e dois artigos submetidos a periódicos de circulação internacional. Os artigos apresentam distintas abordagens, conforme segue abaixo:

No capítulo 2, o artigo “*Reassessment of the geology of the southeastern Tapajós Gold Province, Amazonian Craton, Brazil, based on field, petrographic, and airborne geophysical data*”, apresenta as contribuições à geologia e estratigrafia da porção sudeste da Província Mineral Tapajós com apoio de dados de geofísica aérea de alta resolução (gravimetria e magnetometria) aliados aos dados levantados durante campanhas de campo. Este artigo já se encontra publicado no periódico internacional *Journal of the Geological*

Survey of Brazil. A principal contribuição desse artigo reside no reconhecimento de uma unidade (fácies) de rochas vulcânicas e piroclásticas félsicas de alta magnetização em relação às demais unidades geológicas em seu entorno.

No capítulo 3, o artigo “*Geochemical and isotopic constraints on the host rocks of the magmatic-hydrothermal Coringa gold-silver (Cu–Pb–Zn) deposit of the Tapajós Mineral Province, Amazonian Craton, Brazil*”, a partir dos resultados da estratigrafia consolidada no artigo anterior, apresenta uma discussão com dados de U–Pb (LA–ICPMS) em zircão, Sm–Nd, Lu–Hf e litogeoquímica. A intenção é fornecer dados de petrogênese para auxiliar na definição de ambiente tectônico visto que a granitogênese e o vulcanismo nesta região são bem marcantes, quimicamente variados e de diferentes idades. Este artigo está publicado no periódico internacional *Journal of South American Earth Sciences*.

No capítulo 4, o artigo “*Metallogenesis of the Orosirian magmatic-hydrothermal Coringa gold-silver (Cu–Pb–Zn) deposit, Southeastern Tapajós Mineral Province, Amazonian craton, Brazil*”, apresenta dados de petrografia, química mineral, inclusões fluidas e isótopos estáveis aplicados ao depósito do Coringa, com intuito de determinar as características dos principais corpos mineralizados, determinar estágios de alteração hidrotermal, a fim de discutir os processos de formação do depósito e do sistema mineral como um todo. Este artigo foi submetido ao periódico internacional *Ore Geology Reviews*.

No Capítulo 5, são apresentadas as conclusões de forma unificada ao conteúdo dos artigos de forma a apresentar os principais avanços proporcionados por esta pesquisa, bem como apontar desafios futuros.

1.3 PROBLEMÁTICAS ABORDADAS

1.3.1 Acresção crustal

A adição de fragmentos crustais diversos como arcos de ilhas, platôs oceânicos e trilhas de *hot spots* à margens continentais, corresponde a um processo comum e particularmente importante em eventos de modificação e espessamento da crosta continental em regiões conhecidas como cinturões orogênicos. Se tais segmentos crustais forem acrescidos aos continentes por meio de subducção e/ou colisão frontal ou oblíqua, estes serão limitados por importantes falhas ou zonas de sutura, sendo, portanto denominados de terrenos tectono-estratigráficos, ou simplesmente terrenos. Neste âmbito, dois principais processos são

responsáveis por modificação crustal e/ou espessamento crustal: colagem e acreção de terrenos (Cawood *et al.* 2011).

Cinturões orogênicos que registram eventos de acreção de terrenos são chamados de cordilheiranos/andinos ou acrescionários. Por outro lado, independente de sua origem, uma grande parcela dos orógenos conhecidos, registra ao menos um estágio de acreção ou colagem (Cawood *et al.* 2011). Exemplos variam desde Províncias arqueanas como Slave no Canadá, até as mais recentes, como os orógenos que compõem toda a região do círculo Pacífico (Cawood *et al.* 2009).

As causas da instalação das orogenias e da deformação subsequente não são muito distintas daquelas já conhecidas para a instalação e formação de bacias sedimentares cratogênicas. As diferenças residem na escala e na intensidade dos processos. Os esforços gerados e advindo de interações de placas (divergência, convergência sem colisão e com colisão, transformância, etc) sejam estes de interações próximas ou distantes podem adentrar o interior do continente e serem responsáveis tanto pela formação (ao menos, em parte), quanto pelo dobramento intenso de pilhas sedimentares acumuladas sobre frações litosféricas previamente enfraquecidas (por acumulação de HPE, LIPs, magmatismo máfico-ultramáfico, anomalias gravimétricas etc. (Neves 2015).

O resultado mais imediato na acreção de terrenos é sempre o crescimento crustal, mas eventos de retrabalhamento e reciclagem crustal também podem estar associados. Crescimento crustal é o resultado da adição progressiva de material às margens continentais. Um caso clássico é a Cordilheira Norte-americana, onde os diversos terrenos adicionaram material à margem oeste de Laurentia no fim do Paleozoico (Coney *et al.* 1980).

Amalgamação de terrenos ocorre quando dois terrenos colidem anteriormente a um episódio acrescionário. Acreção é um processo muito importante, pois pode afetar consideravelmente a história evolutiva do terreno, obscurecendo ou obliterando feições anteriores. Durante eventos acrescionários, zonas de cisalhamento inversas representam os elementos estruturais mais importantes, principalmente em processos de colagem frontal de terrenos à margem continental.

Zonas de cisalhamento de alto ângulo, no entanto, também representam importantes elementos estruturais, em consequência de acreção oblíqua ou colagem lateral, ou ainda em virtude de reativação de falhas contracionais antigas. Outro aspecto importante na indicação de acreção de terrenos é a presença de ofiolitos, vinculados a regimes de obducção sin-acrescionária e preservados em casos de baixas taxas de exumação do orógeno.

Para Santos *et al.* (2004) a província Tapajós representa um orógeno acrescionário tipo andino que evolui entre 2050 e 1880 Ma, e no qual a placa oceânica colidiu com um continente a leste. Baseados nas associações do Domínio Tapajós propuseram dois eventos orogênicos: a Orogênese Mundurucus relacionada à acreção de três arcos magmáticos entre 2040 e 1957 Ma, e a Orogênese Tropas relacionada à acreção de dois arcos entre 1906 e 1886 Ma.

1.3.2 Depósitos epitermais

Os depósitos minerais, em geral, são classificados de acordo com a sua profundidade de formação variando de mesothermal a epitermal. Segundo Groves *et al.* (1998) os depósitos mesotermiais podem ser classificados como orogênicos com base no arcabouço tectônico e tempo de formação. Estes depósitos são gerados por fluidos derivados de devolatilização metamórfica, tipicamente com salinidades muito baixas ($<2\% \text{NaCl eq.}$) e alterações carbonáticas.

Os depósitos epitermais são importantes fontes primárias de metais como cobre, zinco, ouro, prata, estanho, chumbo, mercúrio e molibdênio. Estes depósitos foram primeiramente definidos por Lindgren (1922, 1933) como acumulações de metais preciosos e metais de base formados pela ascensão de fluidos hidrotermais em profundidades relativamente rasas ($\leq 900 \text{ m}$) e baixa temperatura (50 a 200°C), normalmente hospedada em vulcânicas e rochas adjacentes. Com avanço das pesquisas, atualmente é consensual a denominação de depósitos epitermais como associados a rochas vulcânicas, formados a profundidade inferior a $\pm 1,5 \text{ km}$ e geralmente a temperaturas entre 150 e 300°C (Hedenquist *et al.* 2000, Simmons *et al.* 2005).

Os depósitos epitermais são subdivididos em três classes (alta, intermediária e baixa sulfetação), de acordo com os minerais de alteração, características dos fluidos hidrotermais e ambiente geológicos de formação (Hedenquist *et al.* 2003, Wang *et al.* 2019).

Depósitos de intermediária sulfetação (IS) geralmente têm um teor de ouro mais baixo que em veios de baixa sulfetação (BS). Contudo, o que torna os depósitos de IS importantes na exploração é o seu potencial para conteúdo significativo de metais pesados e prata, além de estreitas relações estreitas com depósitos pórfiro (Cu-Mo) e depósitos de alta sulfetação (AS).

Depósitos de alta sulfetação (AS) são caracterizados por altos conteúdos de sulfetos (10-90%), sendo os mais comuns: pirita, enargita, luzonita, famatinita, covelita, e os minerais

de ganga são quartzo e sulfatos (barita). A ausência de carbonatos é um diferencial, e minerais de alteração proximal quartzo-alunita-pirofilita são característicos. Espessas camadas com alunita, caulinita e quartzo (do tipo “*vuggy*”) são formadas a partir da lixiviação ácida da condensação de um sistema vapor e água meteórica, também conhecida como *lithocap* ou alteração argílica avançada (ácida). (Sillitoe & Hedenquist 2003). Desta forma, representam depósitos formados por fluidos mineralizantes oxidados e de pH ácido

Depósitos de baixa sulfetação (BS), em geral associados ao magma subalcalino, é um tipo de depósito epitermal caracterizado por baixo teor de sulfetos (normalmente < 2% vol), com pirita (pouca), arsenopirita ± pirrotita ± esfalerita ± galena ± calcopirita ± tetraedrita/tennantita como minerais de minério, e calcedônia, quartzo ± carbonato ± fluorita como minerais de ganga, e illita/esmectita e adularia como minerais chave de alteração hidrotermal proximal.

Depósitos de intermediária sulfetação (IS) são um tipo de depósito epitermal com intermediários teores de sulfetos (5 a 20% em vol.), com pirita, esfalerita, galena, calcopirita, tetraedrita / tennantita como principais minerais de minério, e conta com quartzo, carbonato manganífero ± adularia ± silicato manganífero ± barita como minerais de ganga, e illita como minerais de alteração proximal. O conteúdo relativo de minerais de minério e de ganga em veios pode ser usado como recursos de diagnóstico para distinguir os depósitos de IS e BS em campo, ambos são estruturalmente semelhantes e são formados por fluidos de pH baixo a neutros. O diferencial pode ser que nos depósitos IS ocorrem sulfetos (> 5%), muita mica branca e pouco quartzo, enquanto que nos depósitos de BS são pobres em sulfetos (<1%) e ricos em quartzo e adularia (Sillitoe & Hedenquist 2003).

Os depósitos de IS tem grande afinidade com os de AS e do tipo pórfiro, comumente associadas a rochas andesíticas a dacíticas cálcio-alcálinas.

1.4 OBJETIVOS E JUSTIFICATIVAS DE TESE

O depósito Coringa difere da maioria dos depósitos conhecidos na Província Mineral Tapajós (PMT) por tratar-se de um depósito polimetálico (Au, Ag, Cu, Pb, Zn), embora até o momento apenas ouro e prata sejam considerados econômicos, com minério concentrado em veios. Recentemente, alguns estudos abordaram de forma superficial o sistema mineral do depósito em alvos periféricos aos corpos principais (Corrêa-Lima & Klein 2020, Tokashiki *et al.* 2015). Além disso, pouco se conhece a cerca da geologia local, disponível apenas na escala 1:1.000.000 (Vasquez & Rosa-Costa 2008) e 1:100.000, mas sem utilização de

geofísica de alta resolução (Guimarães *et al.* 2015), exceto pelos relatórios internos da empresa *Magellan Minerals*.

Devido à escassez de trabalhos e dados na área, este trabalho é oportuno e se faz necessário para melhor compreensão do contexto metalogenético local. Neste âmbito, o trabalho tem o objetivo global de contribuir para o conhecimento da metalogênese do depósito Coringa. Isto se enquadra também no objetivo geral de contribuir para o avanço no conhecimento da geologia e da metalogênese da PMT, o que vem sendo efetuado por trabalhos do Serviço Geológico do Brasil (CPRM) e do Grupo de Pesquisa em Geologia Econômica da Universidade Federal do Pará (UFPA), dos quais a autora também participa.

Para o estudo metalogenético é essencial um bom conhecimento acerca da geologia regional, suas relações estratigráficas, características químicas e geocronológicas. Portanto, para que os objetivos desta Tese sejam alcançados, faz-se necessário:

- a) Caracterização das rochas hospedeiras e encaixantes da mineralização e de seu entorno no que se refere a (1) petrografia, (2) assinatura química, (3) idade e (4) tempo de residência crustal e, com isso, investigar a evolução magmática e ambiente tectônico em que se formaram essas rochas, compará-las e relacioná-las com as unidades conhecidas na PMT;
- b) Discutir os principais controles estruturais;
- c) Caracterização mineralógica do minério e da alteração hidrotermal no depósito Coringa;
- d) Determinação dos principais parâmetros físico-químicos do sistema mineralizador;
- e) Investigação das fontes de fluidos e dos processos envolvidos na concentração do minério;
- f) Propor um modelo genético para a mineralização.

1.5 MATERIAIS E MÉTODOS

1.5.1 Trabalho de campo

Duas etapas de campo foram realizadas com intuito de reconhecimento geológico e identificação das principais unidades regionais, sendo possível assim atualizar o mapa geológico e a litoestratigrafia. Foi realizado um total de 155 pontos de campo, com

amostragem de rocha em todos eles. Uma etapa de campo foi destinada para visita a alvos/corpos mineralizados que compõem o depósito Coringa e descrição (*in locu*) e amostragem dos testemunhos de sondagem disponibilizados pela empresa *Magellan Minerals*. Foram amostrados segmentos de 35 furos de sondagem de alvos principais e periféricos.

1.5.2 Integração de dados geofísicos

A partir de informações coletadas em campo foram feitas interpretações e integrações de imagens aerogeofísicas e de sensores remotos, principalmente para auxiliar no fechamento do mapa geológico devido a vasta cobertura vegetal presente na região estudada, impossibilitando acesso a alguns locais, além de existir uma reserva indígena, onde o acesso é vedado. Os dados aerogeofísicos utilizados são provenientes do Projeto Rio Curuá, contratados pelo Serviço Geológico do Brasil (CPRM). Os processamentos dos dados geofísicos são realizados pelos pesquisadores da área de geofísica da CPRM com o *software* Geosoft. Para informações mais detalhadas sobre a metodologia, vide artigos desta Tese.

1.5.3 Litogeoquímica

Foram realizadas 51 análises químicas de rocha total em amostras representativas das unidades estratigráficas mapeadas na região do depósito e em amostras de testemunhos de sondagem coletadas.

A preparação e as análises foram realizadas na SGS Geossol Laboratórios Ltda em Belo Horizonte-MG. Foram analisados os óxidos de elementos maiores (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , MnO , Na_2O , K_2O , P_2O_5), com abertura por fusão com metaborato de lítio e determinação por ICP-ES (Induced Coupled Plasma- Emission Spectrometry) e/ou por Fluorescência de Raios-X, e elementos menores, inclusive os Terras Raras (Ba, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Zr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), por fusão com metaborato de lítio e determinação por ICP-MS (Induced Coupled Plasma – Mass Spectrometry). Os elementos Mo, Cu, Pb, Zn, Ni, As, Cd, Sb, Bi, Au, Ag, Hg, Tl e Se tiveram abertura realizada por diluição com água régia e a dosagem por ICP-MS. O tratamento dos dados foi realizado no programa Geochemical Data Toolkit (GCDkit) (Janousek *et al.* 2006).

1.5.4 Petrografia (Microscópio convencional e MEV)

A partir da descrição macroscópica dos testemunhos de sondagem e amostras coletadas durante etapa de campo, foram selecionadas amostras para confecção de lâminas polidas para o estudo petrográfico sob a luz transmitida e refletida.

As descrições microscópicas de 270 lâminas foram realizadas no Laboratório de Petrografia e Microanálises da CPRM em Brasília, e considerou as relações entre os minerais, como textura e limites entre os cristais, proporções de cada um deles, além dos processos de alteração presentes.

Quando necessário, para dirimir dúvidas em relação aos minerais presentes, as lâminas foram analisadas também sob Microscópio Eletrônico de Varredura (MEV) nos Laboratórios do IG-UFGA, CPRM (Belém e Brasília). O uso das imagens de elétrons retroespalhados (BSE- *back scattered electrons*) e análises de EDS (*Energy Dispersive X-ray Spectrometer*) foram importantes para a descrição das texturas e estimativa de composição dos minerais da paragênese sulfetada.

1.5.5 Química mineral

As análises químicas para determinação de composição de minerais do minério e da alteração hidrotermal foram realizadas no Laboratório de Microsonda Eletrônica, da Universidade de Brasília, por meio de convênio com a CPRM. Este laboratório está equipado com Microsonda Eletrônica da marca JEOL, e os padrões utilizados para calibração são substâncias sintéticas e naturais fornecidas pelo fabricante.

1.5.6 Inclusões fluidas

Para o estudo de inclusões fluidas foram confeccionadas 36 lâminas bipolidas no laboratório de laminação da CPRM em Belém. Entretanto, destas somente 10 apresentaram inclusões fluidas satisfatórias que permitissem a aquisição de dados termométricos. A petrografia e a aquisição de dados termométricos foram realizadas no Laboratório de Microanálises da CPRM em Brasília, que está equipado com platina de aquecimento e resfriamento Linkan THMSG 600 acoplada em microscópio petrográfico Olympus BX-51. A calibração da platina é realizada utilizando padrão sintético CSCO2 fornecido pelo fabricante.

1.5.7 Isótopos radiogênicos

U-Pb

Nesta pesquisa, a separação de concentrados de zircão foi realizada nos laboratórios de preparação de amostras da CPRM. Em todos os casos a amostra foi reduzida via britador e extraída a fração inferior a 500 μm . A partir do material recolhido os minerais pesados foram concentrados com o processo de deslame e bateamento. Após esta primeira etapa o concentrado foi passado pelo separador isodinâmico Frantz e finalmente o zircão foi separado manualmente em lupa binocular. As seções foram confeccionadas com resina epóxi (a frio), desgastadas e polidas para exposição do interior dos grãos. Todas as amostras foram imageadas em MEV por elétrons retroespalhados e/ou catodoluminescência com o objetivo de mostrar a estrutura interna dos cristais de zircão (identificar a presença de zonações e bordas, inclusões, fraturas, alterações, corrosão etc...). Para a limpeza das seções polidas foi utilizado banho com ácido nítrico diluído (3%), seguido de água Nanopure® em ultrassom e por último em acetona para extração de qualquer resíduo de umidade.

As análises isotópicas foram realizadas em dois laboratórios. Análises de quatro amostras foram executadas pelo Laboratório de Geocronologia da UnB, por LA-ICP-MS (U-Pb e Lu-Hf) e duas amostras (U-Pb) no Laboratório de Geocronologia da Universidade Federal do Pará (Pará-Iso) e ambos seguiram o procedimento apresentado por Buhn *et al* (2009), usando o equipamento LAM-MC-ICP-MS Neptune (Thermo-Finnigan) acoplado ao Nd-YAG ($\lambda=213\text{nm}$) Laser Ablation System (New Wave Research, USA).

A redução dos dados brutos, que inclui as correções para branco, deriva do equipamento e chumbo comum, foram realizadas em planilha EXCEL, confeccionada no próprio laboratório. As incertezas associadas às razões apresentadas nas tabelas são de 1σ , em porcentagem. As idades foram calculadas utilizando o programa ISOPLOT 3.0 (Ludwig 2003).

A ablação dos grãos é realizada em pontos (spots) com 25-30 μm de diâmetro, com frequência de 10 Hz e intensidade de 0.19 a 1.02 J/cm². O material pulverizado foi carregado por um fluxo de He (~0.40 L/min) e Ar (~0.90 L/min). Em todas as análises utiliza-se o padrão internacional GJ-1 para a correção da deriva do equipamento, assim como o fracionamento entre os isótopos de U e Pb. Para a verificação da acurácia foram realizadas análises no padrão interno PAD-1. Os dados são adquiridos em 40 ciclos de 1 segundo. O procedimento de coleta de dados segue a sequência de leitura: - 1 branco, 1 padrão, 4

amostras (ou 8 amostras, quando o equipamento se apresenta estável), 1 branco e 1 padrão. Em cada leitura são determinadas as intensidades das massas ^{202}Hg , $^{204}(\text{Pb}+\text{Hg})$, ^{206}Pb , ^{207}Pb , ^{208}Pb e ^{238}U .

Lu-Hf

As análises de Lu-Hf em zircão foram realizadas na Universidade de Brasília e seguiram o procedimento descrito por Matteini *et al.* (2010). Os dados de isótopos são coletados durante ciclos de ablação de 40 segundos, usando um diâmetro de ponto de 40 μm , e ocorre a determinação da relação entre os isótopos com as massas 171, 173, 175, 176, 177, 178, 179 e 180. As medições foram feitas próximo ao ponto de ablação a laser anterior deixado pelas análises de U-Pb, com o objetivo de amostrar a mesma porção do grão de zircão.

As razões isotópicas medidas são processadas off-line, a fim de escolher apenas as porções homogêneas de um grão de zircão analisado. Para remover interferências isobáricas de ^{176}Yb e ^{176}Lu na massa ^{176}Hf , os isótopos isentos de interferências ^{171}Yb , ^{173}Yb e ^{175}Lu foram monitorados durante as análises. Para corrigir o fracionamento de viés de massa, os ^{176}Lu e ^{176}Yb foram calculados usando um fator de normalização de $^{176}\text{Yb}/^{173}\text{Yb}$ de 0,796218 (Chu *et al.* 2002), enquanto as razões de isótopos de Hf foram normalizadas para um fator $^{179}\text{Hf}/^{177}\text{Hf}$ de 0,7359 (Chu *et al.* 2002). A redução e os cálculos dos dados foram realizados em uma planilha EXCEL® de Milhomem Neto *et al.* (2017). Os valores de ϵHf (t) foram calculados usando a constante de decaimento $\lambda = 1,865 \cdot 10^{-11}$, proposta por Scherer *et al.* (2001) e valores de $^{176}\text{Lu}/^{177}\text{Hf}$ e $^{176}\text{Hf}/^{177}\text{Hf}$ CHUR de 0,0336 e 0,282785 (Bouvier *et al.* 2008). As idades do modelo de Hf do manto empobrecido em duas etapas (TDM Hf) são calculadas usando $^{176}\text{Lu}/^{177}\text{Hf} = 0,0384$ e $^{176}\text{Hf}/^{177}\text{Hf} = 0,28325$ para o manto empobrecido (Chauvel & Blichert-Toft 2001) e valor de $^{176}\text{Lu}/^{177}\text{Hf}$ de 0,0113 para a crosta média (Taylor & McLennan 1985, Wedepohl 1995).

Sm-Nd

As análises isotópicas de Sm-Nd em rocha total foram executadas no Laboratório de Geocronologia da Universidade de Brasília, por meio de convênio com a CPRM, que segue o método descrito por Gioia & Pimentel (2000), com modificações.

Neste procedimento cerca de 50 mg de amostra pulverizada é misturada a uma solução traçadora de ^{149}Sm e ^{150}Nd . A amostra é dissolvida em cápsulas Savillex® por meio de sucessivos ataques ácidos em HF, HNO_3 e HCl. Os conteúdos de Sm e Nd são extraídos através de colunas de trocas catiônicas, confeccionadas em Teflon e preenchidas com resina LN-Spec. Os sais de Sm e Nd são depositados em filamentos de rênio com ácido nítrico e evaporados. As leituras das razões foram realizadas no espectrômetro de massas multicoletor, modelo Finnigan MAT 262 em modo estático. As incertezas para as razões de Sm/Nd e $^{143}\text{Nd}/^{144}\text{Nd}$ são inferiores a $\pm 0.5\%$ (2σ) e $\pm 0.005\%$ (2σ), respectivamente, baseados em repetidas análises nos padrões internacionais BHVO-1 e BCR-1. A razão $^{143}\text{Nd}/^{144}\text{Nd}$ foi normalizada em função da razão $^{146}\text{Nd}/^{144}\text{Nd}$ de 0,7219. Os valores de TDM foram calculados usando o modelo de De Paolo (1981).

1.5.8 Isótopos estáveis

Isótopos O e H

Para a determinação dos isótopos de foram realizadas análises no Laboratório de Isótopos Estáveis (LABISE) da Universidade Federal de Pernambuco (UFPE), Recife, em 10 amostras de grãos de quartzo de veios do depósito Coringa; e também no Laboratório de Isótopos Estáveis da Universidade de Cape Town (UCT), na África do Sul onde foram analisadas 11 amostras de quartzo e 2 de muscovita. O laboratório da UFPE é equipado com espectrômetro de massa Thermo Finnigan Delta V Advantage, enquanto na UCT é o espectrômetro Finnigan Delta XP. Ambos os laboratórios usam metodologias analíticas semelhantes e por método de fluorinação (Clayton & Mayeda 1963, Harris & Vogeli 2010). Consequentemente, o oxigênio é liberado por reação com BrF_5 usando o laser de CO_2 como fonte de calor e convertido em CO_2 por reação com grafite a 750°C .

Dados de isótopos de hidrogênio também foram produzidos na UCT, usando a metodologia de Vennemann & O'Neil (1993), com uma redução do "*Low-blank Indiana Zinc*" (Schimmelmann & DeNiro 1993). Os padrões internos de água CTMP2010 (Cape Millipore Water 2010, $D = -7,4\text{‰}$) e RMW (*Rocky Mountain Water*, $D = -131,4\text{‰}$) foram usados para converter dados brutos na escala *Standard Average Ocean Ocean* (SMOW).

Isótpos de S

Dados de isótopos de enxofre foram obtidos para galena e pirita de um total de dezoito amostras. As análises foram realizadas no Laboratório de Isótopos Estáveis da Universidade de Brasília, por meio de convênio com a CPRM. Para análise de enxofre, o SO₂ é produzido por combustão de cerca de 0,5 mg de amostra, que é carregado em cápsulas de estanho e reagindo a 1080 °C. Os gases queimados foram transportados em corrente e reduzidos pelo contato com fios de cobre de alta pureza, e o SO₂ foi separado por cromatografia em fase gasosa. As análises foram realizadas pelo EA-IRMS (Análise Elementar e Espectrometria de Massa com Razão Isotópica) usando um Analisador de Elemento Flash e um espectrômetro de massa ThermoFisher MAT 253.

Isótopos de C

Três amostras de carbonato foram analisadas para isótopos de carbono e oxigênio no Laboratório de Isótopos Estáveis da Universidade de São Paulo. Os resultados foram obtidos usando um espectrômetro de massa de razão isotópica Delta V Advantage, acoplado a um equipamento Thermo Finnigan Gas-Bench II e um amostrador automático GC-PAL por análise CT. Este equipamento mede as relações isotópicas de carbono e oxigênio com a extração inicial de CO₂ por reação com 100% de ácido fosfórico (H₃PO₄) a 72°C. Após a extração, o gás é analisado no espectrômetro de massa calibrado de acordo com os padrões internacionais e a partir de referências internas do laboratório.

1.6 CONTEXTO GEOLÓGICO REGIONAL

1.6.1 Província Mineral Tapajós (ou domínio Tapajós)

Nos últimos anos houve avanços acerca do conhecimento sobre a evolução do Cráton Amazônico, com novas propostas de compartimentação tectônica com base em dados isotópicos e geocronológicos. Inicialmente a região central do cráton Amazônico foi denominada como Província Amazônia Central, e consistia de rochas com idades > 2,1 Ga (Cordani *et al.* 1979). Posteriormente, foi individualizado um núcleo mais antigo de idade > 2,3 Ga na porção oriental do cráton, margeado por faixas móveis sucessivamente mais jovens em direção ao sudoeste do cráton (Teixeira *et al.* 1989).

No segmento mais ocidental desta parte central foi definida uma faixa paleoproterozoica (1,96-1,80 Ga), a Província Ventuari-Tapajós, com evolução relacionada à

acresção de um arco magmático na borda do cráton arqueano (Tassinari 1996). Os dados isotópicos de Nd das rochas deste segmento marcavam uma fonte predominantemente mantélica acrescida há cerca de 2,2 Ga na margem de crosta arqueana de 2,5 a 3,1 Ga (Sato & Tassinari 1997). Com base em idades de 2,01 a 1,87 Ga por geocronologia em zircão, e alguns dados Sm-Nd, obtidos para as rochas da região do Tapajós, bem como para rochas de outras regiões, foram individualizados domínios para a Província Tapajós-Parima (Santos *et al.* 2004).

Além de uma redefinição dos limites e denominação da província geocronológica, houve uma proposta de evolução envolvendo a acresção de sucessivos arcos magmáticos (Cuiú-Cuiú, Jamanxim, Creporizão, Tropas e Parauari), seguidos de um magmatismo alcalino (tipo A) pós-orogênico marcado pelos granitos da Suíte Intrusiva Maloquinha (Santos *et al.* 2000).

Contrariando o modelo de sucessivos arcos magmáticos, Vasquez *et al.* (2017) propõem colisão de apenas um arco precoce, o Arco Cuiú-Cuiú (2,03-2,05 Ga), sucedida por eventos magmáticos pós-colisionais transcorrentes de 2,0-1,96 Ga e extensionais de 1,89-1,87 Ga (**Fig. 1.1**). Propostas recentes sugerem que os eventos vulcano-plutônicos de 1,90 a 1,87 Ga de composição ácida a intermediária, conhecidos como Uatumã, estão relacionados a uma pluma mantélica e riftes continentais, característicos de *Silicic Large Igneous Province* – SLIP (Klein *et al.* 2012).

Os modelos acrescionários para a evolução da Província estipulam uma subducção de litosfera oceânica de sudoeste para nordeste com amalgamação, ou acresção de um ou mais arcos magmáticos orosirianos a um continente com núcleos arqueanos a leste, retrabalhados ou margeados por arcos magmáticos do Riachão (Cordani & Teixeira 2007, Santos *et al.* 2000).

Estes modelos foram baseados na assinatura juvenil paleoproterozoica, ou de fraca contribuição de crosta mais antiga, das rochas formadas entre 2,03 e 1,88 Ga na porção oeste da província, e ao aumento das fontes crustais arqueana para leste no cráton em direção ao núcleo arqueano de Carajás. No modelo de sucessivos arcos, teria ocorrido a acresção de dois arcos insulares (Cuiú-Cuiú e Tropas) (Santos *et al.* 2000, 2004).

Alguns autores contrariam a orientação da subducção e propõem que a litosfera oceânica subductou de sul para norte sob a margem do continente arqueano, com a formação de dois arcos magmáticos continentais orientados segundo a direção E-W (Fernandes *et al.* 2011, Juliani *et al.* 2013). Além disso, a progressiva migração da litosfera oceânica subductada para posição horizontal (*flat-subduction*) à medida que adentrou sob a litosfera

continental há cerca de 1,88 Ga formou magmas cálcio-alcálico de alto K e shoshonítico distantes da fossa oceânica, e desencadeou um processo de fusão crustal que gerou magmas félsicos tipo A contemporâneos (Fernandes *et al.* 2011).

Recentemente, alguns trabalhos veem questionando os limites entre as províncias no cráton Amazônico e argumentam necessidade de revisão, ao passo que apresentam o conceito de domínios, e agrupam unidades com similar história evolutiva para que o entendimento do contexto geológico seja realizado de forma integrada (Fraga *et al.* 2017, Klein *et al.* 2017, Kroonenberg *et al.* 2016).

O Domínio Tapajós (DT), considerado sinônimo de Província Mineral Tapajós, é o maior segmento da Província Tapajós-Parima, e sua orientação segundo a direção NW-SE reflete as principais falhas e zonas de cisalhamento transcorrentes que controlaram o posicionamento da maioria das intrusões e extrusões ígneas na metade meridional do domínio (**Figs. 1.1, 1.3**). Na metade norte se destacam as estruturas de direção E-W, elas controlaram o posicionamento de diversos corpos ígneos e bacias sedimentares paleoproterozoicas.

No Domínio Tapajós as associações de embasamento são representadas pelas rochas supracrustais do Grupo Jacareacanga e os granitoides e ortognaisses do Complexo Cuiú-Cuiú. As rochas metavulcanossedimentares do Grupo Jacareacanga sofreram metamorfismo de fácies xistos verdes a epidoto anfíbolito (Vasquez *et al.* 2017).

O Complexo Cuiú-Cuiú é composto por ortognaisses tonalíticos e granodioríticos bandados e porfiroclásticos, com subordinados termos monzograníticos, quartzo dioríticos, quartzo monzodioríticos e dioríticos. Os granodioritos a dioritos são de afinidade cálcio-alcálica relacionada a arcos magmáticos pouco evoluídos associados à subducção de litosfera oceânica, possivelmente em ambiente de arco de ilha (Santos *et al.* 2004, Vasquez *et al.* 2002).

Os eventos magmáticos do Orosiriano que sucederam o magmatismo do Arco Cuiú-Cuiú se concentraram nas porções central, sudeste e leste do DT (**Fig. 1.3**). Na parte leste do domínio, Lamarão *et al.* (2002) individualizaram a Formação Vila Riozinho, que são rochas vulcânicas que cristalizaram por volta de 2000 Ma, com uma assinatura cálcio-alcálica de alto K a shoshonítica, similar à de arcos magmáticos maduros. Estes autores ainda mapearam um plúton de monzogranitos, o Granito São Jorge Antigo, que corta as rochas da Formação Vila Riozinho. Estes granitos de afinidade cálcio-alcálica de alto K cristalizaram entre 1983 e 1981 Ma.

No sudeste e centro-sul do domínio ocorrem principalmente os granitoides da Suíte Intrusiva Creporizão (SIC), que são afetados por deformação dúctil fraca a moderada relacionada às zonas de cisalhamento de direção NW-SE, enquanto nas demais porções as rochas sofreram principalmente deformação rúptil. Santos *et al.* (2004) interpretam os granitos da SIC como relacionados a um arco magmático posterior a Arco Cuiú-cuiú.

A Suíte Intrusiva Tropas abrange tonalitos, quartzo dioritos, granodioritos, andesitos e basaltos (Santos *et al.* 2004) de idades de 1907 a 1892 Ma, apresentam assinatura cálcio-alcalina de arco de ilha e a assim representam o Arco Mágmatco Tropas, que é considerada como evento magmático anterior aos eventos de 1.88 Ga (Parauari, Ingarana, Maloquinha) e posterior aos de 1.98 Ga (Creporizão).

As rochas sedimentares das formações Abacaxis e Sequeiro, de idades em torno de 1.9 Ga, são consideradas remanescentes ds bacias associadas ao Arco Tropas (Santos *et al.* 2004).

O vulcanismo paleoproterozoico no DT é bastante expressivo, e é representado pelas rochas do Grupo Iriri, que conta com quatro formações. A Formação Salustiano compreende rochas vulcânicas essencialmente ácidas (riolitos a dacitos) de derrame; a Formação Aruri é composta por rochas piroclásticas ácidas e epiclásticas (Pessoa *et al.* 1977); a Formação Bom Jardim com andesitos, basaltos, latitos, traquitos e dacitos cálcio-alcalinos de alto K a shoshonítico (Almeida *et al.* 2000); e a Formação Moraes Almeida que abriga ignimbritos e riolitos de afinidade alcalina (tipo A) (Lamarão *et al.* 2002).

A Suíte Intrusiva Parauari (SIP) (1883-1879 Ma) é representada por corpos de granodioritos, com monzogranitos e sienogranitos associados. Estas rochas têm filiação cálcio-alcalina relacionadas a arcos magmáticos maduros (Santos *et al.* 2004). Entretanto, Vasquez *et al.* (2002) propuseram que estes granitoides podem representar um magmatismo cálcio-alcalino de alto K de ambiente extensional pós-colisional.

Contemporânea a SIP, existe a Suíte Intrusiva Ingarana que corresponde a corpos máficos e intermediários (gabros, gabronoritos, diabásios, monzodioritos etc.) na porção oeste e central do DT que, também apresenta similaridade geoquímica (Vasquez & Dreher 2011).

Os granitos da Suíte Intrusiva Maloquinha (1882-1864 Ma) ocorrem por todo DT, geralmente com orientação NW-SE a N-S. Compreendem sienogranitos e feldspatos alcalino granitos, com subordinados monzogranitos e quartzo sienitos, com assinatura geoquímica de rochas ácidas alcalinas (tipo A) típicas de ambiente extensional intracontinental (Lamarão *et*

al. 2002, Vasquez *et al.* 2002). Estes autores ainda observam a contemporaneidade desta unidade com as suítes intrusivas Parauari e Ingarana.

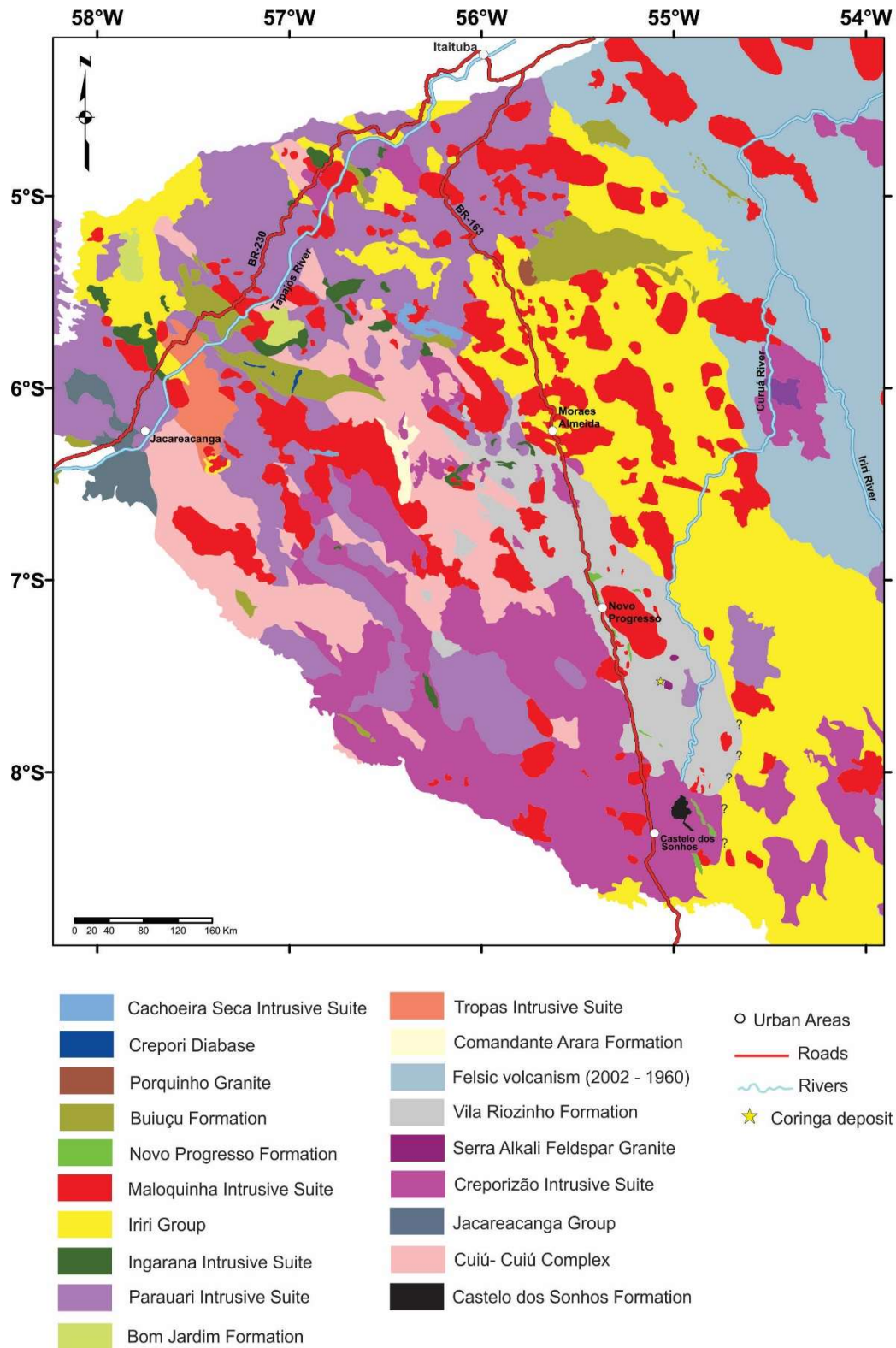


Fig. 1.3 - Mapa geológico da Província Mineral Tapajós. Fonte: modificado de Guimarães *et al.* (2019) e Vasquez *et al.* (2017).

Um plúton definido com Granito Porquinho (Prazeres *et al.* 1979), com biotita granitos e feldspato alcalino granitos, localmente com riebeckita, que hospedam mineralização de Sn, Nb e Ta, apresentou idade de cristalização de 1786 Ma. Ou seja, representa magmatismo tipo A cerca de 100 Ma mais jovem que o da Suíte Intrusiva Maloquinha, possivelmente relacionado ao magmatismo Teles Pires que ocorre mais a sul Santos *et al.* (2004).

O evento magmático mais jovem registrado no DT são os diques de diabásio orientados nas direções E-W e NE-SW, correlacionados ao período Jurássico, são o registro de magmatismo toleítico do evento penatecaua (Vasquez & Rosa Costa 2008).

As coberturas sedimentares no DT relacionadas a diferentes eventos. A mais antiga é a Formação Castelo dos Sonhos, localizada na parte sudeste, no limite com o Domínio Iriri-Xingu (**Fig. 1.3**). É formada por metaconglomerados auríferos e metarenitos depositados em ambientes fluviais entre 2011 a 2050 (Queiroz *et al.* 2015). Klein *et al.* (2017) observaram que a deposição da Formação Castelo dos Sonhos precede a evolução orogênica do TGP, e a bacia foi interpretada como uma relíquia de um sistema *foreland* maior relacionado ao orógeno transamazônico que ocorre a leste no Cráton amazônico. Por outro lado, as coberturas das formações Novo Progresso e Buiucu tem suas fontes detríticas relacionadas aos eventos vulcânicos do Domínio Tapajós.

Ainda no sudeste do DT, está a Formação Novo Progresso, composta por arenitos arcoseanos e líticos, com níveis conglomeráticos, intercalados com argilitos e siltitos tufáceos. Sua frequente associação com as rochas vulcânicas e piroclásticas da Formação Vila Riozinho, e a contribuição detrítica de material vulcânogênico sugerem tratar de um retrabalhamento sedimentar posterior à erupção. Klein *et al.* (2018) estabeleceram idade máxima de deposição para esta formação de 1840 Ma enquanto as relações estruturais sugerem uma idade mínima de 1780 Ma (Klein *et al.* 2018). Estudos de proveniência indicam que as rochas Orosirianas circundantes dos domínios Tapajós e Iriri-Xingu foram as principais fontes para os sedimentos, com contribuições subordinadas de domínios mais antigos e mais distantes do Craton da Amazônia (Klein *et al.* 2018).

Na porção oeste do DT ocorrem segmentos de bacias orientadas E-W preenchidas por rochas sedimentares reunidas na Formação Buiucu, onde predominam arcóseos líticos e arenitos ortoquartzíticos, siltitos e argilitos (Vasquez *et al.* 2017). A idade máxima de sedimentação definida por Santos *et al.* (2001) é > 1879 Ma para as fontes detríticas da bacia.

Metagênese na PMT

A Província Tapajós foi responsável por uma parcela expressiva do ouro lavrado no Brasil nas décadas de 70 e 80. Estimativas não oficiais sugerem que podem ter sido lavradas mais de 800 t de ouro (Assunção & Klein 2014).

A notável atividade garimpeira nos depósitos auríferos primários filoneanos é registrada há décadas, mas também são registrados na PMT garimpos ativos de cassiterita aluvionar (Ferreira *et al.* 2000, Santos *et al.* 1975), indícios de mineralização de molibdênio (Klein & Vasquez 2000, Pessoa *et al.* 1977) e ocorrências em aluviões de turmalina, topázio, ametista e diamante (Klein *et al.* 2001).

Os dados geológicos atuais demonstram um maior potencial para depósitos orogênicos de ouro na parte sudoeste-oeste do Domínio Tapajós, região de ocorrência das rochas mais antigas, de maior grau metamórfico e mais fortemente afetadas por deformação dúctil, ou com componente dúctil. Além do grau metamórfico e da deformação caracterizados nessa região, deve ser ainda notado que a menor favorabilidade para ocorrência de depósitos orogênicos no restante do Domínio Tapajós deve-se, em grande parte, à cobertura de rochas vulcânicas e sedimentares (Juliani *et al.* 2014).

Entretanto, pode-se inferir movimentações intensas de blocos na província, responsável pela colocação de depósitos epitermais e rochas plutônicas de mesma idade em níveis estratigráficos semelhantes (Juliani *et al.* 2011). Isso sugere que algumas zonas nas quais a erosão da cobertura foi maior, especialmente ao longo do vale das principais drenagens, podem ainda expor depósitos orogênicos.

**2. REASSESSMENT OF THE GEOLOGY OF THE SOUTHEASTERN TAPAJÓS
GOLD PROVINCE, AMAZONIAN CRATON, BRAZIL, BASED ON FIELD,
PETROGRAPHIC, AND AIRBORNE GEOPHYSICAL DATA.**

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Reassessment of the geology of the southeastern Tapajós Gold Province, Amazonian Craton, Brazil, based on field, petrographic, and airborne geophysical data

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Abstract

The Tapajós Gold Province, central portion of the Amazonian Craton, is one of the main metallogenic provinces in Brazil, but lack geological studies at an appropriate scale in its southeastern portion. Fieldwork, petrography, and high-resolution airborne geophysics (magnetometry and gamma spectrometry) allowed us to produce a new map at the 1:100,000 scale. In this study, we identified two new geological units: (1) the volcanic and pyroclastic rocks of the Vila Riozinho Formation, previously attributed to the Iriri Group, including a newly described facies of this formation, which comprises a group of rocks with the highest magnetic contents of the study area, and (2) the Serra Alkali Feldspar Granite, which intruded into the Vila Riozinho Formation. Based on available geochronological information these units can be associated to a volcano-plutonic event that occurred in the Orosirian period, at about 1.98 Ga. In addition, our work allowed us to define better the areas of occurrence of other units. The Parauari Intrusive Suite and Iriri Group areas were strongly reduced, whereas the areas of the Creporizão Intrusive Suite and of the Novo Progresso Formation were increased.

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1. Introduction

The Tapajós Gold Province (TGP), which is basically synonymous of Tapajós Domain (Faraco et al. 1997), is located in the south-central portion of the Amazonian Craton (Fig. 1) and is considered one of the main metallogenic provinces of Brazil. A significant part of the province comprises felsic volcanic and volcanoclastic rocks and granitoids, which formed predominantly in two time intervals, 2.02 to 1.95 Ga and 1.91 to 1.87 Ga and are grouped in several stratigraphic and lithodemic units (Vasquez et al. 2017).

Several issues regarding the TGP are still pending, including the limits with adjacent provinces or domains, the tectonic setting in which formed the volcano-plutonic units and the metallogenic evolution (e.g., Lamarão et al. 2002; Vasquez et al. 2017; Juliani et al. 2013; Tokashiki et al. 2015; Borgo et al. 2017; Fraga et al. 2017; Carneiro et al. 2018; Klein et al. 2012, 2017, 2018).

Another issue is the scarcity of geological maps in suitable scales for certain parts of the TGP, which is the case of its

southeastern sector, where maps are available only at the 1:1,000,000 scale (Fig. 2, Vasquez and Rosa-Costa 2008), and produced by regional integration and satellite image interpretation. A preliminary attempt to improve the cartography of the region was made by Guimarães et al. (2015), using outcrop investigation, little petrographic data, but without the use of geophysical information. In addition, the southern sector of the TGP is growing in importance because of the discovery of paleoplacer and hydrothermal gold deposits (Tokashiki et al. 2015; Queiroz and Klein 2018). Furthermore, the host rocks for the hydrothermal deposits are felsic volcanic and volcanoclastic rocks and granitoids from uncertain stratigraphic units.

Therefore, this paper aims to contribute to the understanding of the geology and stratigraphy of southeastern Tapajós Gold Province, based on field geology and petrography, with the support of new high-resolution airborne geophysics (magnetometry and gamma spectrometry). The results will bear implications for the future discussion of the crustal and metallogenic evolution of the southeastern Tapajós Gold Province.



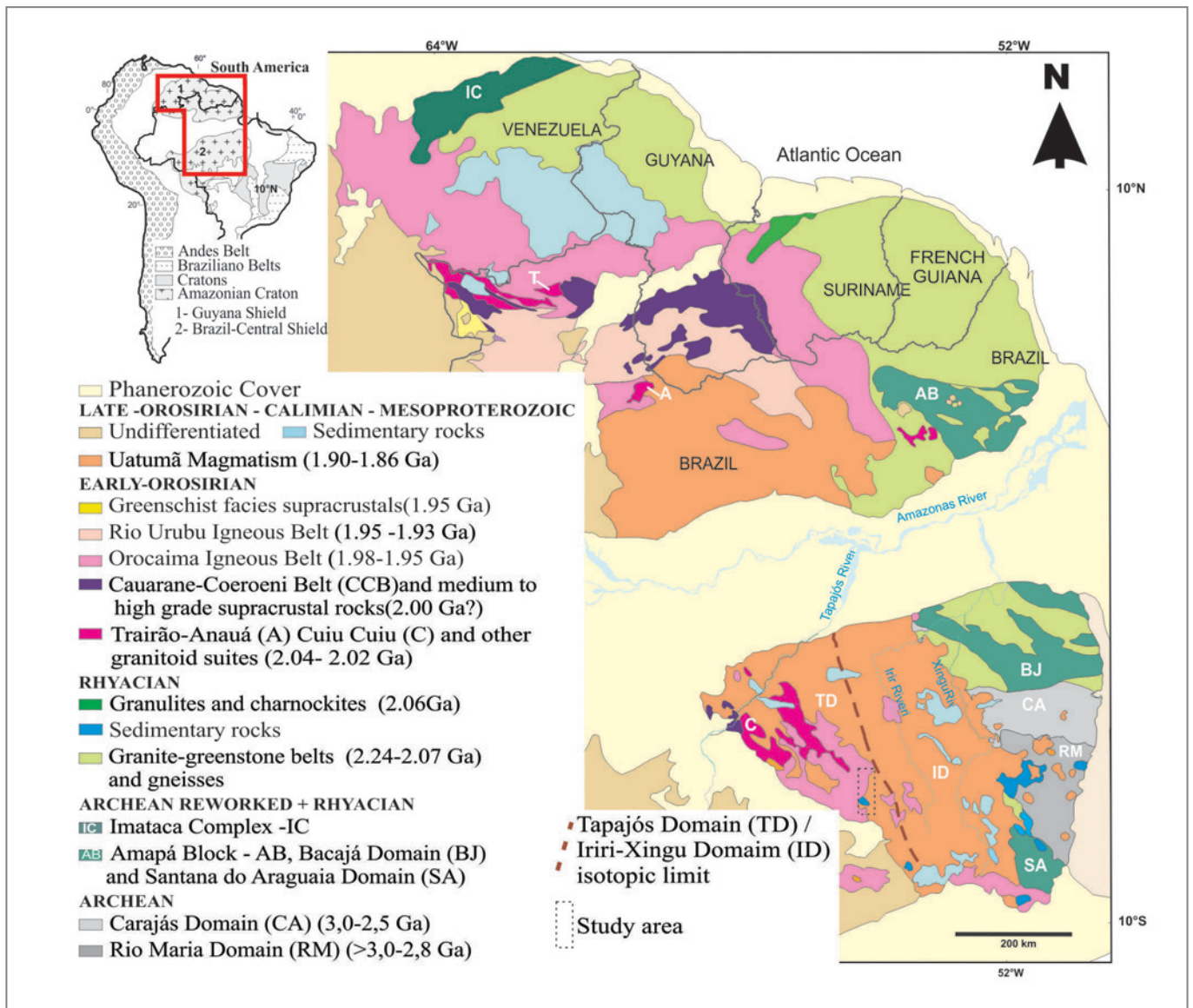


FIGURE 1 – Geological sketch of the Central Brazil Shield (south) and Guiana Shield (north) which form the Amazonian Craton, with location of the study area. Modified from Fraga et al (2017).

2. Geotectonic context

The Amazonian Craton presents heterogeneous lithologic and structural characteristics, which depicts an evolutionary history from the Paleoarchean to the Mesoproterozoic. The craton is part of the South American Platform (Almeida et al. 1981) and includes the Guiana Shield to the north and the Central Brazil Shield to the south, which are separated by Phanerozoic sedimentary basins (Fig. 1).

In the Central Brazil Shield, where the Tapajós Gold Province (or Tapajós Domain) is located, several tectonic/geological domains are recognized (Fig. 1 – Vasquez and Rosa-Costa 2008; Fraga et al. 2017). The oldest sequences of the shield occur to the east, comprising the Archean Carajás and Rio Maria domains, which consist predominantly of granite-greenstone assemblages, intruded by several generations of mafic-ultramafic and granitoid rocks, and covered by volcanic and sedimentary sequences (Santos et al 2000). These domains are limited by the Bacajá Domain, to the north, and by

the Santana do Araguaia Domain, to the south, which include Archean remnants tectonically reworked during the Siderian and Rhyacian periods, along with greenstone sequences and granitoids formed during these periods (Transamazonian cycle). The central portion of the shield is represented by the Iriti-Xingu Domain, which contains mostly Orosirian felsic volcanic and granitoid rocks of the Uatumã SLIP (Silicic Large Igneous Province), and by the Orosirian Tapajós Domain/Tapajós Gold Province (Klein et al 2017, Fraga et al 2017).

The Tapajós Gold Province shows its main structures orientated according to the NW-SE direction (Fig. 3), reflecting the main faults and transcurrent shear zones that controlled the positioning of most igneous intrusions and extrusions in the southern half of the domain (which obviously contrasts with the existence of subduction derived magmatic arcs from south to north). The northern part of the TGP is marked by E-W trending structures, which controlled the positioning of several igneous bodies and Paleoproterozoic (Statherian) sedimentary basins (Klein et al. 2002; Santos and Coutinho 2008).

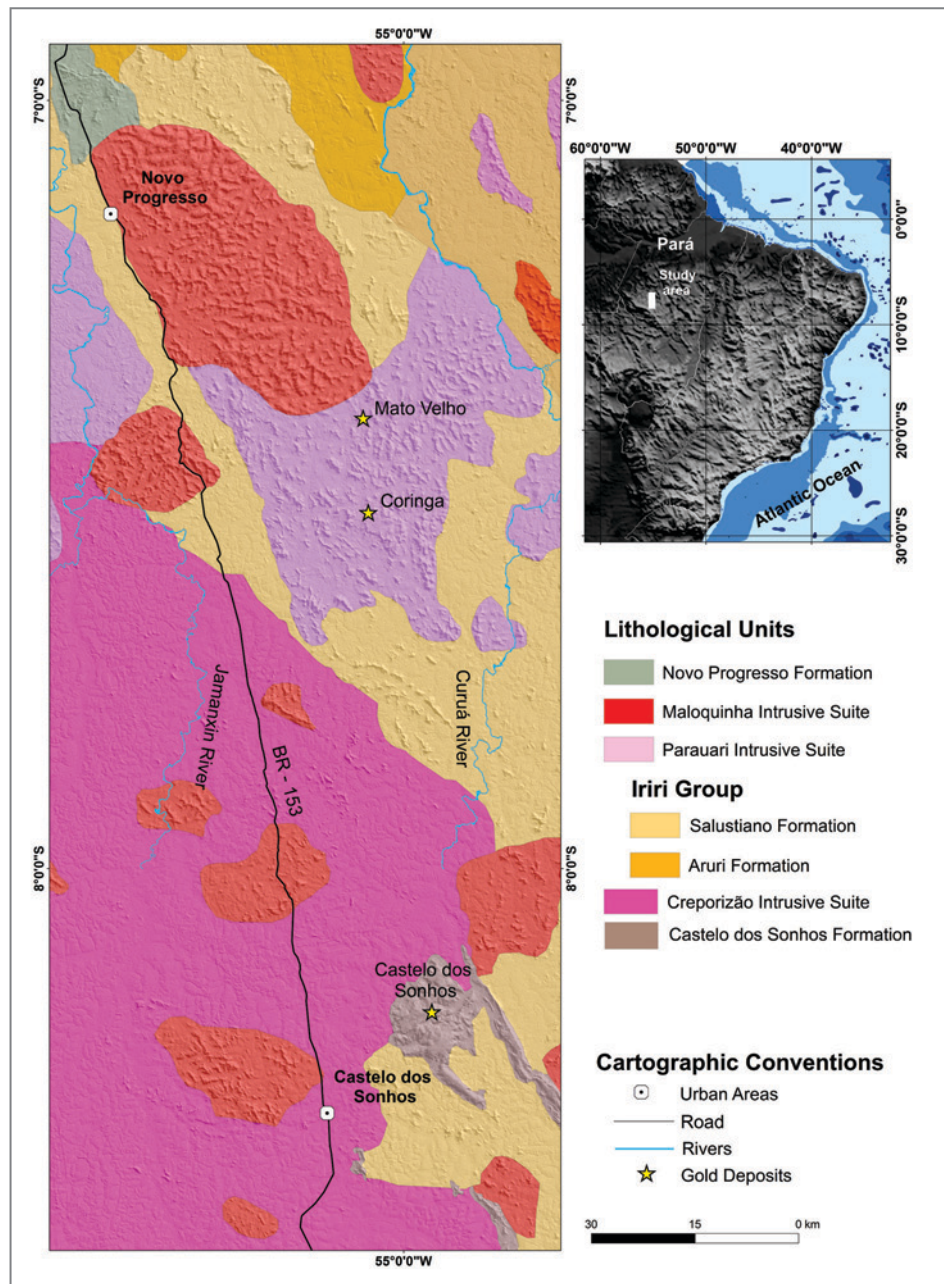


FIGURE 2 – Geological map of Southeast Tapajós Gold Province (modified from Vasquez and Rosa-Costa 2008).

The dominant brittle tectonics of transcurrent and extensional regimes have not modified the stratigraphic stacking of TGP units, which allowed Vasquez et al. (2008, 2017) assemble associations of rocks based on the ages related to each event.

Vasquez et al. (2008, 2017) established that the oldest magmatic event of the Tapajós Gold Province occurred at 2,033-2,005 Ma. This event comprises calc-alkaline rocks, which correspond to the basement represented by granites and orthogneisses from Cuiú-Cuiú Complex, along with the supracrustal rocks of the Jacareacanga Group and volcanic and volcanoclastic rocks of the Comandante Arara Formation (Fig. 2). The rocks of the Cuiú-Cuiú Complex are related to slightly evolved magmatic arc associated to the subduction of oceanic lithosphere, possibly an island arc setting, named Cuiú-Cuiú Arc (Vasquez et al. 2002).

All magmatic events of the Orosirian period, which followed the magmatism of the Cuiú-Cuiú Arc, were concentrated in the central, southeastern and eastern portions of the Tapajós Gold Province. The 2002-1956 Ma event (Orocaima Magmatism) comprises high-K calc-alkaline and shoshonitic magmatism represented by volcanic rocks of the Vila Riozinho Formation, and granitoids of the Creporizão Intrusive Suite (Lamarão et al. 2002; Vasquez et al. 2002; Santos et al. 2004). The transcurrent faults with NW-SE orientation controlled/reoriented the igneous bodies and the formation of the volcano-sedimentary basins related to this event.

After c. 50 Ma, a high-K calc-alkaline magmatism occurred between 1907 and 1864 Ma originated the São Jorge Jovem Granite (Tropas Suite), which was succeeded by the voluminous and widespread high-K calc alkaline magmatic events of the Parauari Intrusive Suite, and basic to intermediate Ingarana

Intrusive Suite (Vasquez et al. 2002, 2017; Santos et al. 2004).

Simultaneously an acidic alkaline magmatism represented by the Maloquinha Intrusive Suite granitoids and its extrusive equivalents of the Moraes Almeida Formation and Iriri Group occurred (Lamarão et al. 2002; Vasquez et al. 2017). The Iriri Group is subdivided into the Salustiano Formation (Andrade et al. 1978), which comprises dominantly acidic volcanic flows (rhyolites to dacites), and the Aruri Formation (Pessoa et al. 1977), composed of pyroclastic and acidic epiclastic rocks.

The youngest magmatic events in the region are diabase dikes correlated to the Jurassic period, a tholeiitic magmatism of the Penatecaua event (Vasquez and Rosa-Costa 2008). These dikes clearly show an aeromagnetometry signature and are oriented according to the E-W and NE-SW directions.

Sedimentary sequences occur in different portions of the domain and in different moments of the geological evolution of the TGP. In the southeast sector, close to the limit with the Iriri-Xingu Domain occur the Castelo dos Sonhos and the Novo Progresso formations. Castelo dos Sonhos Formation is the oldest unit of the TGP, and is composed of auriferous metaconglomerates and metasandstones deposited by fan and fluvial systems between 2011 and 2050 Ma (Queiroz et al. 2015; Klein et al. 2017). Klein et al. (2017) observed that the deposition of the Castelo dos Sonhos Formation precedes the orogenic evolution of the TGP, and the basin was interpreted as a relic of a larger foreland system related to the Transamazonian orogen occurring to the east in the Amazonian Craton. The Novo Progresso Formation is composed of quartz- and lithic-arenites and siltstones with volcanic/volcanoclastic contributions, and was deposited in fluvial and lake systems. The maximum depositional age was established at 1840 Ma, whereas structural relationships suggest a minimum age of 1780 Ma (Klein et al. 2018). Provenance studies indicate that surrounding Orosirian rocks from Tapajós and Iriri-Xingu were the main sources for the sediments, with subordinate contributions from older and more distant domains of the Amazonian Craton (Klein et al. 2018).

In the west TGP occurs segments of sedimentary sequence orientation E-W, filled by sedimentary rocks of the Buiçu Formation. It is composed of lithic arkoses and sandstones, with subordinate polymithic conglomerates, siltstones and argillites. Santos et al. (2001) presented a maximum sedimentation age > 1879 Ma for the detrital sources of this basin. On the other hand, Vasquez et al. (2018) state that it corresponds to a continental, or intra cratonic, rift basin, which succeeded post-orogenic magmatism from 1.88 to 1.86 Ga (Uatumã).

3. Geophysical methods

In addition to classic field and petrographic work, we used two airborne geophysical surveys (Rio Curuá e Cachoeiras do Curuá) for magnetic and radiometric interpretation. These surveys are part of the database of the Geological Survey of Brazil (CPRM), which collected information on N-S flight lines spaced of 500 m. The raw data were interpolated with a 125 x 125 m cell and integrated using the suture method of Johnson et al. (1999). The magnetic interpretation was performed on the vertical derivative of the magnetic anomaly, which highlights the near surface sources (Fig. 3A). This interpretation defined the variation

of magnetization intensity, principal structural directions, shear relations and depth of structures. As such, the study area was divided into units of magnetic rocks (high and medium magnetization), magnetic discontinuities, and dikes (Fig. 3B). This interpretation follows the method of Isles and Rankin (2013). The radiometric data were interpreted in the RGB ternary image of potassium, thorium and uranium on the digital terrain model (Fig. 4).

4. Geophysical interpretation

The magnetic discontinuities follow, in general, the regional structure of the Tapajós Gold Province with preferential NW-SE direction, as well as the NE-SW trending faults, which apparently form a Riedel pair (Fig. 3B). However, corridors of E-W-trending faults intersect the NW-SE trend, which becomes less spaced and more sinuous in the southwest portion of the area, indicating rocks formed at deeper crustal levels. In the central-western portion of the study area, it is possible to interpret sigmoidal forms due to transtensional regime along E-W-trending shear zones. In the central-eastern sector of the area, there is expressive presence of circular magnetic bodies oriented along the N-W trend.

The most striking feature is an anomalous magnetic pattern that occupies an area around 30 x 15 km in the central portion of the study area (Fig. 3A). This pattern corresponds to a set of volcanic rocks with a distinct signature from the others described elsewhere for the Tapajós Gold Province (e.g., Vasquez et al. 2017), which are ascribed to the Vila Riozinho Formation and that are characterized by low magnetization. Besides the high magnetization, the units in the study area present a rugged relief with relatively high concentrations of potassium, thorium and uranium (Figs. 3 and 4).

To the south of the area, NE-SW-trending lineaments with dike signature are observed. However, these lineaments are scarce in comparison with the rest of the Tapajós Gold Province (Fig. 2). Although Teixeira et al. (2018) presented dike swarms between 1.88 and 1.80 Ga associated with the Uatumã SLIP, Vasquez et al. (2017) described diabase dikes with the same orientation and relates to the younger magmatic events correlated to the Jurassic tholeiitic magmatism of the Penatecaua event. As such, we interpret this direction as formed in the Paleoproterozoic, being reactivated until the Phanerozoic.

The RGB ternary image of potassium, thorium and uranium (Fig. 4) shows the radiometric signatures separated along NW-SE trending contacts. There are a series of bodies with granitoid signature placed along the NW-SE direction. Larger bodies show weak changes in the signatures at their edges, which might have been produced by changes in facies or by hydrothermal processes.

5. Proposed lithostratigraphy

The combination of magnetic, radiometric, field data and petrography allowed the consolidation of a new geological map for the southeastern sector of the Tapajós Gold Province drawn originally at the 1:100,000 scale (Fig. 5), greatly improving previous maps (Fig. 2). The stratigraphic units occurring within the study area are described below.

Although the Parauari Intrusive Suite represents an expressive and widespread plutonic event in most of the

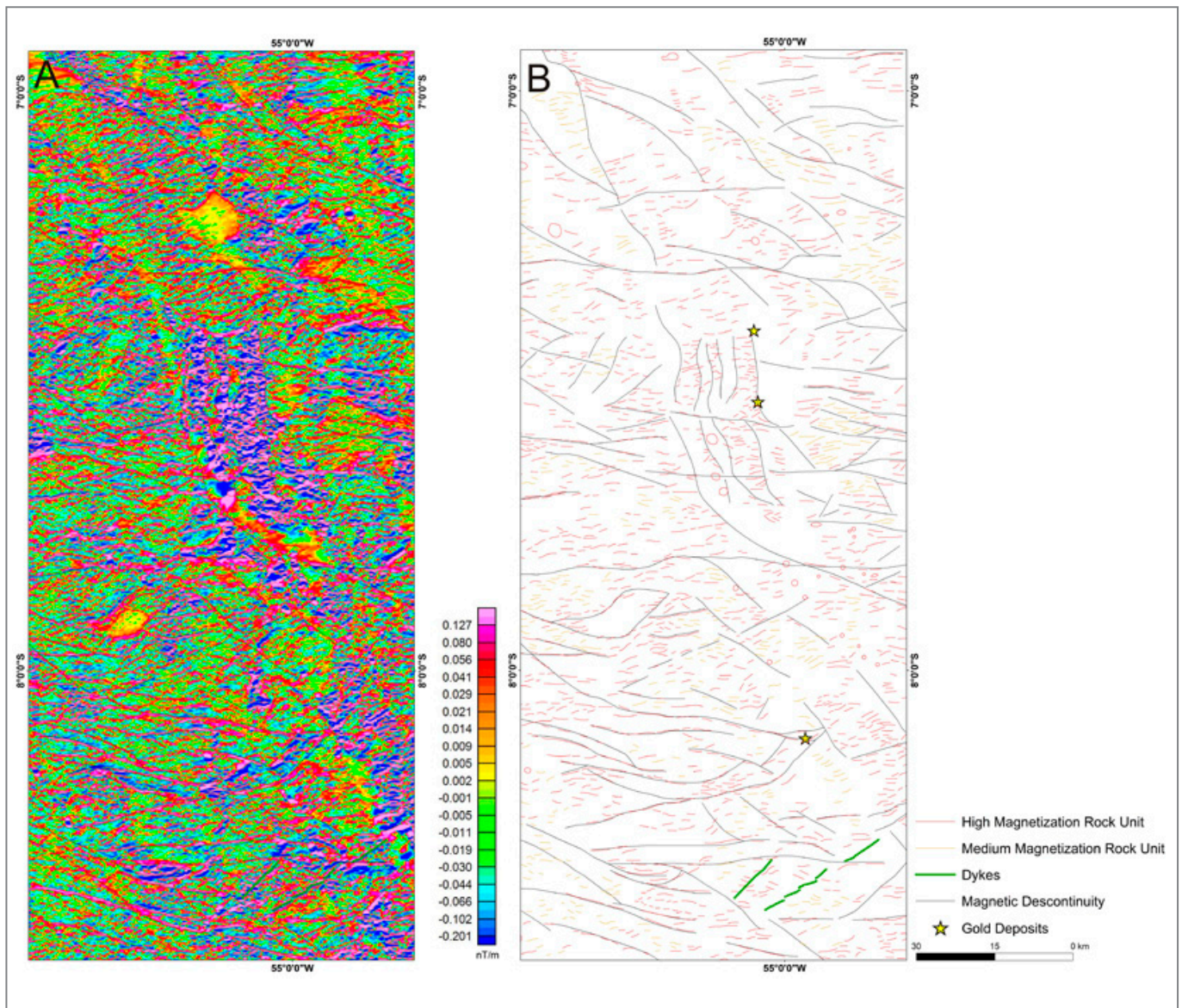


FIGURE 3 – A) Vertical derivative of the magnetic anomaly. B) Structural interpretation

Tapajós Gold Province, it is little represented in the study area. Due to access difficulties in this area, the definition of one body was made only by analogy between the airborne geophysical information (low magnetization, low concentrations of the three radioelements, and isolated portions with high potassium concentrations) and a body with the same shape and size mapped elsewhere by Coutinho (2008). Therefore, no description for this unit is presented in this paper.

The northeastern portion of the studied area coincides with an indigenous reserve region, thus, for geological map modifications, the airborne geophysical information were used and compared with other studied units. In this way, the Iriri Group was maintained in the stratigraphy but not described in this paper either.

5.1. Castelo dos Sonhos Formation

The Castelo dos Sonhos Formation (Yokoi et al. 2001) is a siliciclastic metasedimentary unit located at the boundary between the Tapajós and Iriri-Xingu domains (Fig. 1).

Satellite gravimetric information indicates that the crustal region in which this formation emerges is contiguous with that of the Tapajós Domain (Klein et al. 2017). The formation is composed of metamorphosed conglomerates and sandstones. The geophysical information indicates that the sequence presents high concentration of potassium, intermediate concentration of thorium, low concentration of uranium, and relatively low magnetization (Fig. 3). The low uranium grades are in line with the absence of uranium minerals in the sedimentary package, as reported by Queiroz and Klein (2018).

According to Klein et al. (2017), the metaconglomerates are polymictic and composed predominantly of pebbles of quartz and subordinately of quartzite, tourmalinite, schist and rare metavolcanic rocks (Fig. 6A). In general, the pebbles show rounded to sub-rounded shapes and millimetric to centimetric size. Locally, decametric pebbles may occur. In some portions, the quartz pebbles are stretched and fractured, with these fractures being filled by hematite. The metaconglomerates exhibit grayish color, with reddish and

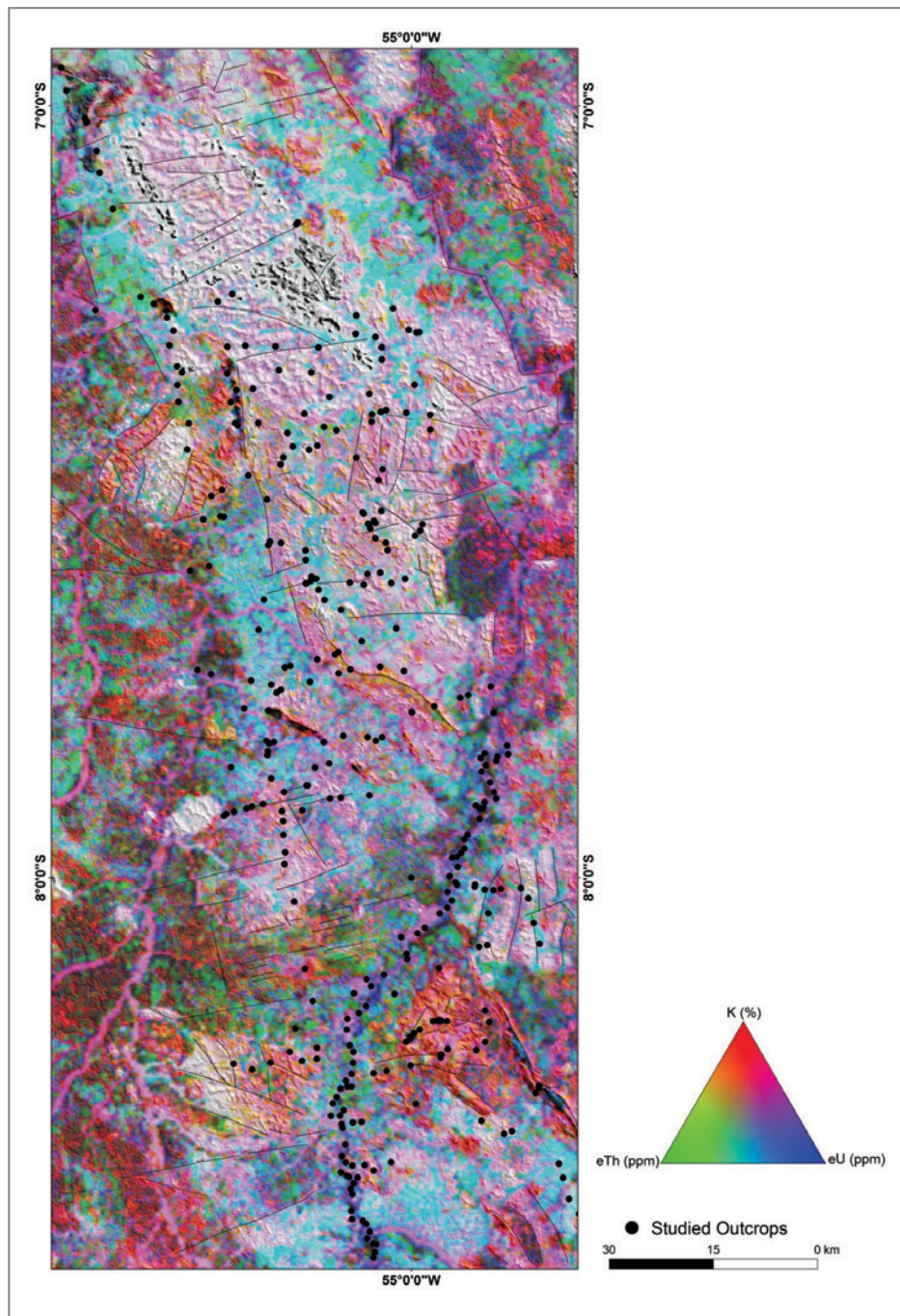


FIGURE 4 – Ternary composition of K, eTh e eU showing the interpreted radiometric domains.

whitish portions according to the presence or absence of hematite impregnation.

The metasandstones present light gray to dark color, with reddish and whitish tones, and are medium- to coarse-grained. They are poorly sorted and composed of quartz and sericite. They present NW-SE bedding (S0) with dip around 12° to SW, or NE-SW cross-bedding with dip around 23° to SE (Fig. 6B). They also present mylonitic foliation. In the southern portion of the area, metasandstones rich in magnetite (ironstones) were also found.

Klein et al. (2017) interpreted the lithological association and the sedimentary structures as evidence of transport in continental environment by interlaced fluvial system, associated

with alluvial fans and wind dunes. The sedimentary basin underwent very low metamorphism and synformal folding, and was intruded by andesites and granitoids between 2011 Ma and 1918 Ma (Queiroz et al. 2015), which constrains the minimum age of sedimentation at 2011 Ma. Using U-Pb geochronology in detrital zircon, Klein et al. (2017) established the maximum age of sedimentation at 2050 Ma, and that the source areas of the sediments would be associated with Rhyacian-Siderian orogenic belts, and Mesoarchean terrains located today in the eastern, southeastern, and northeastern sectors of the Amazonian Craton, including portions of the Guiana Shield (see Fig. 1).

Furthermore, the Castelo dos Sonhos basin was considered a relic of a larger foreland basin, whose basement

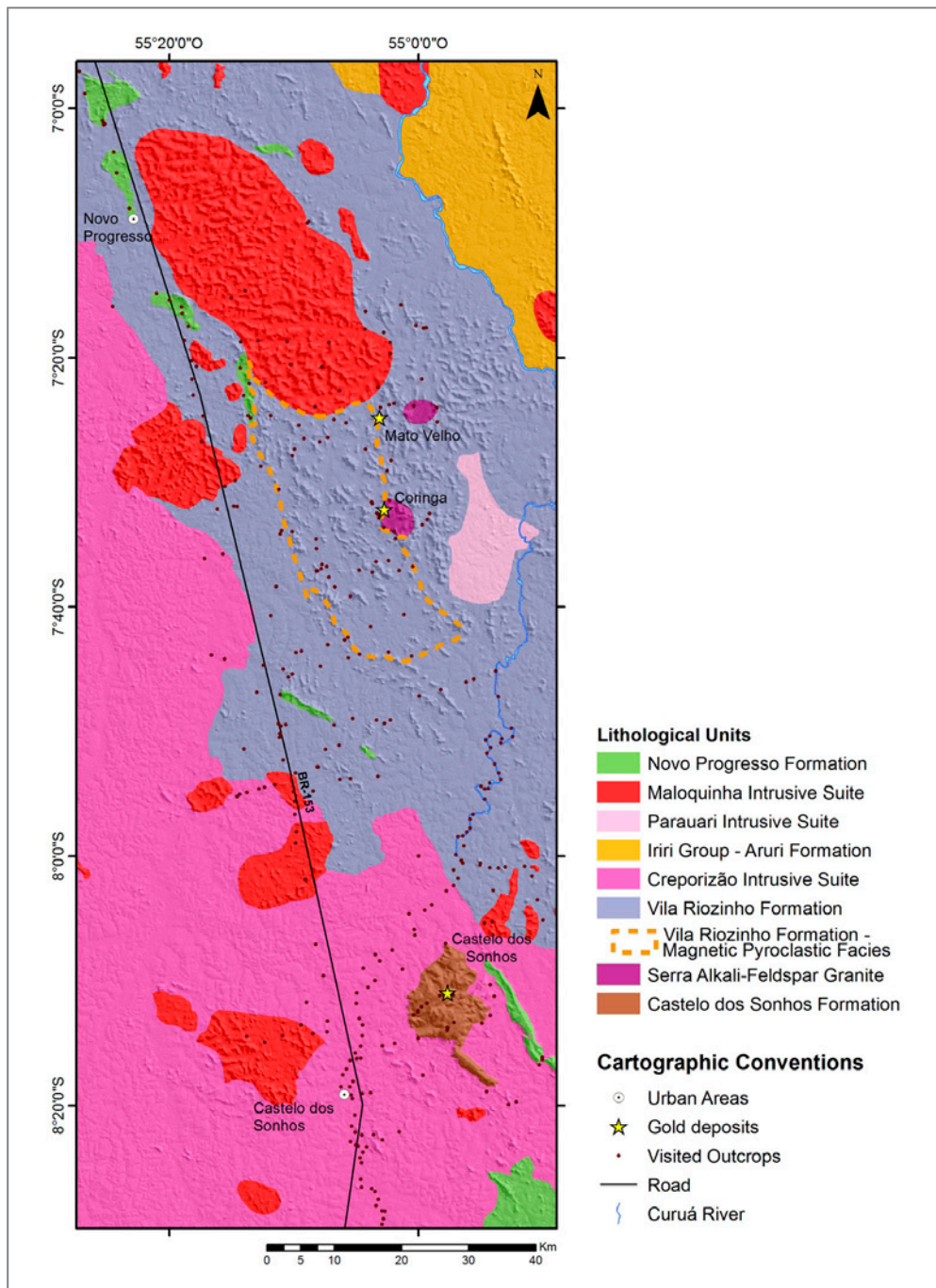


FIGURE 5 – New Geological map of the SE-Tapajós Gold Province.

in the southeast of Tapajós is still unknown, because all the volcanic and granitic rocks of the adjacent areas are younger than the Castelo dos Sonhos Formation.

5.2. Vila Riozinho Formation

Volcanic and pyroclastic rocks form an abundant association in the study area (Fig. 5). In previous works, these sequences have not been mapped and were considered as part of the Parauari Intrusive Suite (Vasquez and Rosa-Costa 2008). Furthermore, Tokashiki et al. (2015) recognized and dated some of the volcanic rocks, but these have not been separated in maps or related to any known stratigraphic unit.

In this work they are correlated to the Vila Riozinho Formation, defined by Lamarão et al. (2002, 2005), increasing the area of occurrence of this formation. From the radiometric point of view, they have relatively higher uranium and thorium concentrations than those presented by the younger Iri Group volcanic rocks.

Rhyolitic ignimbrites, latite, rhyolite, dacite and andesite are the main rock types, which are associated with flattened relief, sometimes cut by granite stocks. In addition, volcanogenic sandstones and conglomerates with rhyolitic ignimbrites were correlated with more rugged relief. This observation corroborates with that of Vasquez et al. (2017) for the same unit to the north.

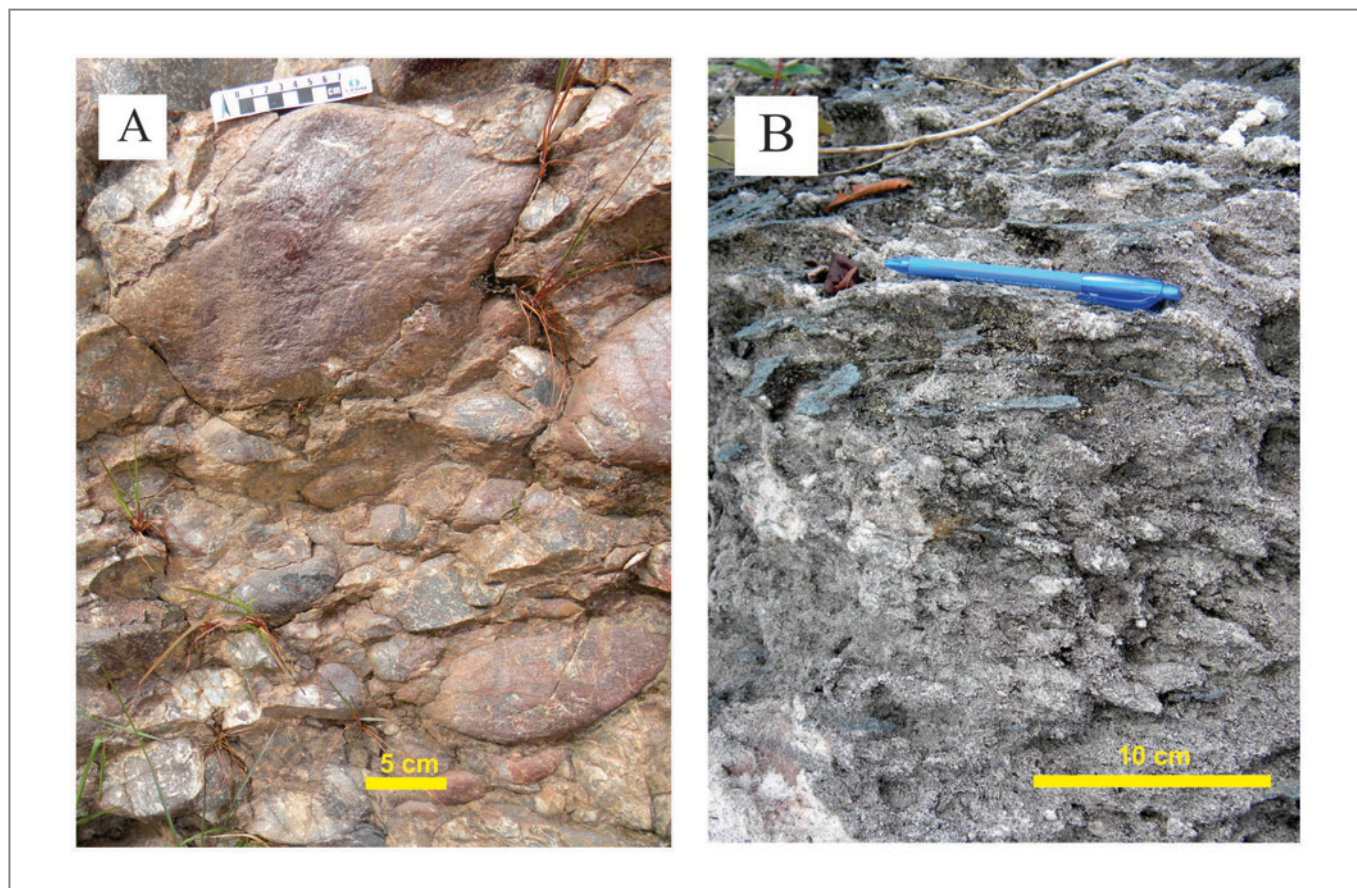


FIGURE 6 – Mesoscopic aspects of rocks of the Castelo dos Sonhos Formation A) Polymictic metaconglomerate with B) Medium-grained gray metasandstone, rich in magnetite, with undulated S0 striking N20W/12SW.

5.2.1. Rhyolitic Ignimbrite

Ignimbrites are abundant and occur as metric blocks, where flow structures are commonly oriented to N25W. These rocks, with a purplish gray matrix, have a reasonable amount of subangular to sub-rounded phenocrysts of quartz, potassium feldspar, plagioclase and lithic fragments (Figs 7A,B,C). Pyrite is commonly found occurring as disseminations and in fractures.

The ignimbrites exhibit preserved diagnostic volcanic structures, such as pumice (devitrified), fiamme, shard, stylolite, and flow structure (Figs 7 D,E,F). The matrix can be glassy, brownish aphanitic with many flow structures, or (in more preserved samples) it can even be microcrystalline to cryptocrystalline and composed of feldspar and quartz, locally having hematite grains that gives a reddish color to the rock. The matrix is strongly sericitized. The accessory minerals in the matrix are apatite, titanite, magnetite, pyrite and chalcopryite (rare), and sericite, chlorite and carbonate are alteration minerals, the latter occurring also as late veins.

The alkali feldspar phenocrysts are subhedral to anhedral, frequently zoned and have perthite texture. The phenocrysts are locally corroded and usually altered to clay minerals and sericite. In some samples, adularia grains (pseudomorph after potassium feldspar) were also observed within the sericitic matrix.

The plagioclase phenocrysts are subhedral, fragmentary, poorly zoned, strongly corroded at the edges and central

portions, and are strongly saussuritized and epidotized. The quartz crystals are subhedral to the anhedral, usually corroded, sometimes skeletal, and fragmentary. Thin lamellae of chlorite have also been identified, as alteration product of mafic minerals.

Two types of veins are observed in some rhyolitic ignimbrite samples. The type 1 is generally composed of quartz, pyrite, chalcopryite, galena and sphalerite (Fig. 7G). Type 2 are quartz-chlorite veins, which are thinner than type 1 veins.

We also found lenticulite, a specific type of welded ignimbrite, with 75% glassy matrix, shards and many flow structures, and 25% of phenocrysts of quartz, potassium feldspar, plagioclase, which are 1 mm to 1 cm in size.

5.2.2. Latite

The latite shows brownish glassy matrix and many flow structures surrounding the potassium feldspar (48%) and plagioclase (40%) phenocrysts, which are euhedral, of various sizes, completely saussuritized and partially chloritized and epidotized (Fig. 7H). Rounded olivine grains occur widely among feldspars and is locally chloritized, having magnetite and chalcopryite inclusions. Less frequent and smaller, quartz grains occur in the interstices of plagioclase grains. Elongated chlorite lamellae with bluish interference color occur disseminated, probably as an alteration product of biotite.

5.2.3. Rhyolite

The rhyolite is porphyritic, with alkali feldspar, plagioclase, and rare amphibole phenocrysts set in a very fine matrix. Large crystals of hematite and pyrite are found disseminated (Fig. 7I). The matrix is quartz-feldspathic with sericitic alteration. Fine grains of hematite, alkali feldspar, zircon, apatite and titanite are disseminated in this matrix.

The phenocrysts of alkali feldspar are strongly altered to clay minerals, fractured (fractures filled by chlorite, sericite and magnetite) and epidotized. Some crystals are replaced by carbonates. The phenocrysts of plagioclase are locally fractured and almost completely sericitized. There were possible amphibole phenocrysts, which were completely pseudomorphosed by a mixture of chlorite, magnetite and titanite. Cavities in the rhyolite are filled with carbonate and sericite.

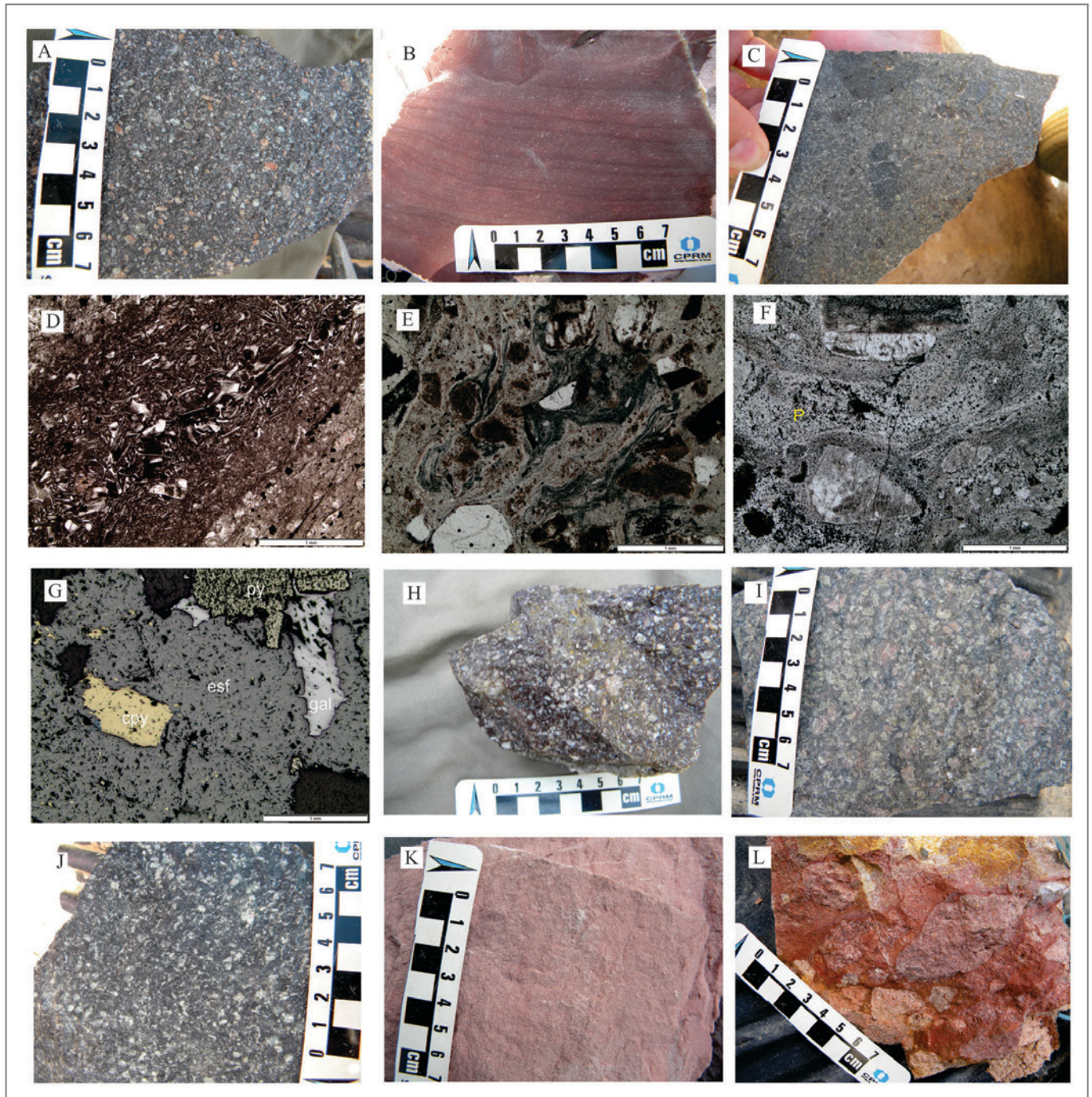


FIGURE 7 – A) Mesoscopic and microscopic aspects of rocks of the Vila Riozinho Formation. A) Ignimbritic rhyolite sample with phenocrysts of quartz, potassium feldspar, plagioclase and gray matrix; B) Reddish rhyolitic ignimbrite due to hematite alteration, with flow structures; C) Rhyolitic ignimbrite with gray matrix and lithic fragments; D) Photomicrograph of rhyolitic ignimbrite showing shards (cusp forms); E) Ignimbrite showing flow texture between phenocrysts; F) Ignimbrite with devitrified pumice (P) and flow structure; G) Photomicrography of type 1 quartz vein with pyrite (py), chalcopyrite (cpy), sphalerite (sph) and galena (gal); H) Latite showing phenocrysts of potassium feldspar and plagioclase; I) Porphyritic rhyolite with phenocrysts of quartz, potassium feldspar, plagioclase ; J) Fine grained andesite with plagioclase phenocrysts; K) Fine pinkish-colored sandstone; L) Volcanic conglomerate with reddish matrix and angular lithoclasts.

5.2.4. *Dacite*

The dacite shows porphyritic texture, thin to aphanitic gray matrix with cryptocrystalline to microcrystalline quartz, and phenocrysts of potassium feldspar, plagioclase and quartz, rare olivine crystal are present. Devitrified elongated pumices and magnetite grains have also been observed as disseminations.

The potassium feldspar is elongated, twinned and a weakly sericitized. Plagioclase may be twinned, and weakly saussuritized and sericitized. Quartz occurs as disseminations in the matrix and filling fractures. Olivine crystals occur in association with magnetite. Chlorite lamellae present green to pale green pleochroism and result from biotite alteration, likewise olivine and feldspars.

There are many epidote-chlorite veins, with local pyrite and chalcopyrite, which also occur disseminated. Except for the presence of hematite alteration, the alteration of the dacites is similar to that observed in the rhyolites.

5.2.5 *Andesite*

The andesite is a medium to fine grained rock, with microcrystalline to porphyritic texture. The matrix is holocrystalline, quartz-feldspathic composition with chlorite, epidote, apatite and hematite disseminated (Fig. 7J). Plagioclase phenocrysts are 54% of rock and are subhedral, elongated, and are partially to completely saussuritized. Chlorite and carbonate are also products of the alteration of plagioclase, whereas epidote was produced after pyroxene and magnetite occurs filling microfractures.

5.2.6. *Sandstones and conglomerates*

Rounded blocks of light to rosy gray colored and fine-grained tuffaceous sandstone show flat stratification, veins and fractures filled by quartz, and localized disseminated pyrite and chalcopyrite (Fig. 7K). The conglomerates have a reddish (hematite) matrix with subangular to subrounded, centimetric sandstone and ignimbrites clasts (Fig. 7K,L).

5.2.7 *Magnetic pyroclastic facies*

This new occurrence of pyroclastic rocks, is separated here in map (Fig. 5) as a facies of the Vila Riozinho Formation based on its distinctly different magnetic properties (high magnetism) and petrographic features. Mores studies (geochemical and geochronological) are necessary to better constrain the stratigraphic position of this facies.

This magnetic facies forms regions of rugged relief and comprises the most magnetic rocks in the study area, also showing high counts in the three radioelements. The magnetic pyroclastic facies consists essentially of ignimbrite sequences of rhyolitic composition, and minor occurrences of breccias.

The ignimbrites show preserved flow structures, pumices, and porphyritic texture (Fig. 8A,B), and have aphanitic to microcrystalline quartz-feldspathic matrix, which may or may not be sericitized. Structures of volcanic flow, pumices (with spherulitic texture), shards and stylolite, typical of welded to densely welded ignimbrites can be observed in the matrix (Figs 8 D,E,F,G). Occasionally, the presence of hematite in the matrix gives a reddish color to the rock, which usually present shades of gray and brown (Fig. 8C). Alteration minerals such

as titanite, apatite, chlorite, magnetite and ilmenite, and some sulfides (pyrite, chalcopyrite, galena and sphalerite) may also occur in the matrix.

K-feldspar phenocrysts may present Carlsbad twinning and are partially to completely replaced by chlorite, sericite and carbonate. The plagioclase phenocrysts are weakly sericitized and epidotized, and it is still possible to observe albite twinning along with neoformed crystals. Some quartz phenocrysts also occur. This assemblage suggests rhyolitic composition.

Fractures filled with carbonate and discontinuous veins of quartz (with comb texture) + chlorite + titanite + carbonate + sericite cut across the ignimbrites. Veins having pyrite + chalcopyrite + galena + sphalerite locally cut the quartz veins.

The volcanic breccia shows angular clasts of varying sizes, composed of sandstone immersed in a reddish matrix. The cavities in this breccia are filled with quartz crystals, as well as pyrite (Fig. 8H). Reddish-pink sandstone occurs associated with this breccia.

5.3. *CrepORIZÃO Intrusive Suite*

The largest surface extension of granitic rocks in the study area is associated to the Creporizão Intrusive Suite, as it was originally stated in Vasquez and Rosa-Costa (2008) (Fig. 2). The Creporizão Intrusive Suite has relatively low to intermediate concentrations in the three radiometric channels (Fig. 4).

In southeast of TGP this suite is composed of equigranular to porphyritic biotite-syenogranite and monzogranite, with medium grain size and whitish gray color (Fig. 9A). Locally, reddish colors are due to hematite alteration. It is common the presence of other varieties as hornblende granodiorite (Fig. 9B) and quartz monzonite. All varieties may show sericitization, saussuritization, epidotization.

Structurally, the rocks show fractures mainly oriented to N10-35E/80-86SE, which are occasionally filled by quartz. We have not observed the ductile tectonic fabric, which are described elsewhere in the Tapajós Gold Province (e.g., Vasquez et al. 2002).

In microscopic analysis, it is possible to observe zoned plagioclase grains and some grains with myrmekite intergrowth and microcline (Figs. 9 C, D). The potassium feldspar shows preserved perthite and, when associated with quartz grains, they form granophyric texture. Locally, the phenocrysts are reddish due to hematite alteration.

The hornblende crystals may be fractured and have corroded edges when in contact with quartz, and inclusions of biotite, magnetite and titanite (Figs. 9 E, F). Chloritized grains are also commonly found. Rare fractured orthopyroxene grains were recognized.

The biotite lamellae have brown to yellow pleochroism, and local association with magnetite, hematite and ilmenite. Biotite is replaced chlorite of bluish interference color (pennine variety). Titanite, apatite, zircon and fluorite are accessory phases, in addition to disseminated magnetite, hematite, ilmenite, pyrite and chalcopyrite (in smaller amounts).

5.4. *Serra Alkali Feldspar Granite*

In the central portion of the study area, we have defined the occurrence of two alkali-feldspar granite bodies (Serra Alkali Feldspar Granite, Guimarães et al. 2015), occurring

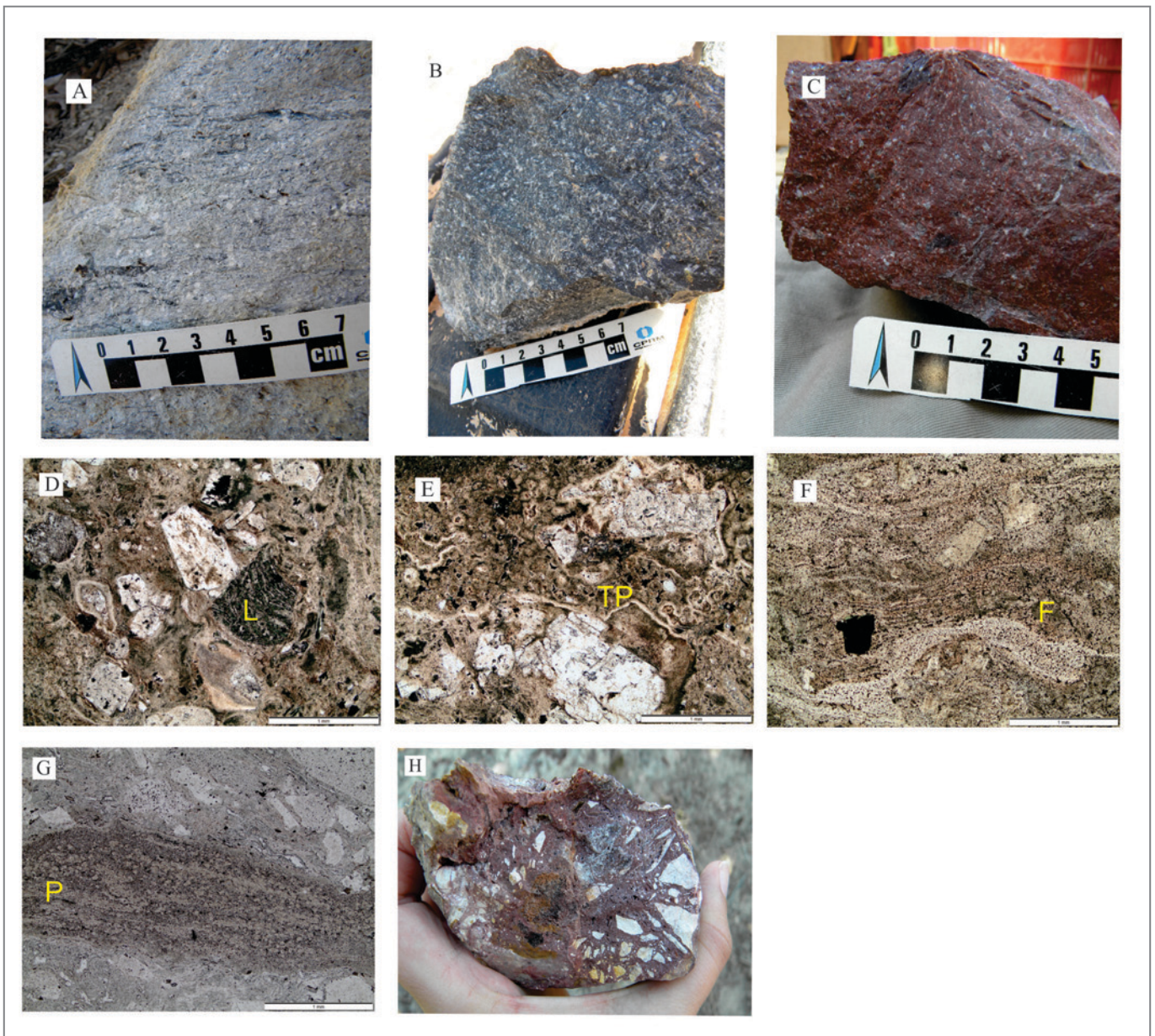


FIGURE 8 – Mesoscopic and microscopic aspects of rocks of the magnetic pyroclastic facies of the Vila Riozinho Formation. A) Ignimbrite outcrop with flow structures and stretched pumices; B) Gray ignimbrite sample with fine porphyritic texture; C) Ignimbrite with fine porphyritic texture and matrix with hematite alteration; D) Ignimbrite photomicrograph showing matrix flow between phenocrysts and lithic fragments (L); E) Ignimbrite photomicrograph with tube pumices (TP); F) Ignimbrite photomicrograph showing matrix flow between stretched phenocrysts; G) Ignimbrite photomicrograph with pumices (P); H) Volcanic breccia sample with red matrix and angular phenocrysts and pyrite boxwork occurrence.

in contact (intrusive/tectonic?) with the magnetic pyroclastic facies of the Vila Riozinho Formation. The gold mineralization of the Coringa deposit is partially hosted at the contact between the Vila Riozinho Formation and one of the bodies of the Serra granite (Fig. 5). The granitic body presents high concentrations of the radioelements potassium, thorium and uranium when compared to those of the Creporizão Intrusive Suite. On the other hand, its radiometric signature does not stand out due in the comparison with the Vila Riozinho Formation rocks to the west (Figs. 3 and 4).

The Serra Alkali Feldspar Granite holds fine- to medium-grained equigranular pinkish rocks with no ductile tectonic fabric (Fig. 10A, B). About 60% of the rock is composed of subhedral crystals of potassium feldspar (3.0 to 4.0 mm),

which shows pinkish to reddish colors, and weak sericite alteration. Quartz makes up about 35% of the rock, are smaller and rounded milky crystals. Granophyric texture in quartz and potassium feldspar grains is commonly found (Fig. 10 C). The mafic phase is represented by brown biotite lamellae (5%), which are weakly chloritized (pennine variety), with associated magnetite. When strongly altered, the granite presents intense red color, which is the result of hematite alteration and feldspar argillization.

In zones proximal to mineralization, it is frequent to observe disseminations of pyrite and chalcopyrite. The pyrite is euhedral and pale yellow in color. The chalcopyrite appears as anhedral grains, strongly yellow in color, with little covellite at the edges, and as few inclusions in pyrite.

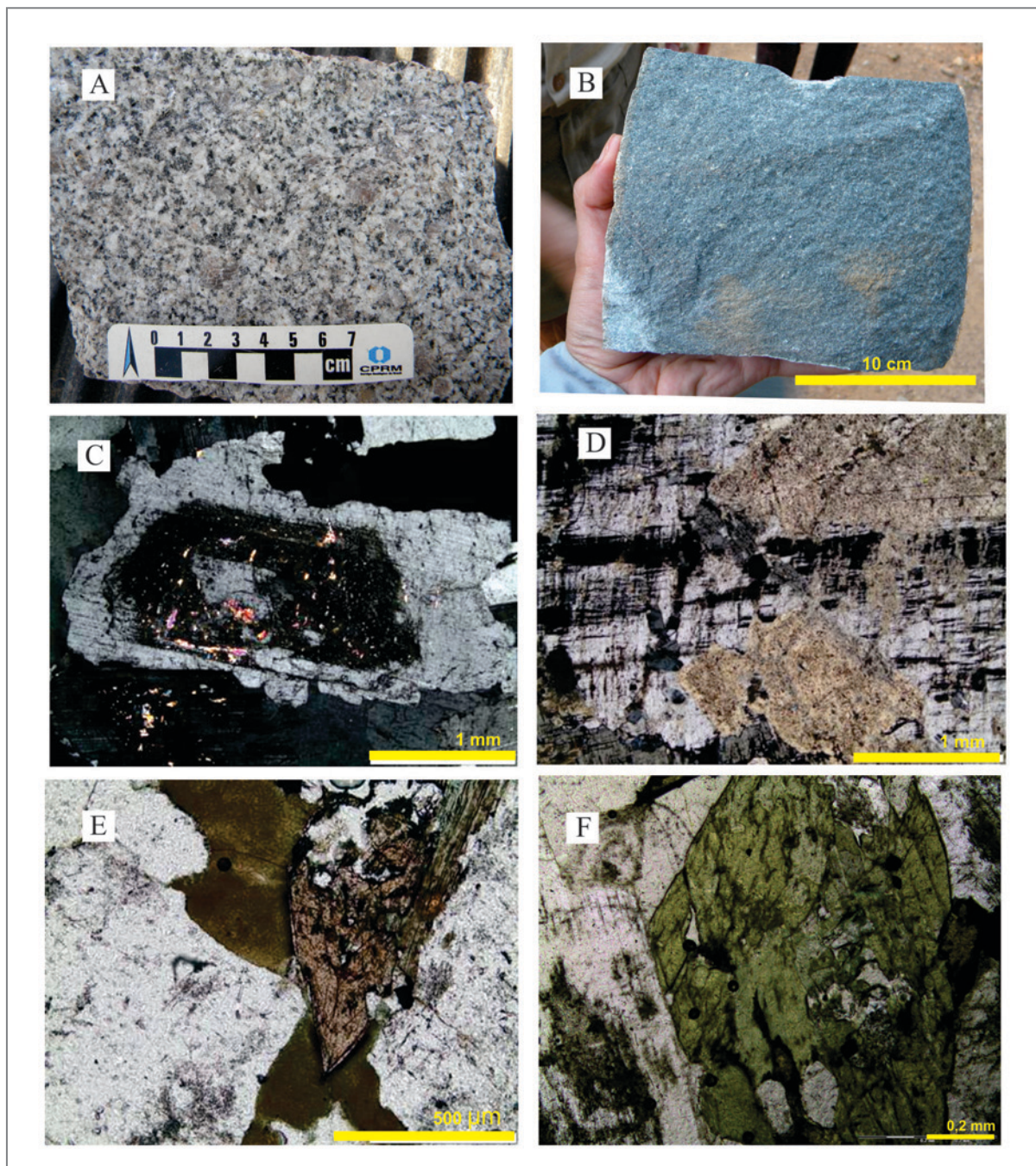


FIGURE 9 – Mesoscopic and microscopic aspects of the Creporizão Intrusive Suite (CIS). A) Gray equigranular monzogranite; B) hornblende granodiorite; C) zoned plagioclase phenocryst with epidote grains in the core; D) partially sericitized microcline phenocryst; E) titanite grain associated with chlorite lamella, adjacent to a brown biotite lamella F) hornblende phenocryst with inclusions of magnetite and quartz.

5.5. Maloquinha Intrusive Suite

The Maloquinha Intrusive Suite crops out as several stocks distributed throughout the study area. This unit intruded both the Creporizão Intrusive Suite and the Vila Riozinho Formation (Fig. 5). In general, it stands out by the high relief and shows intermediate to high concentrations of the three radiometric elements, along with intermediate magnetization (Fig. 4). However, it is locally observed an inverse correlation between magnetization and thorium concentrations.

The Maloquinha Intrusive Suite consists of pinkish, medium- to coarse-grained inequigranular to porphyritic

rocks, which are mostly magnetic. We have identified the syenogranite and monzogranite varieties, and subordinate quartz-monzonite. Rapakivi texture is common (Fig. 11A, B), and the suite also exhibit pegmatite and aplite pockets. These features (pegmatite and aplite) denote a significant participation of late fluids and crystallization at shallow depths.

The concentration of mafic minerals (essentially biotite, rare hornblende) is variable depending on the location within the granitic body, decreasing towards the pluton margins. Locally, it is observed a magmatic flow structure with general orientation of K-feldspar grains to N40-60W/10SW. Pyrite



FIGURE 10 – Aspects of the Serra Alkali Feldspar Granite. A) Fine-grained equigranular pinkish granite; B) drill holes from the Coringa deposit with the same granite of “A”; C) granophyric texture; D) twinned potassium feldspar crystal; E) sericitization of potassium feldspar.

occurs disseminated and in fault planes (N25E/76 SE), whereas chalcopyrite is disseminated in the rocks.

Discontinuous veins and fractures filled by quartz are common (Fig. 11C). We have also observed fine-grained, pink colored, magnetic dikes with saccharoidal texture and incipient banding, which we interpreted to be syn-magmatic in origin. Occurrences of diabase dikes are also commonly found cutting across the granites.

In microscopic analyses, we observed granophyric texture, along with fluorite, apatite, titanite, zircon and allanite as accessory phases. Magnetite, hematite and ilmenite are

generally concentrated near the brown biotite lamellae, which in turn are partially to completely replaced by chlorite. Sericitization of the potassium feldspar and saussuritization of plagioclase is also observed.

5.6. Novo Progresso Formation

In the Southeast region of the Tapajós Domain, NNW-SSE-trending elongated and discontinuous hills are composed of sedimentary rocks dominated by sandstones and siltstones with volcanic contributions (Guimarães et al. 2015; Klein et

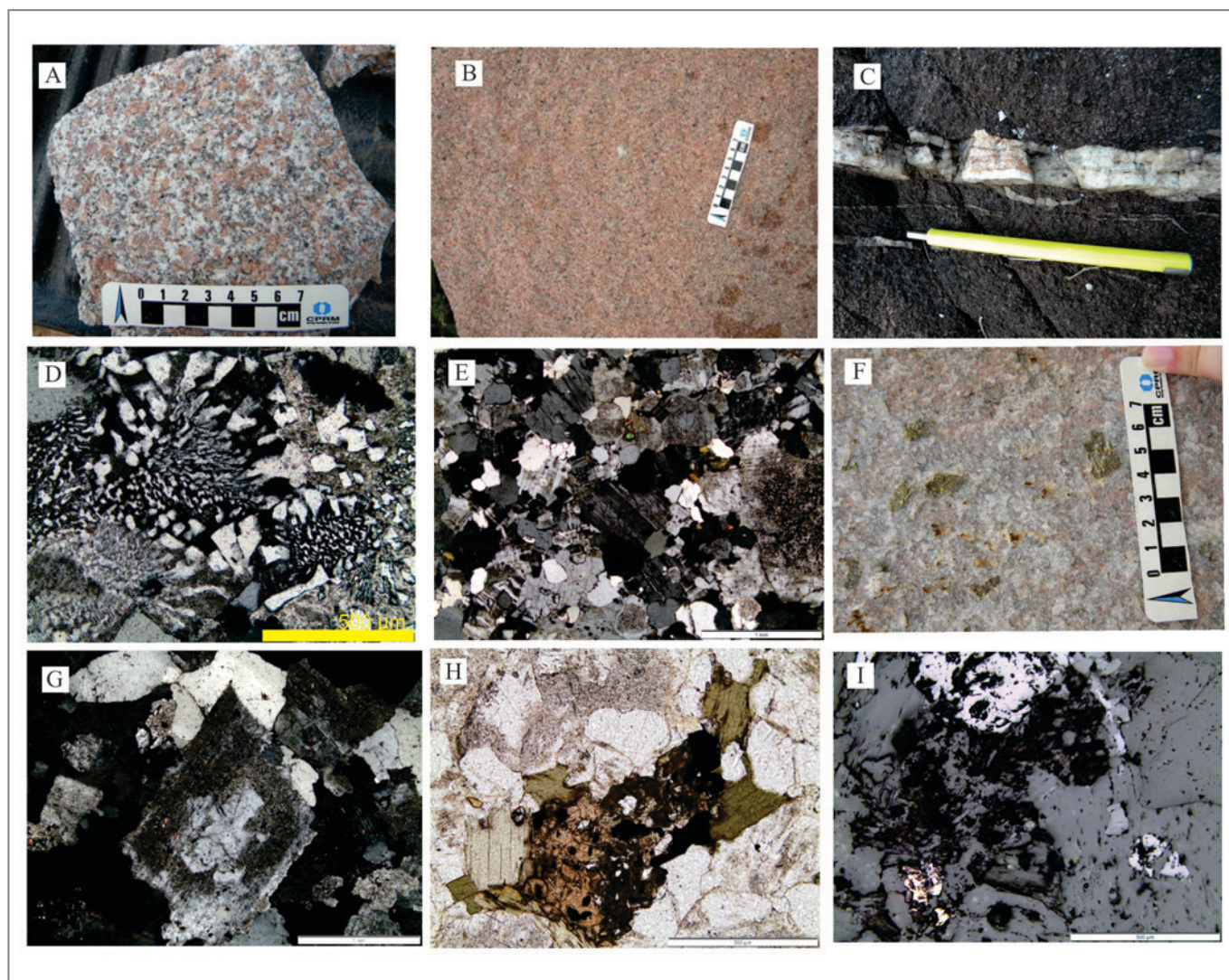


FIGURE 11 – Mesoscopic and microscopic aspects of the Maloquinha Intrusive Suite. A) Medium-grained inequigranular syenogranite; B) fine-grained equigranular syenogranite; C) fractures filled by quartz in syenogranite; D) granophyric texture in syenogranite; E) monzogranite with saussuritization of plagioclase; F) syenogranite with pyrite in fault planes; G) zoned K-feldspar phenocryst; H) anhedral titanite, dark green biotite laminae with apatite inclusions in syenogranite; I) magnetite and disseminated pyrite in monzogranite.

al. 2018). In this work we defined new occurrences of the formation (Fig. 5), in addition to those previously described in Guimarães et al. (2015) and in Klein et al. (2018).

This unit shows geophysical signature characteristic of sedimentary rocks, which are the low concentrations in the radioelements and low magnetization.

The formation is surrounded by granites of the Maloquinha, Parauari and Creporizão intrusive suites, felsic metavolcanic and pyroclastic rocks of the Vila Riozinho Formation and Iriri Group, and by metasedimentary rocks of the Castelo dos Sonhos Formation (Fig. 5). Contacts with these units are probably faulted and erosive. The rocks show sedimentary structures (stratification and lamination) that strike predominantly to N15-55°W/3-45°NE, which is grossly parallel to the regional structures (Klein et al. 2018).

Klein et al. (2018) reported the following lithological components: (1) massive to layered sandstone with plane-parallel and cross stratification and channeled sets, (2) relatively thick packages of purple to pinkish laminated siltstones, and (3)

rhythmic intercalations of laminated siltstones and laminated, microcrystalline quartz-rich “cherty” rock.

U-Pb LA-ICP-MS data in detrital zircon from a lithic arenite show two well-defined peaks at 1846 and 1968 Ma, and statistically secondary peaks. These results indicate that surrounding Orosirian rocks from the Tapajós Gold Province and Iriri-Xingu Domain (including their counterparts in the Guiana Shield), and from the Rondonia-Juruena Province were probably the main sources for the sediments. This is consistent with the low maturity of the sediments and proximal sources. The maximum depositional age was set at 1840 Ma (Klein et al. 2018).

6. Concluding remarks

Intensive fieldwork, petrography, and high-resolution airborne geophysics, in addition to published information, allowed improving significantly the knowledge about the geology and stratigraphy of the southeastern portion of

the Tapajós Gold Province. The main findings of our work is as follows:

a) All units cropping out in the study area have their geophysical signature described and defined.

b) Most of the areas that were previously mapped as Parauari Intrusive Suite (1.89 Ga) and Iriri Group (1.88 Ga), in fact comprise felsic volcanic and pyroclastic rocks, which, based on available geochronology, we ascribe to the Vila Riozinho Formation (1.98 Ga).

c) We defined two new units: (1) the Serra Alkali Feldspar Granite, which probably intruded the Vila Riozinho Formation, and (2) a magnetic facies of the Vila Riozinho Formation, which holds the rocks with the highest magnetic contents of the study area.

d) The rocks that surround the Castelo dos Sonhos basin are granites, and not volcanic rocks as previously stated, which we ascribe to the Creporizão Intrusive Suite.

This contribution forms the basis for future works, which have to deal with the crustal evolution of the southeastern Tapajós Gold Province, employing geochemistry, U-Pb geochronology, and Sm-Nd and Lu-Hf studies. These studies will allow a more confident discussion about the tectonic setting in which formed the mapped lithological units, and the crust forming events that produced this part of the Amazonian Craton.

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References

- Almeida F.F.M., Hasui Y., Brito Neves B.B., Fuck R.A. 1981. Brazilian structural provinces: an introduction. *Earth Science Review*, 17, 1-29.
- Andrade A.F., Santiago A.F., Melo C.F., Bizinella G.A., Moreira H.L., Santos J.O.S., Oliveira J.R., Moura P.A., Lopes R. da C., Rosa Filho S.F., Neves S.A.V. 1978. Projeto Tapajós-Sucunduri: Relatório de Integração Geológica. Manaus: DNPM/ CPRM, 3 v. (Unpublished report). Available at <http://rigeo.cprm.gov.br/jspui/handle/doc/9546> (access on 14/11/2018).
- Borgo A., Biondi J.C., Chauvet A., Bruguier O., Monié P., Baker T., Ocampo R., Friedman R., Mortensen J. 2017. Geochronological, geochemical and petrographic constraints on Paleoproterozoic Tocantinzinho deposit (Tapajós Gold Province, Brazil): implications for timing, regional evolution and deformation style of its host rocks. *Journal of South American Earth Sciences*
- Carneiro C.C., Juliani C., Carneiro-Araújo S.A., Monteiro L.V.S., Crosta A.P., Fernandes C.M.D. 2018. New Crustal Framework in the Amazon Craton Based on Geophysical Data: Evidences of Deep East-West Trending Suture Zones. *IEEE Geoscience and Remote Sensing Letters*. DOI: 10.1109/LGRS.2018.2867551.
- Coutinho M.G.N. 2008. Província Mineral do Tapajós: geologia, metalogenia e mapa previsional para ouro em SIG. Rio de Janeiro, CPRM, 420 p.
- Faraco M.T.L., Carvalho J.M.A., Klein E.L. 1997. Carta Metalogenética da Província Aurífera do Tapajós. In: Costa M.L. e Angélica R.S. (eds) Contribuições à Geologia da Amazônia, p. 423-445
- Fraga L.M., Vasquez M.L., Dreher A.M. 2017. A influência da Orogenia Eo-orosiana na formação da SLIP Uatumã, parte central do Cráton Amazônico. *Anais do 15º Simpósio de Geologia da Amazônica*, Belém. 405-408 p.
- Guimarães S. B.; Klein E. L.; Chaves C. L.; Souza S. M.; Castro J. M. R.; Queiroz J. D. S.; Feio J. V. B.; Lima R. G. C. 2015. Metalogenia das Províncias Minerais do Brasil: Área sudeste do Tapajós, Estado do Pará. 1. ed. Brasília: CPRM - Serviço Geológico do Brasil, 2016. v. 1. 61p.
- Isles D.J., Rankin L.R. 2013. Geological interpretation of Aeromagnetic Data. *Australian Society of Exploration Geophysicists*. 357 pp.
- Jonhson A., Cheeseman S., Ferris J. 1999. Improved compilation of antarctic Peninsula magnetic data by new interactive grid suturing and blending methods. *Annali di Geofisica* 42(2), 249 – 259.
- Juliani C., Carneiro C.C., Carneiro-Araújo S. A., Fernandes C. M. D., Monteiro L. V. S., Crósta A. P. 2013. Estruturação dos arcos magmáticos paleoproterozoicos na porção sul do Cráton Amazônico: implicações geotectônicas e metalogenéticas. *Anais do 13º Simpósio de Geologia da Amazônia*. Belém, p.157-160.
- Klein E.L., Almeida M.E., Rosa-Costa L.T. 2012. The 1.89-1.87 Ga Uatumã Silicic Large Igneous Province, northern South America. In: International Association of Volcanology and Chemistry of the Earth's Interior, Large Igneous Province Commission, November 2012 LIP of the month.
- Klein E.L.; Rodrigues J.B.; Queiroz J.D.S.; Oliveira R.G.; Guimarães S.B.; Chaves C.L. 2017. Deposition and tectonic setting of the Palaeoproterozoic Castelo dos Sonhos metasedimentary formation, Tapajós Gold Province, Amazonian Craton, Brazil: age and isotopic constraints, *International Geology Review*, 59:7, 864-883.
- Klein E.L., Guimarães S.B., Rodrigues J.B., Chaves C.L., Souza-Gaia S.M., Lopes E.C.S., Castro J.M.R. 2018. The Novo Progresso Formation, Tapajós Gold Province, Amazonian Craton: zircon U-Pb and Lu-Hf constraints on the maximum depositional age, reconnaissance provenance study, and tectonic implications. *Journal of the Geological Survey of Brazil*, 1 (1) 31-42. <https://doi.org/10.29396/jgsb.2018.v1.n1.3>
- Klein E.L., Vasquez M.L., Rosa-Costa L.T., Carvalho J.M.A. 2002. Geology of Paleoproterozoic gneiss and granitoid-hosted gold mineralization in Southern Tapajós Gold Province, Amazonian Craton, Brazil. *International Geology Review*, 44, 544-558.
- Lamarão C.N.; Dall'Agnol R.; Lafon J.M.; Lima E.F., 2002. Geology, geochemistry and Pb–Pb zircon geochronology of the paleoproterozoic magmatism of Vila Riozinho, Tapajós Gold Province Amazonian Craton, Brazil. *Precambrian Research*, 119: 189-23.
- Lamarão C.N.; Dall'Agnol R., Pimentel M.M. 2005. Nd isotopic composition of Paleoproterozoic volcanic and granitoid rocks of Vila Riozinho: implications for the crustal evolution of the Tapajós gold province, Amazon cráton. *Journal of South American Earth Sciences* 18, 277–292
- Pessoa M.R., Santiago A.F., Andrade A.F., Barreto E.L., Nascimento J.O., Santos J.O.S., Oliveira J.R., Lopes R.C., Prazeres W.V. 1977. Projeto Jamanxim. CPRM/ DNPM, v. 1-3, 614 p.
- Queiroz J.D.S., Klein E.L., Rodrigues J.B. 2015. Rochas intrusivas na bacia paleoproterozoica Castelo dos Sonhos, Cráton Amazônico: geocronologia, aspectos geoquímicos e implicações para litoestratigrafia, limite entre os domínios Tapajós e Iriri-Xingu e idade da mineralização no depósito aurífero Castelo de Sonhos. *Boletim Paraense Emílio Goeldi. Ciências Naturais*.
- Queiroz J.D.S., Klein E.L. 2018. The Paleoproterozoic metaconglomerate-hosted Castelo de Sonhos gold deposit, Tapajós Gold Province, Amazonian Craton: a modified paleoplacer origin. *Journal of the Geological Survey of Brazil*, 1 (2), 81-99. <https://doi.org/10.29396/jgsb.2018.v1.n2.3>
- Santos J.O.S., Groves D.I., Hartman L.A., Moura M.A., McNaughton N.J. 2001. Gold deposits of the Tapajós and Alta Floresta Domains, Tapajós – Parima orogenic belt, Amazon Craton, Brazil. *Mineralium Deposita*, 6: 279-299.
- Santos J.O.S., Van Breemen O.B., Groves D., Hartmann L.A., Almeida M.E., McNaughton N.J., Fletcher I.R. 2004. Timing and evolution of multiple paleoproterozoic magmatic arcs in the Tapajós Domain, Amazon Craton: constraints from SHRIMP and TIMS zircon, baddeleyite and titanite U-Pb geochronology. *Precambrian Research*, 131: 73-109.
- Santos R. A.; Coutinho M. G. N. Geologia estrutural. In: Coutinho, M.G.N. (Ed.). Província Mineral do Tapajós: geologia, metalogenia e mapa previsional para ouro em SIG. Rio de Janeiro: CPRM-Serviço Geológico do Brasil, 2008. p. 97-135.
- Teixeira W., Hamilton M.A., Girardi V.A.V., Faleiros F.M., Ernst R.E. 2018. U-Pb baddeleyite ages of key dike swarms in the Amazonian Craton (Carajás/Rio Maria and Rio Apa areas): Tectonic implications for events at 1880, 1110 Ma, 535 Ma and 200 Ma. *Precambrian Research*. In press. <https://doi.org/10.1016/j.precamres.2018.02.008>
- Tokashiki C. C., Juliani C., Monteiro L. V. S., Echeverri-Missas C. M., Aguiar M. A., Arrais, L. B., 2015. Eventos vulcânicos de 1,97 Ga com

- mineralizações de ouro epitermais low- e intermediate sulfidation na porção sul da Província Mineral Tapajós (PA). Contribuições à Geologia da Amazônia, 9, 119-138.
- Vasquez M. L., Chaves C. L., Moura E. M., Oliveira J. K. M. 2017. Geologia e Recursos Minerais das Folhas São Domingos - SB.21-Z-A-II e Jardim do Ouro - SB.21-Z-A-III, Estado do Pará, Escala 1:100.000. Belém: CPRM - Serviço Geológico do Brasil, 2017. 305 p.
- Vasquez M.L., Klein E.L., Ricci P.S.F. 2002. Granitoides pós-colisionais da porção leste da Província Tapajós. In: E.L. Klein, M.L.Vasquez, L.T. Rosa-Costa. (eds.). Contribuições à Geologia da Amazônia, Belém v.3, p. 67-84.
- Vasquez M.L., Rosa-Costa L.T., Silva C.M.G., Klein E.L. 2008. Compartimentação Tectônica. In: M.L. Vasquez, L.T. Rosa-Costa (orgs.). 2008. Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará. Escala 1:1.000.000. Belém: CPRM. p. 39-112.
- Vasquez M.L.; Rosa-Costa (orgs.). 2008. Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará. Escala 1:1.000.000. Belém: CPRM. p. 39-112.
- Yokoi Y. O., Oliveira A. L. A. M., Tachibana J. 2001. General economic geology of the High Tapajós Basin (The "Cachimbo" Gráben) and its boundaries: a regional geological survey with exploratory purpose. In: Simpósio de Geologia da Amazônia, 7, Belém, Resumos expandidos. Belém: SBG. 1 CD-ROM.

3. GEOCHEMICAL AND ISOTOPIC (U-PB, LU-HF, SM-ND) CONSTRAINTS ON THE HOST ROCKS OF THE MAGMATIC-HYDROTHERMAL CORINGA GOLD-SILVER (CU-PB-ZN) DEPOSIT AND ITS SURROUNDINGS, AND IMPLICATIONS FOR THE CRUSTAL EVOLUTION AND TECTONIC SETTING OF THE TAPAJÓS MINERAL PROVINCE, AMAZONIAN CRATON, BRAZIL

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Geochemical and isotopic constraints on the host rocks of the magmatic-hydrothermal Coringa gold-silver (Cu–Pb–Zn) deposit of the Tapajós mineral province, amazonian craton, Brazil

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ABSTRACT

The Coringa gold-silver (Cu–Pb–Zn) deposit, in southeastern Tapajós Mineral Province, is hosted in felsic volcanic rocks of the Vila Riozinho Formation and the Serra Alkali Feldspar Granite (hereafter Serra Granite). Field, petrographic, geochemical, and U–Pb, Lu–Hf, Sm–Nd data allowed us to constrain the magmatic evolution and tectonic setting of these units and surrounding volcano-plutonic sequences, with bearing in the tectonic evolution of the Tapajós Province, and the Amazonian Craton.

The granites of the Creporizão Intrusive Suite (1956–2002 Ma) are high-K, calc-alkalic to alkali-calcic (sub-alkaline), metaluminous, and magnesian. The Serra Granite (1968–2020 Ma) is alkali-calcic and ferroan, with moderate to strongly negative ϵ_{Nd} values (−8.0 to +0.1), and model ages of 2.27–3.15 Ga, the same range of those presented by the intrusions of the Creporizão Suite, with Serra Granite being interpreted as a differentiated variety of the Creporizão Suite. Volcanic and pyroclastic rocks of the Vila Riozinho Formation (1996–2033 Ma) are high-K, calc-alkaline and magnesian, whereas the predominant “magnetic pyroclastic facies” of this formation is mostly ferroan alkalic (relatively reduced crystallization conditions). Despite the chemical difference, the magnetic pyroclastic facies, dated at 2024 to 1968 Ma, is similar in age to the “normal” Vila Riozinho Formation. The Nd–Hf isotopes reveal model ages between 2.38 and 2.42 Ga, and ϵ_{Hf} and ϵ_{Nd} values ranging from −2.1 to −3.2, which are very similar to those of the “normal” Vila Riozinho Formation (Sm–Nd $T_{\text{DM}} = 2.49$ –2.25 Ga, epsilon values of −3.71 to −1.03). The Maloquinha Intrusive Suite, which intruded older units, shows alkali-calcic to alkali and ferroan signature, along with trace-element distribution typical of silica saturated alkaline granites and was dated at 1883 ± 17 Ma.

The geochemical and isotopic signature of the coeval Creporizão Suite and Vila Riozinho Formation indicate that they belong to the same Orosirian magmatic event. Considering the age relationships with precedent magmatic events in the Tapajós Mineral Province, attributed to arc setting, we interpret this event as post-collisional, with the collision assemblages occurring outside the Tapajós Province, in the Guiana Shield, as part of a large Orosirian orogenic belt. The Maloquinha Suite is associated with the Uatumã silicic large igneous province (~1.89–1.86 Ga), which was established in a craton-wide extensional event that followed the Orosirian orogeny.

1. Introduction

In the past two decades, tectonic compartmentalization of the Amazonian Craton has prioritized geochronological subdivisions (Tassinari and Macambira, 1999; Santos et al., 2000; Santos, 2003). However, this approach has been questioned by several researchers, who

argue that at least the limits between provinces and domains must be reviewed (e.g., Lamarão et al., 2005; Kroonenberg et al., 2016; Klein et al., 2017; Fraga et al., 2017). Internally, the concept of domains has been more useful because it brings together a lithospheric set of similar evolution, but distinct from neighboring areas (e.g., Santos et al., 2000; Vasquez et al., 2008a, 2008b; Costa et al., 2020).

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Intense magmatism during the Orosirian period was responsible for a large volume of felsic volcanic and volcanoclastic rocks and granitoids emplaced in several plutono-volcanic episodes between about 2020 and 1860 Ma (Reis et al., 2000; Fraga et al., 2017; Vasquez et al., 2017). These rocks cover more than one million square kilometers in the central portion of the Amazonian craton (Fig. 1). A significant part of these felsic rocks (andesites, dacites, rhyolites, pyroclastic, and associated plutonic rocks) occur in the Tapajós Domain (or Tapajós Mineral Province, Figs. 1 and 2), which has previously been included in the Ventuari-Tapajós (Tassinari and Macambira, 1999) or Tapajós-Parima (Santos, 2003) geochronological provinces. The Tapajós Mineral Province is an important and underexplored metallogenic province in Brazil, with resources + historical production over 800 t of gold (Assunção and Klein, 2014, and references therein). The Coringa gold-silver (Cu–Pb–Zn) deposit, in southeastern Tapajós Mineral Province (resources of ~12 t Au, 19 t Ag, Prens et al., 2017), is hosted in felsic volcanic rocks and granite and inferred as having formed by a magmatic-hydrothermal system (Corrêa-Lima and Klein, 2020), which is probably associated to these volcano-plutonic associations, and have tentatively been attributed to the Vila Riozinho Formation and Serra Alkali Feldspar Granite units (Fig. 2 and 3), respectively (Guimarães et al., 2019).

The evolution of the volcano-plutonic sequences in the Tapajós Province and its continuation to the east (Irixi-Xingu Domain – Fig. 1) is

a matter of debate. Issues include the tectonic setting in which formed the Orosirian magmatism, whether associated to continental magmatic arcs or extensional environment, the existence of subduction towards northeast or north, operation or not of continental collision, petrogenetic processes, and crustal versus mantle sources (e.g., Lamarão et al., 2002, 2005; Vasquez et al., 2002, Vasquez et al., 2008a, 2008b; 2017; Fernandes et al., 2011; Juliani and Fernandes, 2010; Aguja-Bocanegra, 2013; Juliani et al., 2013; Villas et al., 2013; Tokashiki et al., 2015; Borgo et al., 2017; Klein et al., 2012, 2017; Biondi et al., 2018; Valério et al., 2018; Carneiro et al., 2019).

In this paper, we present whole-rock geochemistry and Sm–Nd data, along with zircon U–Pb and Lu–Hf studies on the granitic and volcanic/volcanoclastic host units of the Coringa deposit and its surroundings in the southeastern Tapajós Mineral Province (Fig. 3). The results allow discussions about the issues listed above and to contribute to the understanding of the crustal evolution of the Tapajós Mineral Province, and the central Amazonian Craton as a whole. In addition, the understanding of the magmatic evolution of the host rocks of the Coringa deposit will contribute for future investigations on the genesis of this deposit.

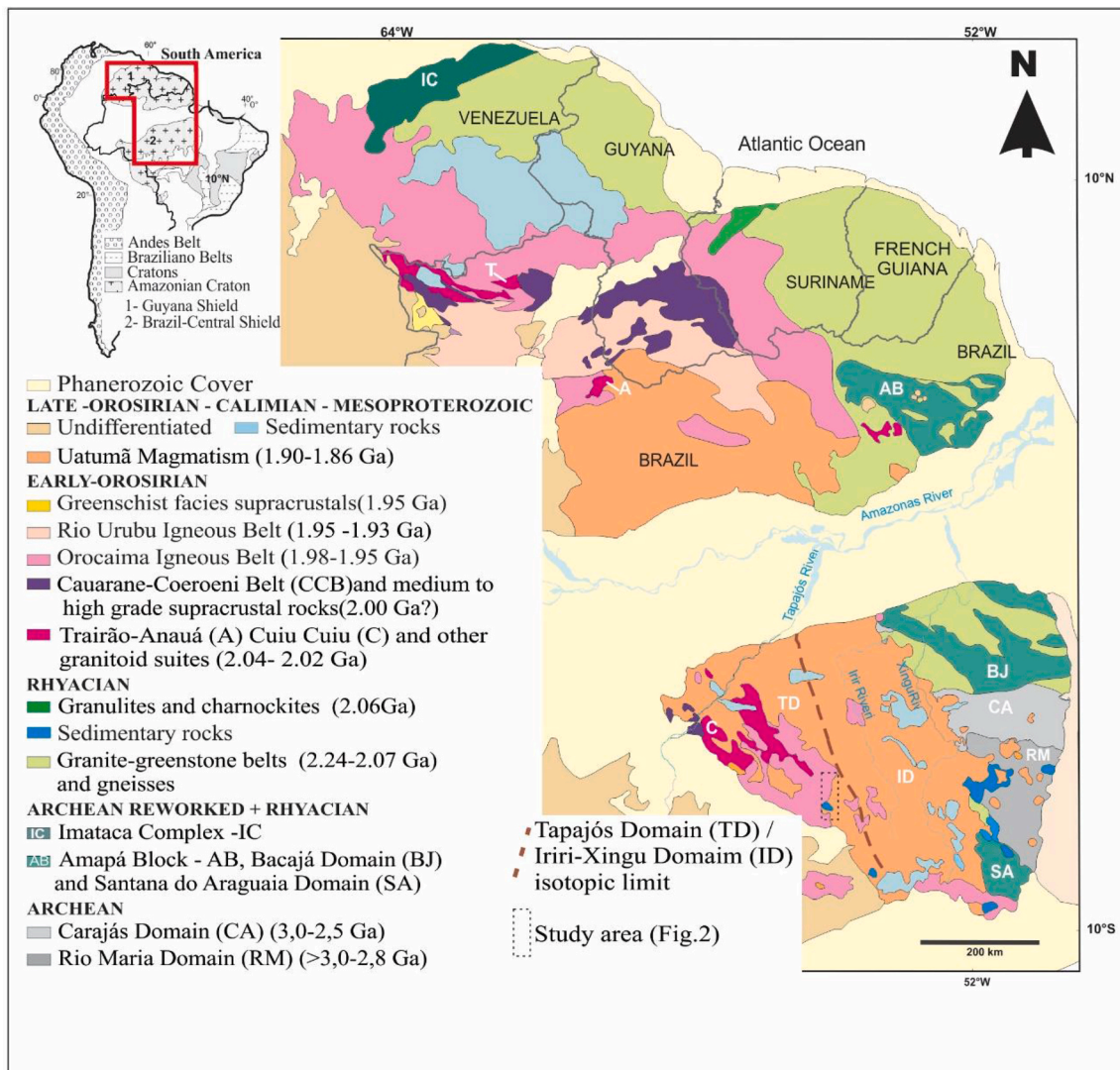


Fig. 1. Simplified geological map of the central and northwestern part of the Amazonian Craton (modified from Fraga et al., 2017), with location of the study area. The isotopic limit between the Tapajós and Irixi-Xingu domains is based in Santos (2003).

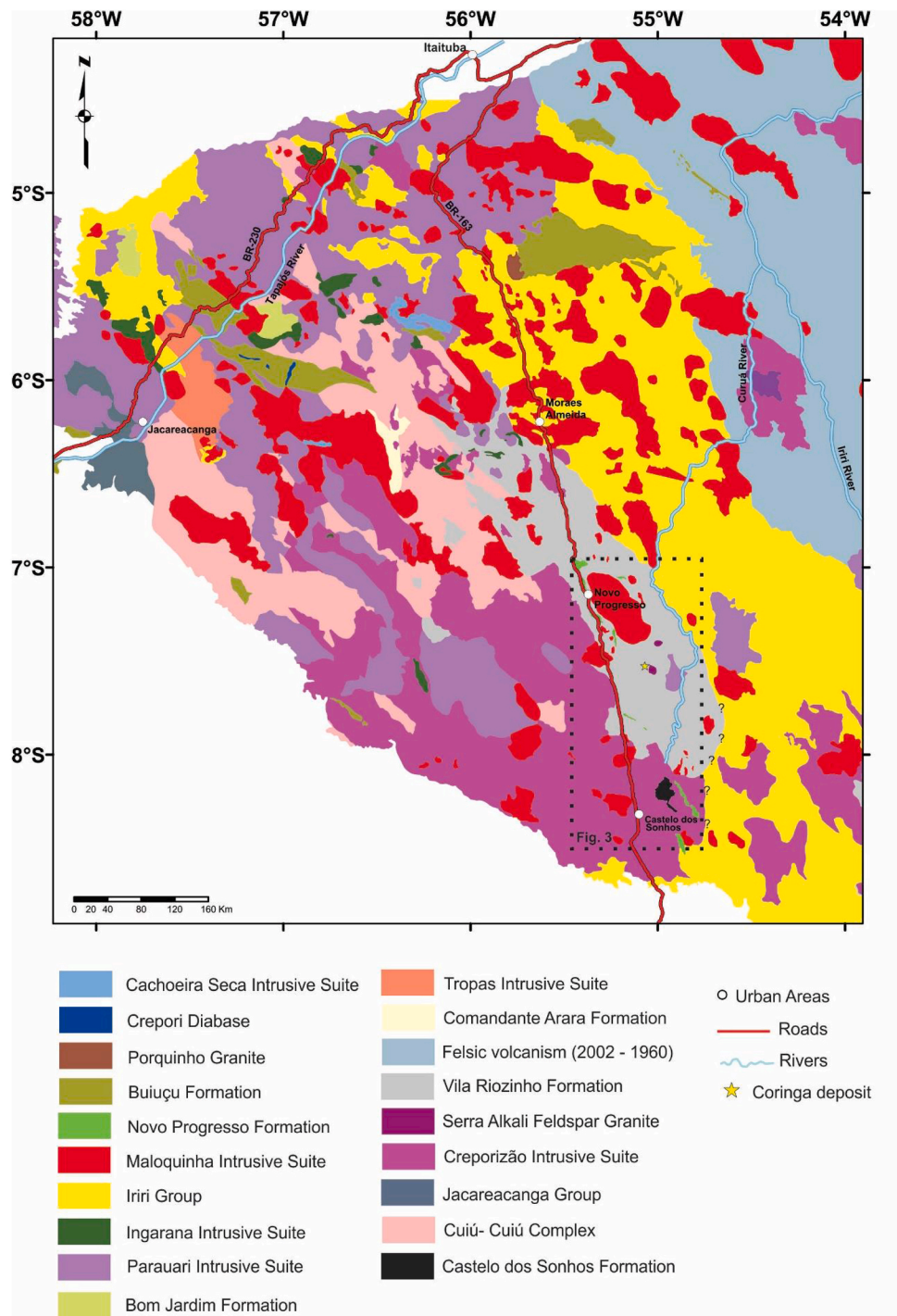


Fig. 2. Geological map of the Tapajós Mineral Province (modified from Vasquez et al., 2017 and Guimarães et al., 2019), with the location of the study area.

2. Geological context

2.1. The Tapajós Mineral Province

The Tapajós Mineral Province, in central-south Amazonian Craton (or Tapajós Domain, in the sense of Santos et al., 2001, and Vasquez et al., 2008a, 2008b), is limited to the east by the Iriri-Xingu Domain, being covered by two Phanerozoic basins, the Amazonas Basin to the north and west, and the Alto Tapajós Basin to the south (Figs. 1 and 2). The geological evolution of the Tapajós Province is controversial. Tassinari and Macambira (1999) suggest an orogenic belt and Santos et al. (2001, 2004) indicate the addition of several magmatic arcs from

southwest to northeast between 2040 and 1870 Ma. Santos et al. (2004) also argue that this evolution took place during two orogenic events: Munducus Orogeny (2040–1957 Ma) and Tropas Orogeny (1906–1886 Ma). These events were followed by post-orogenic magmatism at 1890 to 1870 Ma (Uatuma Magmatism), and finally an anorogenic granitic event at ca. 1780 Ma. Juliani et al. (2013) suggested magmatic arcs oriented to the east-west direction, with subduction from south to north.

In contrast to the model of successive magmatic arcs, Vasquez et al. (2017) proposed the collision of a single arc, the Cuiú-Cuiú Arc (2.03–2.05 Ga) against an Archean continent to the east. Peraluminous leucogranites, similar to those produced by crustal melting in collision

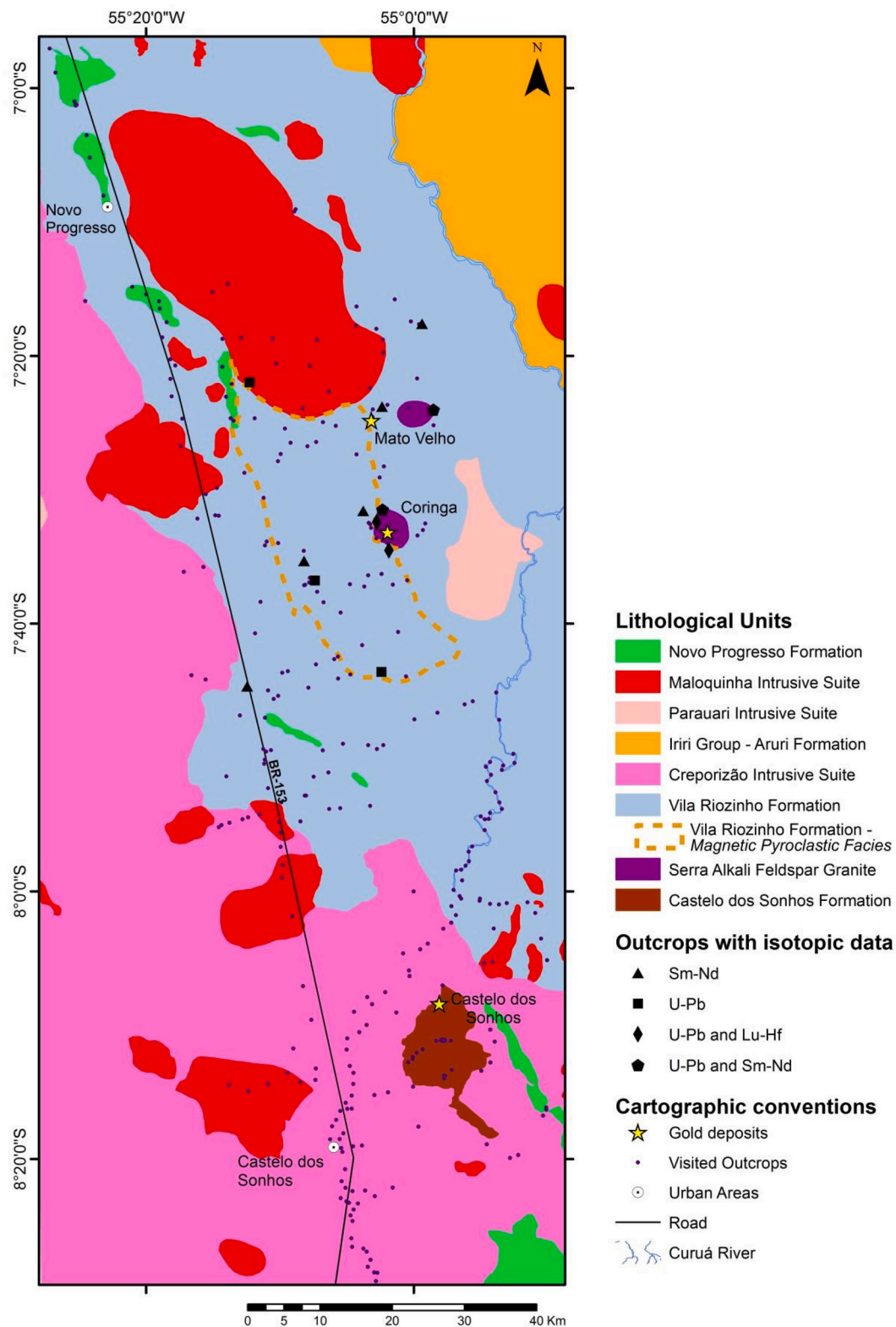


Fig. 3. Geological map of the Southeastern Tapajós Mineral Province (adapted from Guimarães et al., 2019), with location of outcrops visited during this study, and sampling sites. Coordinates of the analyzed samples are listed in Appendix 3 (Electronic Supplementary Material).

settings, are included as subordinate rock varieties within the Cuiú-Cuiú Complex and were taken as representing the collisional phase (Vasquez et al., 2002). This subduction-collision event was followed by a trans-collision post-collision magmatic event of ca. 2.0 to 1.96 Ga, and then by extensional events of 1.90 to 1.87 Ga. Ancient NW-SE directional shear

zones possibly controlled the positioning and/or reorientation of most of the late- to post-orogenic igneous intrusions and volcanic deposits.

Volcano-plutonic events from 1.90 to 1.87 Ga, of predominantly acidic, and subordinately intermediate composition are recorded in the central portion of the Amazonian Craton, loosely named Uatumbá, are

considered by Klein et al. (2012) as part of a Silicic Large Igneous Province (SLIP). The Uatuma SLIP encompasses the Iriri volcanic rocks, and the Maloquinha and Parauari granitoids distributed in the Orosirian domains (Vasquez and Dreher, 2011) (Figs. 1 and 2).

The dominant brittle tectonics of the transcurrent and extensional regimes did not modify the stratigraphic stacking of the Tapajós Province units, which allowed Vasquez et al. (2017) to assemble associations of rocks based on the ages related to each event. Vasquez et al. (2017) established that the oldest magmatic event of the Tapajós Province occurred in 2033 to 2005 Ma with calc-alkaline affinity. These events correspond to the basement associations represented by the supracrustal rocks of the Jacareacanga Group along with the granites and orthogneisses of the Cuiú-Cuiú Complex, and the volcanic and volcanoclastic rocks of Comandante Arara Formation. The rocks of the Cuiú-Cuiú Complex are related to the slightly evolved Cuiú-Cuiú magmatic arc (Vasquez et al., 2002).

All magmatic events of the Orosirian period that succeeded and accompanied the magmatism of the Cuiú-Cuiú Arc were concentrated in the central, southeast and eastern portions of Tapajós Mineral Province. The 2002 to 1956 Ma event shows high-K calc-alkaline and shoshonitic affinities and is represented by volcanic rocks of the Vila Riozinho Formation, and by granitoids of the Creporizão Intrusive Suite (Vasquez et al., 2002, 2017).

After a ca. 50 Ma gap, a high K calc-alkaline magmatism occurred between 1907 and 1864 Ma originating the São Jorge Jovem Granite, which was succeeded by the high-K calcic and alkalic magmatic events that produced the Parauari Intrusive Suite, and the basic to intermediate Ingarana Intrusive Suite. Simultaneously, acidic alkaline magmatism was emplaced and is represented by the Maloquinha Intrusive Suite granitoids and its extrusive equivalents of the Moraes Almeida Formation and Iriri Group (Lamarão et al., 2005; Vasquez et al., 2002, 2017). The NW-SE trending transcurrent faults controlled most of the igneous bodies from 1907 to 1864 Ma events, but the E-W and NE-SW direction components, which mark the transition to extensional tectonics, controlled some mafic bodies (Vasquez et al., 2017).

The youngest magmatic events in the region are tholeiitic diabase dikes correlated to the Jurassic period (Penatecaua event). These dikes are oriented according to the E-W and NE-SW directions (Vasquez et al., 2008).

In the southeast portion of the Tapajós Province, close to the border with the Iriri-Xingu Domain, there are sedimentary covers related to different events. The Castelo dos Sonhos Formation, the oldest unit of all the domain, is composed of auriferous metaconglomerates and meta-sandstones deposited by a fan and fluvial systems between 2011 and 2050 Ma (Queiroz et al., 2015; Klein et al., 2017; Queiroz and Klein, 2018). Klein et al. (2017) also observed that the deposition of the Castelo dos Sonhos Formation precedes the first orogenic event in the Tapajós Province. The sedimentary Novo Progresso Formation is composed of quartz- and lithic-arenites and siltstones with volcanic/volcanoclastic contributions and was deposited in fluvial and lake systems. Reconnaissance detrital zircon U–Pb LA-ICP-MS data indicate maximum depositional age around 1840 Ma, whereas structural relationships suggest a minimum age of 1780 Ma (Klein et al., 2018).

2.2. Geology of the SE-Tapajós Province

The geology of the study area, the southeastern Tapajós Province, was recently reviewed by Guimarães et al. (2019) at the 1:100,000 scale (Fig. 3), based on fieldwork, airborne geophysical data, and limited geochronological information.

The Castelo de Sonhos Formation was considered a relic of a larger foreland basin, whose basement in the southeast of Tapajós is still unknown because all the volcanic and granitic rocks of the adjacent areas are younger than this formation. This formation comprises a siliciclastic metasedimentary unit composed of conglomerates and sandstones with very low metamorphism and synformal folding. The sedimentary

sequence was intruded by calc-alkaline dacite porphyry and granitoids at 2011 ± 6 Ma and 1976 ± 7 Ma, respectively (Queiroz et al., 2015), which constrains the minimum age of sedimentation at 2011 Ma. Based on geochronology and on whole-rock chemical data, Queiroz et al. (2015) attributed the dacite and the granitoids (which do not crop out, and were studied based on drill cores) to the Comandante Arara Formation and Creporizão Intrusive Suite, respectively. Klein et al. (2017) interpreted the lithological association and the sedimentary structures as evidence of transport in continental environment by interlaced fluvial system, associated with alluvial fans and wind dunes. Klein et al. (2017) also established the maximum age of sedimentation at 2050 Ma (U–Pb, detrital zircon), and that the source areas of the sediments would be associated with Rhyacian-Siderian orogenic belts.

The Creporizão Intrusive Suite forms the largest surface extension of granitic rocks whose intrusions were strongly controlled by NW-SE-trending transcurrent shear zones. This suite is composed of gray, equigranular to porphyritic biotite syenogranite and monzogranite having locally reddish tonalities due to hematite alteration. U–Pb zircon dating by Tokashiki et al. (2015), returning ages of 1955 ± 19 Ma and 1980 ± 14 Ma, and were considered rocks of this suite (although the exact location of the dated samples is not clear).

Volcanic and pyroclastic rocks form an abundant association in the southeastern Tapajós Province. In previous works, these sequences have not been mapped and considered as part of the Parauari Intrusive Suite (Vasquez et al., 2008). Furthermore, Tokashiki et al. (2015) recognized and dated some of the volcanic rocks, but these have not been separated in maps or related to any known stratigraphic unit. Guimarães et al. (2019) correlated these volcanic rocks to the Vila Riozinho Formation, defined by Lamarão et al. (2002, 2005), increasing the area of occurrence of this formation. From the radiometric point of view, the Vila Riozinho Formation shows relatively higher uranium and thorium concentrations than those presented by the compositionally similar but younger, Iriri Group volcanic rocks. Rhyolitic ignimbrites, latite, rhyolite, dacite, and andesite are the main rock types of the Vila Riozinho Formation, which are associated with flattened relief, sometimes cut by granite stocks. Volcanogenic sandstones and conglomerates with rhyolitic ignimbrites were correlated with more rugged relief (Guimarães et al., 2019). This observation corroborates with that of Vasquez et al. (2017) for the same unit to the north of the study area. A magnetic pyroclastic facies was separated by Guimarães et al. (2019) from the regional Vila Riozinho Formation (Fig. 3). This magnetic facies forms regions of rugged relief and comprises the most magnetic rocks in southeastern Tapajós Province area, also showing high counts in the three radioelements (K, eU, eTh). The magnetic pyroclastic facies consists essentially of ignimbrite sequences of rhyolitic composition, and minor occurrences of breccias.

The Vila Riozinho Formation (including the magnetic pyroclastic facies) in the southeastern Tapajós Province as described by Guimarães et al. (2019) can be correlated with lithofacies of primary volcanoclastic rocks recognized by Roverato et al. (2019) as massive to banded lava flows and rheomorphic ignimbrites, as well as felsic volcanoclastic rocks of subaerial to subaqueous transition (reworked/secondary volcanoclastic rocks).

The Serra Alkali Feldspar Granite (hereafter Serra Granite), as defined by Guimarães et al. (2019), holds fine-to medium-grained equigranular pinkish rocks with no ductile tectonic fabric. The granophyric texture in quartz and potassium feldspar grains is commonly found. The mafic phase is represented by brown biotite lamellae (5%), which are weakly chloritized (pennine variety), with associated magnetite. One body of Serra Granite occurs in contact (intrusive/tectonic?) with the magnetic pyroclastic facies of the Vila Riozinho Formation (Fig. 3). The gold-silver mineralization in the Coringa deposit is partially hosted at the contact between the Vila Riozinho Formation and one of the bodies of the Serra granite (Fig. 3).

The Maloquinha Intrusive Suite crops out as several stocks distributed throughout the study area. This unit intruded both the Creporizão

Intrusive Suite and the Vila Riozinho Formation, and, apparently, the Iriri Group (Fig. 3). This suite, in the southeast of TMP, consists of pinkish, medium-to coarse-grained inequigranular to porphyritic rocks, which are mostly magnetic. Guimarães et al. (2019) identified syenogranite and monzogranite varieties, and subordinate quartz-monzonite. Rapakivi texture is typical, and the suite exhibits pegmatite and aplite pockets. The concentration of mafic minerals (essentially biotite, rare hornblende) is variable depending on the location within the granitic body, decreasing towards the pluton margins.

The Novo Progresso Formation forms NNW-SSE-trending elongated and discontinuous hills composed of sedimentary rocks dominated by sandstones and siltstones with volcanic contributions (Guimarães et al., 2015; Klein et al., 2018) (Fig. 3). U–Pb LA-ICP-MS data in detrital zircon from a lithic arenite show two well-defined peaks at 1846 and 1968 Ma, and statistically secondary peaks. These results indicate a maximum sedimentation age at ca. 1840 Ma, and that surrounding Orosirian rocks from the Tapajós Mineral Province and Iriri-Xingu Domain (including their counterparts in the Guiana Shield) were probably the main sources for the sediments. This is consistent with the low maturity of the sediments and proximal sources (Klein et al., 2018).

3. Materials and methods

The preparation and chemical analyses of whole rock were carried out at SGS Geosol Laboratories Ltda, in Belo Horizonte-MG, Brazil. The major element oxides (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , MnO , Na_2O , K_2O , P_2O_5) were analyzed by ICP-ES (Induced Coupled Plasma-Emission Spectrometry) and/or X-Ray Fluorescence, and trace elements, including the Rare Earths (Ba, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Zr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) by ICP-MS (Induced Coupled Plasma - Mass Spectrometry), after fusion with lithium metaborate. The elements Mo, Cu, Pb, Zn, Ni, As, Cd, Sb, Bi, Au, Ag, Hg, Tl, and Se were diluted by a mixture of HNO_3 and HCl and concentrations were obtained by ICP-MS. Analysis quality and accuracy were controlled by repeated analyses of blanks (below the minimum detection limit for each element) and of internal standards SG_142 and TILL-3. Chemical diagrams were mostly generated using the GCDkit software (Janousek et al., 2006).

The concentration of zircon crystals for U–Pb and Lu–Hf analyses was performed in the Geological Survey of Brazil (CPRM) preparation laboratories in Belém, Pará. Samples were crushed, and the fraction below 500 μm was extracted by sieving. This material was tapped to the concentration of the heavy minerals, which passed through the Frantz isodynamic separator. The non-magnetic fraction (at 1.8 Ampère) of heavy minerals was refined by micro panning in a Petri dish and by manual separation in a binocular microscope. For the preparation of the mounts, about 50 zircon crystals were fixed in double-sided tape. The crystals were embedded in epoxy resin (cold), worn for exposing the interior of the grains and polished in 0.25 mm diamond paste. Four zircon U–Pb analyses by LA-MC-ICP-MS were performed at the Geochronology Laboratory of the University of Brasília (UnB), Brazil, and two samples were analyzed at the Geochronology Laboratory of the Federal University of Pará, Belém, Brazil (Pará-Iso). The mounts were cleaned with nitric acid (3%), Nanopure® water in ultrasound and finally acetone was used to extract any residual moisture. The isotopic analyses were done on an MC-ICP-MS Neptune (Thermo-Finnigan) coupled to a Nd-YAG ($\lambda = 213$ nm) Laser Ablation System (New Wave Research, USA). In both laboratories, the equipment and adopted methodologies are the same and follow the procedure presented by Buhn et al. (2009). The ablation of the grains was in 25–40 μm spots, a frequency of 10 Hz and fluence of 0.19–1.02 J/cm^2 . The ablated material was charged with a He (~ 0.40 L/min) and Ar (~ 0.90 L/min) flow. The international standard GJ-1 was used for the correction of the equipment drift, as well as the fractionation between the U and Pb isotopes. For the accuracy check, analyses were performed on the FC-1, Temora, 91500 or UQZ standards.

Data were acquired in 40 cycles/second. The data collection

procedure followed the reading sequence: one blank, one standard, four samples, one blank, and one standard. At each reading, the intensities of the masses ^{202}Hg , $^{204}(\text{Pb} + \text{Hg})$, ^{206}Pb , ^{207}Pb , ^{208}Pb , and ^{238}U were determined. The reduction of the raw data, which includes corrections for blanks, equipment drift, and common lead, were carried out using an in-house EXCEL worksheet. The ages were calculated using the ISOPLOT 3.0 (Ludwig, 2003) package.

The Lu–Hf analyses in zircon were performed at the University of Brasília and followed the procedure described by Matteini et al. (2010), where isotope data were collected during 40 s long ablation cycles, using a 40 μm spot diameter. The relationship between the isotopes with mass 171, 173, 175, 176, 177, 178, 179 and 180 was determined. The measurements were made close to the previous laser ablation pit left by U–Pb analyses, aiming to sample the same portion of the zircon grain.

The measured isotope ratios were processed off-line in order to choose only the homogenous portions of an analyzed zircon grain. To remove isobaric interferences of ^{176}Yb and ^{176}Lu on mass ^{176}Hf , interference-free isotopes ^{171}Yb , ^{173}Yb and ^{175}Lu have been monitored during the analyses. To correct mass-bias fractionation the ^{176}Lu and ^{176}Yb were calculated using a $^{176}\text{Yb}/^{173}\text{Yb}$ normalization factor of 0.796218 (Chu et al., 2002), whereas Hf isotope ratios were normalized to a $^{179}\text{Hf}/^{177}\text{Hf}$ factor of 0.7359 (Chu et al., 2002). Data reduction and calculations were done using an EXCEL® spreadsheet from Milhomem Neto et al. (2017). The $\epsilon\text{Hf}(t)$ values were calculated using the decay constant $\lambda = 1.865 \times 10^{-11}$, proposed by Scherer et al. (2001) and $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ CHUR values of 0.0336 and 0.282785 (Bouvier et al., 2008). The two stages depleted mantle Hf model ages (TDM Hf) are calculated using $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ and $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ for the depleted mantle (Chauvel and Blichert-Toft, 2001) and $^{176}\text{Lu}/^{177}\text{Hf}$ value of 0.0113 for the average crust (Taylor and McLennan, 1985; Wedepohl, 1995).

The Sm–Nd isotopic analyses of whole-rock samples were performed at the Geochronology Laboratory of University of Brasília using a multi-collector Finnigan MAT 262 mass spectrometer in static mode and followed the method described by Gioia and Pimentel (2000). Whole-rock powders (ca. 50 mg) were mixed with a ^{149}Sm – ^{150}Nd spike solution and dissolved in HF , HNO_3 , and HCl in Savillex capsules. Sm and Nd extraction was done by cation exchange techniques, using Teflon columns containing LN-Spec resin (HDEHP—di-ethylhexil phosphoric acid supported on PTFE powder). Sm and Nd samples were loaded onto Re evaporation filaments of a double filament assembly. Uncertainties for Sm/Nd and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are better than $\pm 0.5\%$ (2σ) and $\pm 0.005\%$ (2σ), respectively, based on repeated analyses of the international rock standards BHVO-1 and BCR-1. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd}$ of 0.7219. TDM values were calculated using De Paolo (1981) model.

4. Whole-rock geochemistry

The results of whole-rock geochemistry of granitic and volcanic samples performed in this work are shown in Appendices 1 and 2.

4.1. Creporizão Intrusive Suite

The rocks of the Creporizão Intrusive Suite show SiO_2 content varying between 60 and 76%, which gives composition varying from predominantly granite and granodiorite to subordinate tonalite and rare diorite. These compositions plot in the more evolved portion of the evolutionary trend of the whole suite (Fig. 4). The suite shows a high-K to shoshonitic, calc-alkalic to alkali-calcic, metaluminous to weakly peraluminous, and magnesian to minor ferroan signature (Fig. 5). Despite some scattering of the data, a positive covariation between the SiO_2 and K_2O contents (Fig. 5a), and between SiO_2 and the $\text{FeOt}/(\text{FeOt} + \text{MgO})$ ratio is observed (Fig. 5c), whereas CaO and TiO_2 show inverse covariation with SiO_2 (Fig. 5e and f).

The distribution of trace elements shows strong fractionation

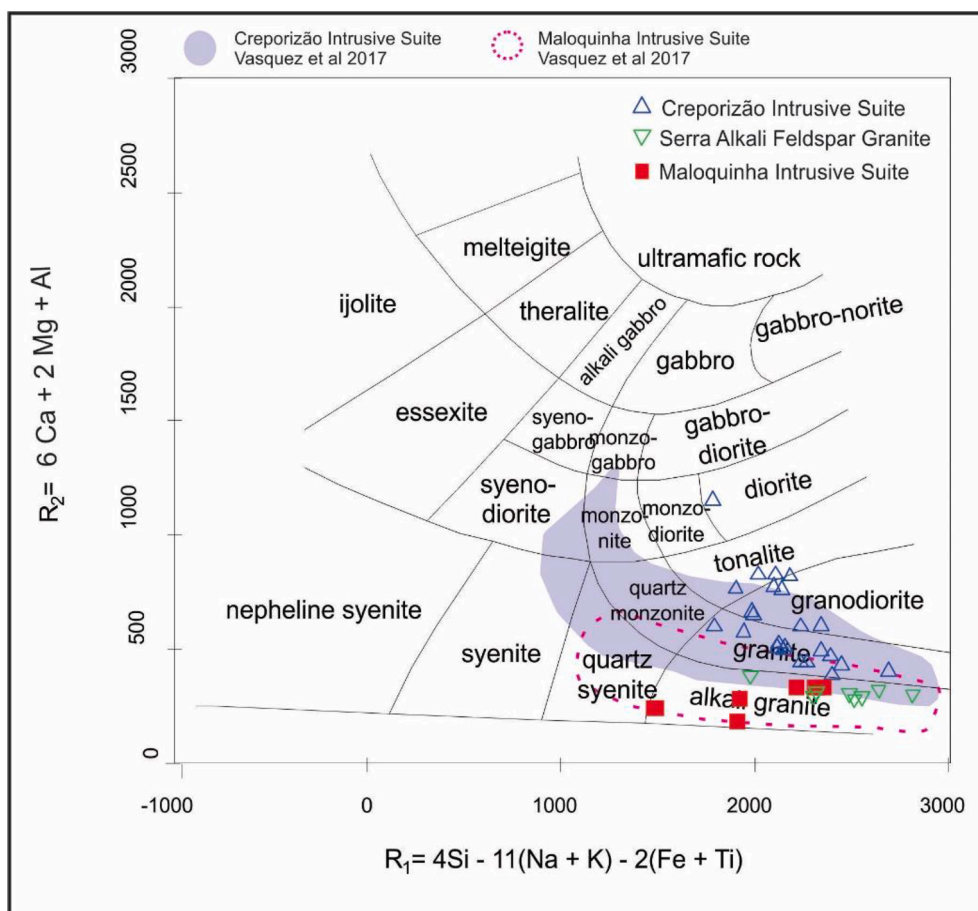


Fig. 4. R1-R2 diagram of chemical classification of plutonic rocks (De La Roche et al., 1980) for samples of granites of the southeastern Tapajós Mineral Province.

between LILE and HSFE, and presence of Ta, Nb, Sr, P, and Ti negative anomalies (Fig. 6a). This is similar to that what is found for the same unit in the eastern portion of the Tapajós Province (Vasquez et al., 2017), except for the discrepancy in the positive anomaly in Ba present in the southeast of TMP. Sr/Y ratios are low to moderate (7–60).

The REE patterns show strong enrichment of LREE, relatively little fractionation of HREE (La/Yb_n ratio = 4.35 to 19.5), and weak to moderate negative Eu anomaly (Eu/Eu* = 0.52 to 1.01) (Fig. 6d). When comparing our rocks with the Creporizão Suite rocks from elsewhere in Tapajós Province (Fig. 6a), the fractionation is similar, with the same pattern but with less content of REE.

4.2. Serra Alkali Feldspar Granite

The Serra Alkali Feldspar Granite samples present SiO₂ content of 71–78.50%, K₂O over 4%, and plot only in the field of alkali granites (Fig. 4). However, the granites are not typically alkaline, but alkali-calcic and reduced ferroan (cf. Frost and Frost, 2013, and Dall'Agnol and Oliveira, 2007 - Figs. 5 and 7). The samples are both metaluminous and peraluminous, but plot nearly parallel to the peralkaline field limit (Fig. 4B). In general, the Serra Granite samples occupy the high-SiO₂ extreme in chemical trends of the Creporizão Suite (Fig. 5).

The granites exhibit very low (<5) Sr/Y ratios. The negative anomalies of Ba, Ta, Nb, Sr, P and Ti (Fig. 6b), are in part similar to those presented by the Creporizão and Maloquinha Suites' rocks. However, the anomalies are more pronounced in the Serra Granite rocks. The REE patterns are enriched in relation to the chondrite (Fig. 6e), and reveal a strong negative anomaly of Eu (Eu/Eu* = 0.01–0.47), suggesting strong fractionation of plagioclase.

4.3. Maloquinha Intrusive Suite

The granitoids of the Maloquinha Intrusive Suite have SiO₂ content between 71.0 and 73.7% and are grouped in the alkali granite in the R1-R2 diagram (De La Roche et al., 1980) (Fig. 4). The Maloquinha Suite rocks show peraluminous to metaluminous, alkali-calcic to alkali, and ferroan signature (Fig. 5).

The trace elements pattern (Fig. 6c) shows negative anomalies of Ba, Ta, Nb, Sr, P and Ti, similar to the Maloquinha Suite described elsewhere in the Tapajós Province (Vasquez et al., 2017). The REE patterns show moderate to strong fractionation between LREE and HREE (La/Yb_n = 11.40–20.14), and moderate negative Eu anomaly (Eu/Eu* = 0.20–0.57) (Fig. 6f). The REE patterns are typical of granites which belong to the silica-saturated alkaline series (type A, Nardi and Bitencourt, 2009), which, together with the whole chemical data indicates that the Maloquinha Suite forms an oxidized, A-type, ferroan suite (Fig. 7).

4.4. Vila Riozinho Formation

The Vila Riozinho Formation in the southeast of Tapajós Province comprises rhyolitic ignimbrites, latite, rhyolite, dacite, and andesite as petrographic types (Guimarães et al., 2019) (Fig. 8). Chemically, these rocks correspond to rhyolite, dacite, and trachy-andesite, in line with what was reported by Vasquez et al. (2017) for the northeastern Tapajós Province. The rocks plot in the field of calc-alkaline and high-K to shoshonite series, which is corroborated by Lamarão et al. (2002) in the type area of the Vila Riozinho Formation, and show predominantly metaluminous and magnesian tendency (Fig. 9).

Negative anomalies of Ta, Sr, Nb, P, and Ti were observed in the

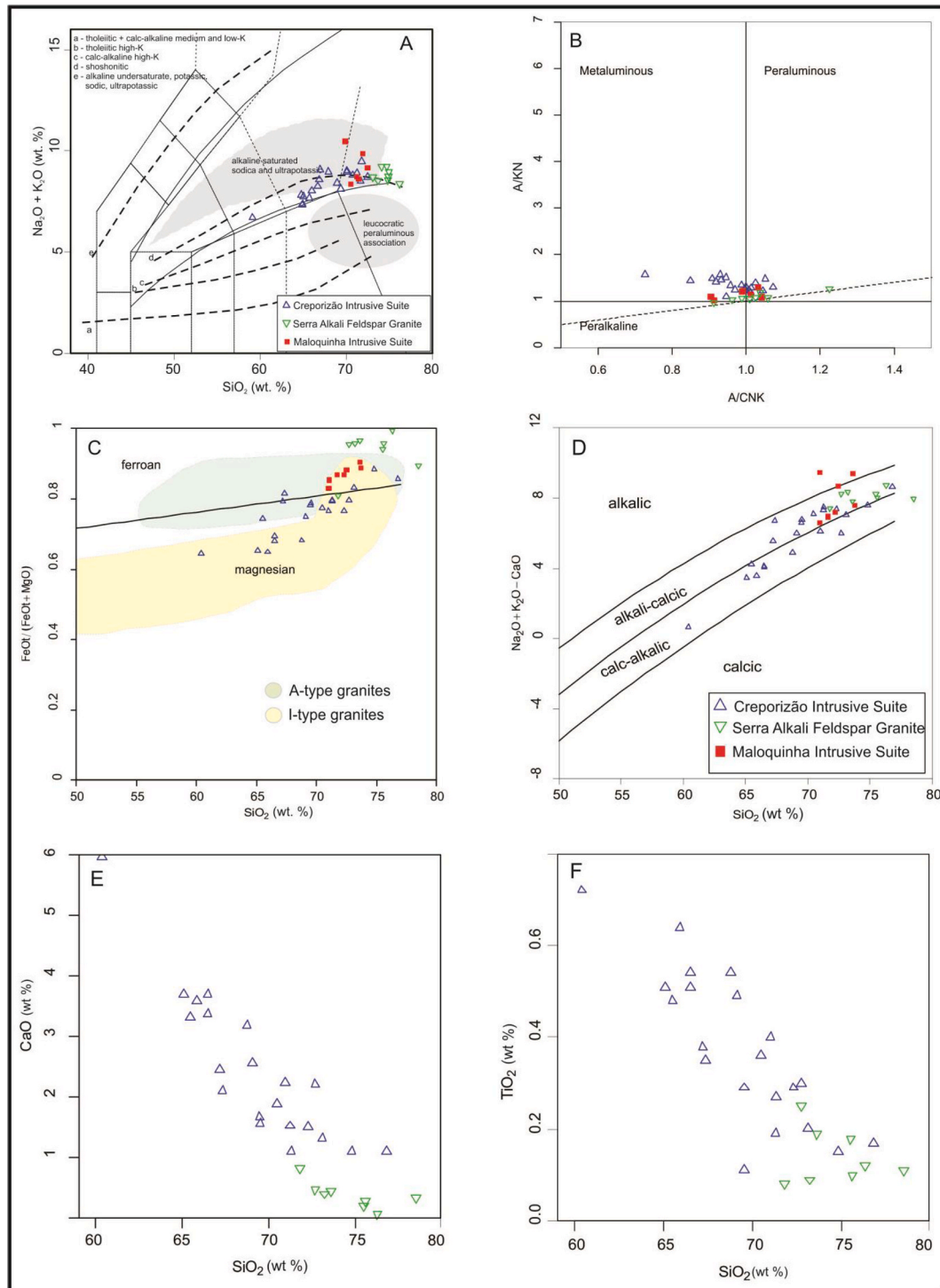


Fig. 5. Discriminant diagrams for granitic suites of the southeastern Tapajós Mineral Province, after (A) Nardi (2016), (B) Maniar and Piccoli (1989), (C and D) Frost et al. (2001), including the fields of I- and A-type granites, (E) binary diagram $\text{SiO}_2 \times \text{CaO}$, (F) binary diagram $\text{SiO}_2 \times \text{TiO}_2$.

multielement diagram normalized to the primitive mantle. Rare earth element patterns show fractionations between light and heavy elements ($\text{La}/\text{Yb}(n) = 17\text{--}29$), and moderate to absent Eu anomaly, given by Eu/Eu^* ratios of 0.5–1.10. Similar behavior was observed for the same unit by Vasquez et al. (2017). The Sr/Y ratios are relatively low (<69), and compatible with those of calc-alkaline rocks.

4.5. Vila Riozinho Formation – magnetic pyroclastic facies

The magnetic pyroclastic facies of the Vila Riozinho Formation comprise, chemically, rhyolite/dacite, and quartz trachyte, which slightly differs from the evolution trend presented by the Vila Riozinho Formation as a whole (Fig. 8). There is a large predominance of ferroan alkalic rocks, with weakly peraluminous to metaluminous character (Fig. 9). The ferroan-alkalic signature, indicating relatively more reduced conditions of crystallization, is a significant difference in

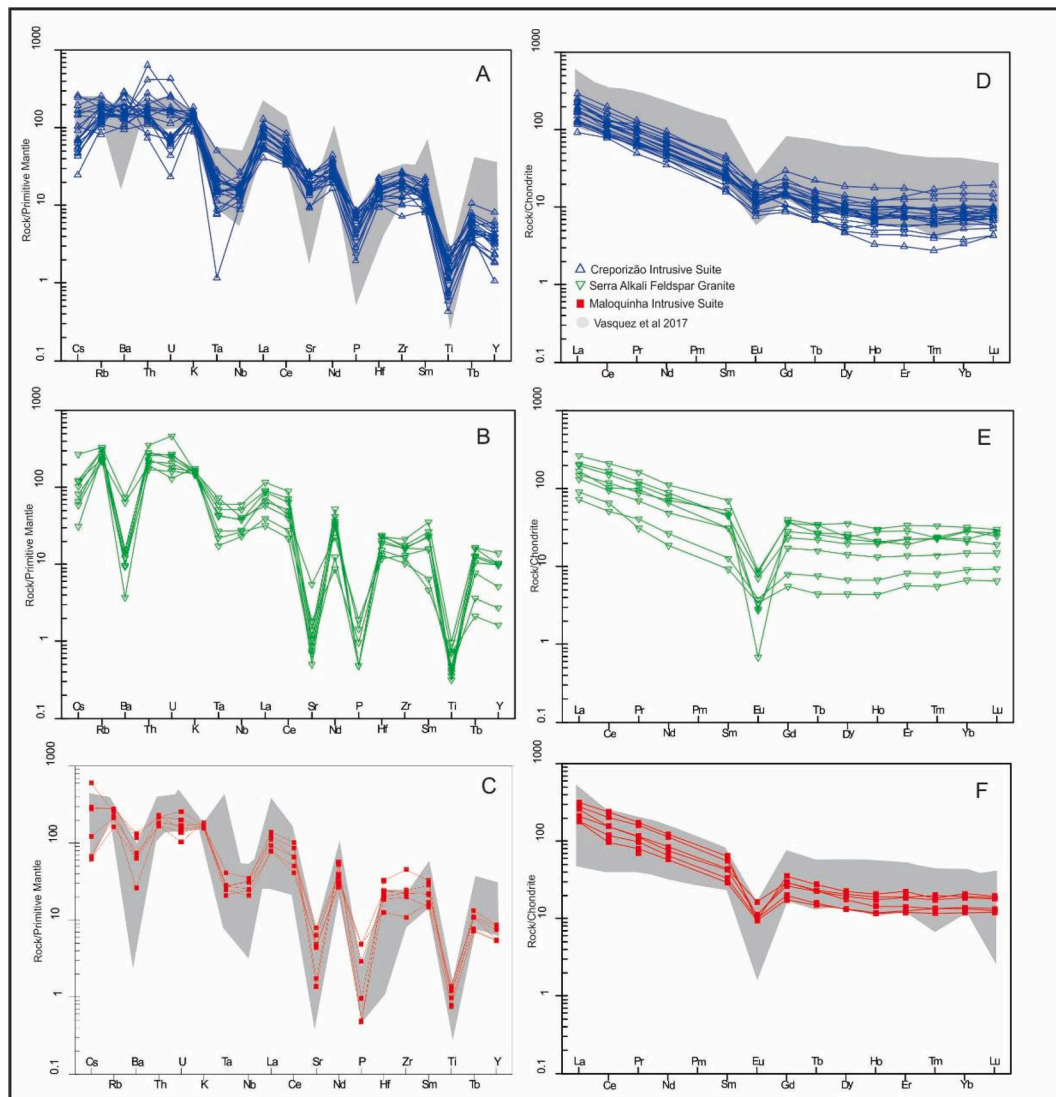


Fig. 6. Trace-element variation spectra of granite suites of the Southeastern Tapajós Gold Province. A, B, and C: normalized to the primitive mantle, according to Wood et al. (1979). D, E, and F: Rare earth element spectra of the same suites normalized to the chondrite of Boynton (1984). The gray polygons refer to the same units described elsewhere in the Tapajós Mineral Province by Vasquez et al. (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

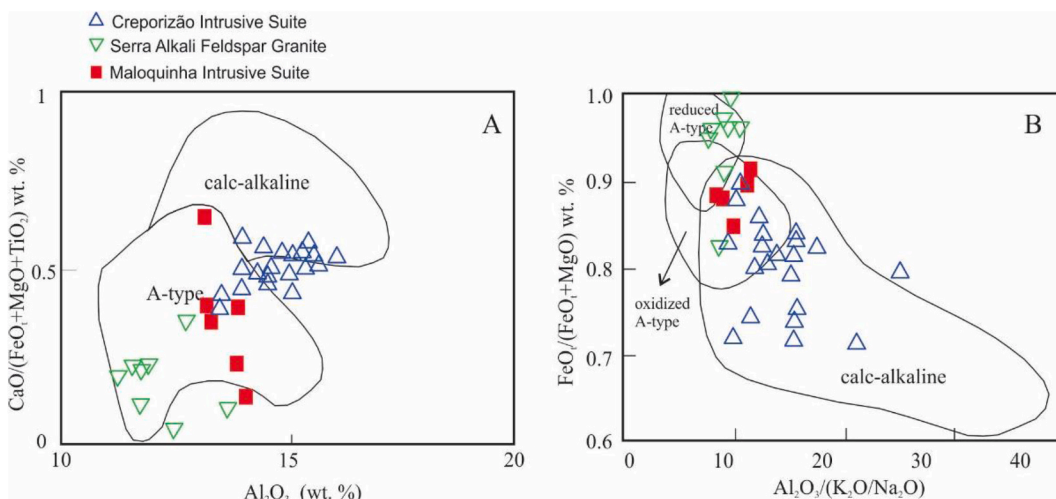


Fig. 7. Discriminant diagram of granites of Dall'Agnol and Oliveira (2007), with the fields of A-type and calc-alkaline granitoids.

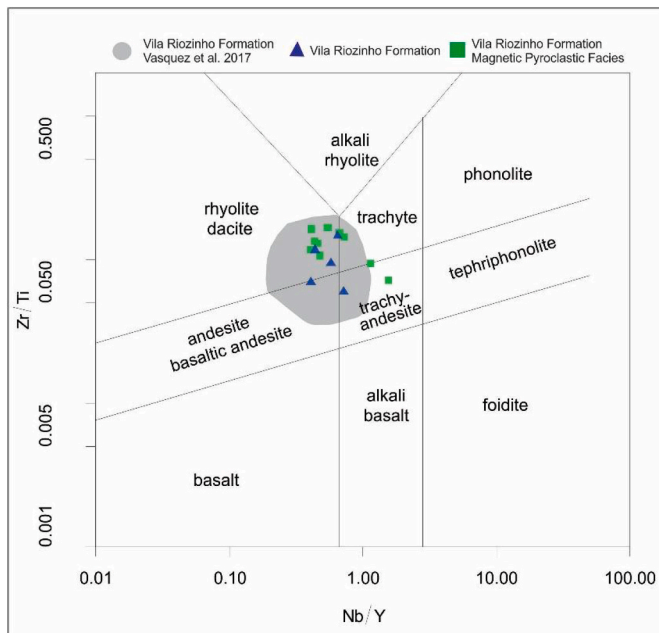


Fig. 8. Diagram for the chemical classification of volcanic rocks (Winchester and Floyd, 1977, modified by Pearce, 1996) for the Vila Riozinho Formation and the Magnetic Pyroclastic Facies. For comparison, the compositional field of the Vila Riozinho Formation from Vasquez et al. (2017) in the northeastern portion of the Tapajós Gold Province is provided. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

relation to the “normal” Vila Riozinho Formation.

The rare earth element patterns show LREE to HREE fractionation and total concentrations higher than the presented by the Vila Riozinho Formation, along with discrete to moderate Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.50$ to 1.10) (Fig. 10c). In the multielement diagram normalized to the primitive mantle, we see similarities with the Vila Riozinho Formation rocks, but the negative breaks in Sr, P, and Ti are closer to the Vila Riozinho Formation in the type localities than in the southeastern TMP itself (Fig. 10d). The Sr/Y ratios are very low (<17).

5. U–Pb LA-ICP-MS in zircon

To improve the understanding of the newly units mapped by Guimarães et al. (2019) in the southeast of the Tapajós Province, one sample from the Maloquinha Intrusive Suite, three samples attributed to the Serra Alkali Feldspar Granite, and four samples from the Vila Riozinho Formation – Magnetic Pyroclastic facies were dated by U–Pb LA-ICP-MS in zircon. Data tables are presented in Appendix 3.

5.1. Serra Alkali Feldspar Granite

Two samples from the southern body of the Serra Granite, which hosts the gold mineralization at Coringa (CE3A, SG83), and one sample from the northern body (SG61A) have been analyzed.

The sample CE03A is an alkali feldspar granite whose zircon crystals are clear, bipyramidal, with 2:1 aspect ratio, 400 to 200 μm in size, and without fractures. In the cathodoluminescence image, the zircons show strong oscillatory zonation and lack overgrowth. Sixteen spots in fifteen crystals were analyzed; six results were not used to calculate the age because of the high content of common lead, and one result (zircon n° 20) with the apparent age of 2634 ± 11 Ma was interpreted as

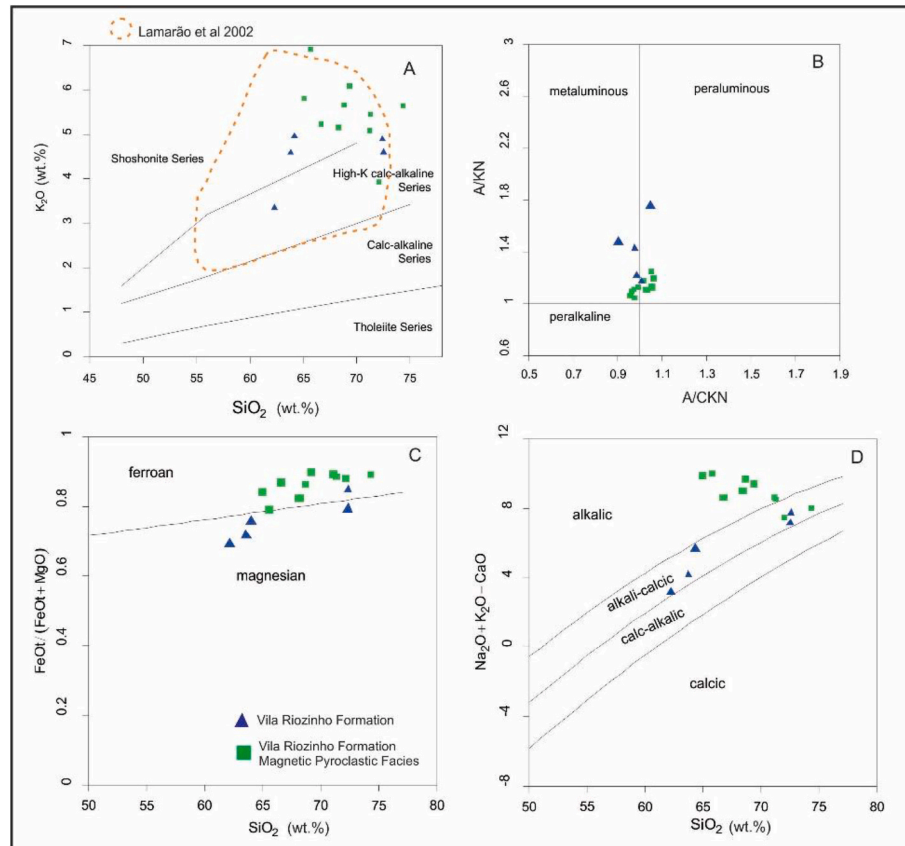


Fig. 9. Discriminant diagrams for the Vila Riozinho Formation and the Magnetic Pyroclastic Facies. (A) Peccerillo and Taylor (1976), (B) after Maniar and Piccoli (1989), (C and D) Frost et al. (2001).

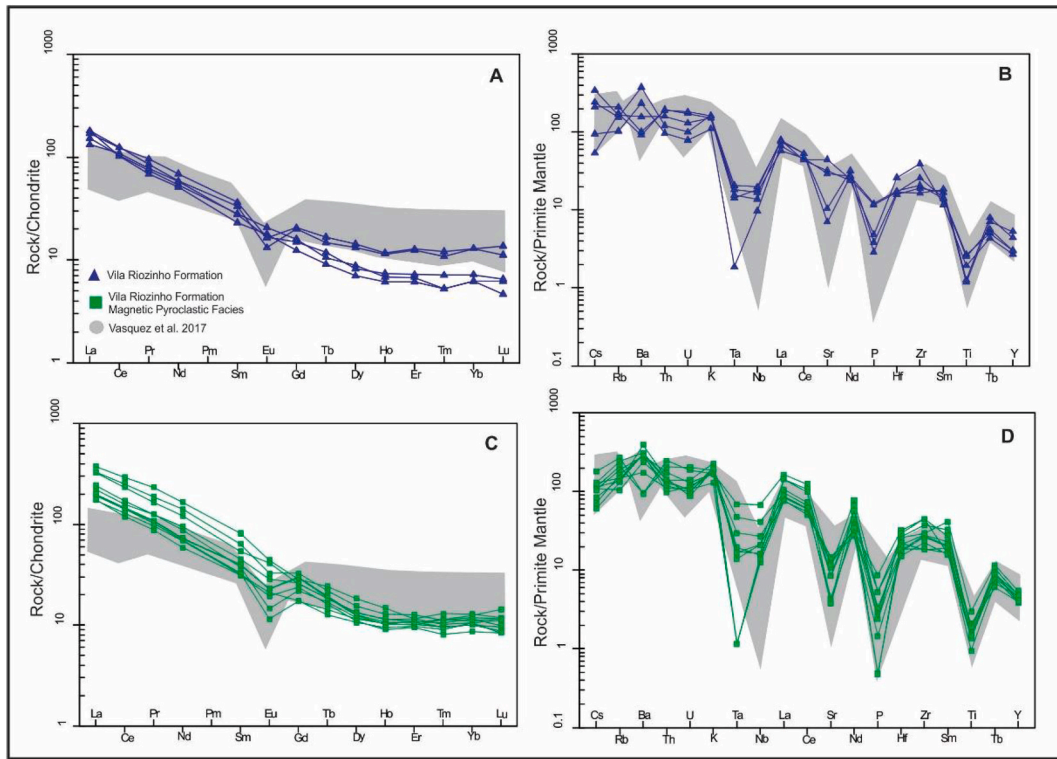


Fig. 10. Variation spectra of elements from the Vila Riozinho Formation and Vila Riozinho Formation – Magnetic Pyroclastic Facies. (A) and (C) REE normalized to the chondrite of Boynton (1984); (B) and (D) Spectra of rare earth elements normalized to the primitive mantle, according to Wood et al. (1979). Gray polygons correspond to the Vila Riozinho Formation described in the eastern portion of the Tapajós Mineral Province (Vasquez et al., 2017).

inheritance or contamination during magma ascent (xenocrystal). The other spots were used in the linear regression, whose superior intercept provided the age of 1998 ± 6 Ma, associated with MSWD of 1.2 (Fig. 11a), which is interpreted as the crystallization age of the sample.

Sample SG-83 has zircon crystals of medium size (150–400 μm)

euohedral, prismatic, bipyramidal, with some fractures and inclusions. In cathodoluminescence image, one can observe strong oscillatory zonation and no overgrowth. In this sample, 26 spots were analyzed in the same number of crystals; in these, seven spots were discarded due to the high content of common lead or large analytical error. The other data

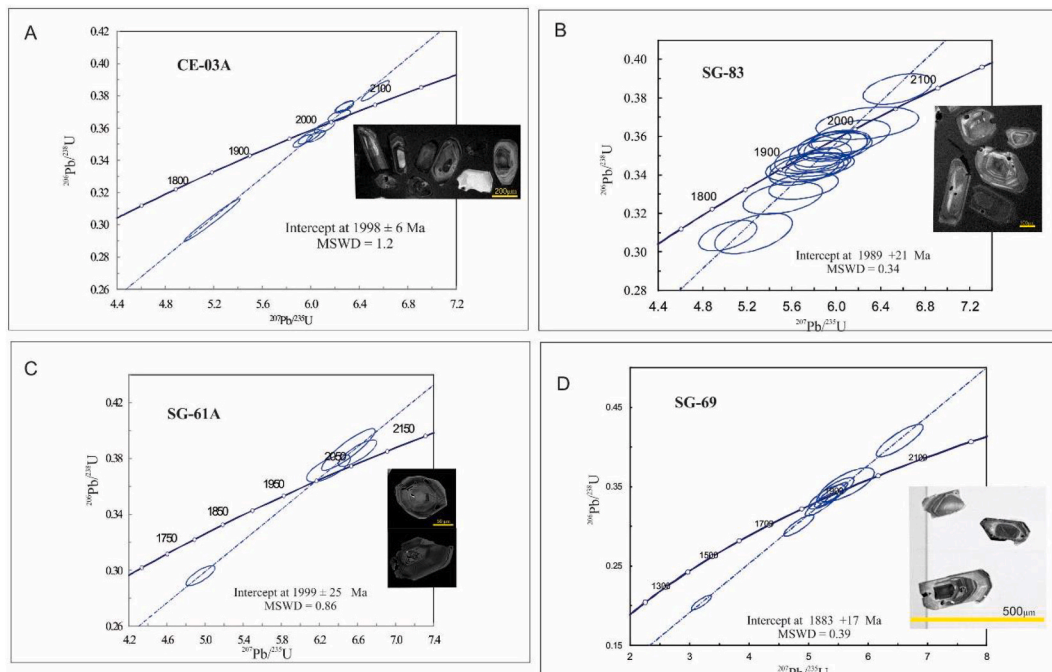


Fig. 11. – (A, B, C) Concordia diagrams for samples of the Serra Alkali Feldspar Granite. Images of selected zircon crystals by cathodoluminescence (samples CE-03A and SG-83) and backscattered electron image (BSE) (SG-61 sample); (D) Concordia diagram for sample of the Maloquinha Intrusive Suite (SG-69), zircons images by cathodoluminescence.

were all used in age calculation, and the upper intercept provided the age of 1989 ± 21 Ma, associated with MSWD of 0.34 (Fig. 11b), and interpreted to be the age of crystallization of the sample.

The SG-61 sample is an alkali feldspar granite with finer grain size than the other two examples dated in this study. The zircon crystals are very small (100–200 μm), euhedral, prismatic, bipyramidal and show fractures. In backscattered electron imaging (BSE) oscillatory zonation was observed, and no overgrowth is present. Few crystals of zircon were recovered from this sample. Isotopic compositions of nine spots were determined in nine crystals, and five spots revealed high content of common lead or large analytical error, which led to the rejection for age calculation. The other results yielded an upper intercept, which defines an age of 1999 ± 25 Ma, associated with MSWD of 0.86 (Fig. 11c), considered to be the age of crystallization of the sample.

The ages of the three samples are similar within analytical uncertainties, and all can be used as the age of granite crystallization.

5.2. Maloquinha Intrusive Suite

The sample SG 69 is a syenogranite with granophyric texture, which is common in rocks of this suite. The zircon crystals are euhedral, prismatic, bipyramidal, with few fractures, and 50–350 μm size. In

cathodoluminescence image, oscillatory zonation was observed, and no overgrowth is present. Isotopic compositions of fifteen spots were determined in thirteen crystals, and seven spots revealed analytical error or high discordance, which led us to the discard them from age calculation. The other results yielded a regression line with an upper intercept, which defines an age of 1883 ± 17 Ma, associated with MSWD of 0.39 (Fig. 11d), considered to be the age of crystallization of the sampled granite.

5.3. Vila Riozinho Formation - magnetic pyroclastic facies

CE-06 is a rhyolitic ignimbrite sample with strong sericitization, hematite alteration, and pyrite dissemination. The zircon crystals are 100–400 μm in size, euhedral, prismatic, fractured and with inclusions. In BSE image, a homogeneous internal structure or discrete oscillatory zonation was observed (Fig. 12a). Some stains are observed along fractures, which may have been produced by percolation of fluids. For the analysis, the most preserved areas were selected, and 20 spots in 20 crystals were analyzed. Among the obtained data, eleven were discarded due to high analytical error (seven data with an error of the $^{207}\text{Pb}/^{235}\text{U}$ age greater than 4%) or high discordance (four data). The other nine data were used for the linear regression, and the upper intercept

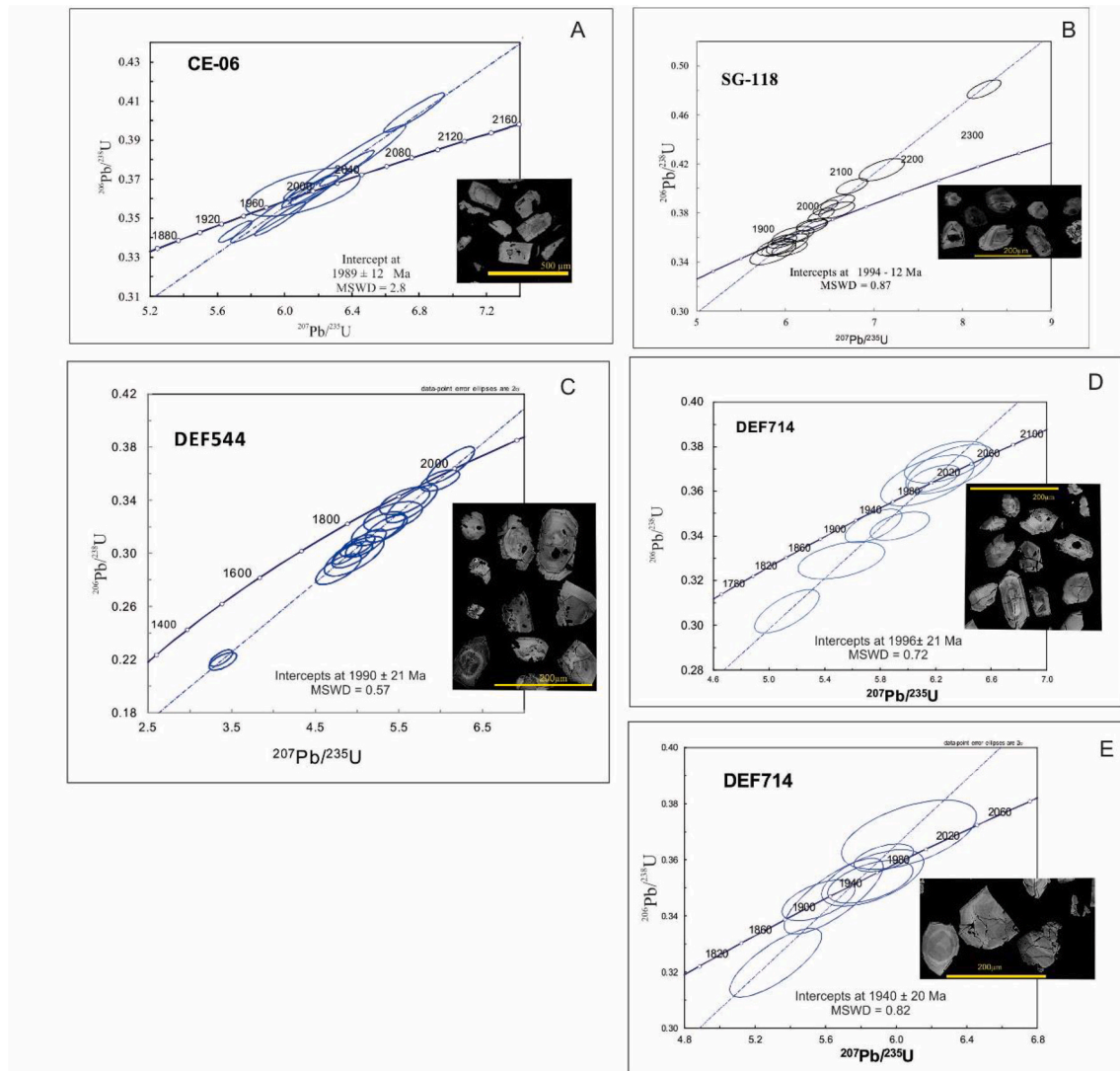


Fig. 12. Concordia diagrams for samples of the Vila Riozinho Formation – Magnetic Pyroclastic, from outcrops (A, B) and from drill holes in the Coringa Au–Ag deposit (D, E, F), with respective backscattered electron images of selected zircon crystals.

indicates the age of 1989 ± 12 Ma, associated with MSWD of 0.28 (Fig. 12a), which is interpreted to be the age of crystallization of the sample.

The sample SG-118 represents a poorly welded ignimbrite with altered phenocrysts (sericitization, chloritization, and carbonatization), and magnetite and pyrite disseminated in the matrix. The zircon crystals are prismatic with 2:1 aspect ratio, euhedral to subhedral, 50–200 μm in size, and with inclusions. In BSE image, a homogeneous internal structure or a discrete oscillatory zonation is observed (Fig. 12b). Analyses of thirty-four spots were performed in the same number of crystals, from which seventeen spots were discarded due to the high content of common lead or large analytical error. The remaining data were all used for the linear regression calculation, and the upper intercept provided the age of 1994 ± 12 Ma, associated with the MSWD of 0.84 (Fig. 12b), which is interpreted to be the age of crystallization of the sample.

Two rhyolite samples obtained from drilling holes of the Coringa deposit, DEF 544 and DEF 714, had zircons analyzed in an attempt to establish relationships with those rocks observed in outcrops. The sample DEF 544 shows pumices and preserved spherulitic texture, phenocrysts, and slightly sericitized matrix. Short prisms and few fractures and inclusions characterize the zircon morphology. In BSE images, the crystals present oscillatory zoning without overgrowth. Thirty spots were analyzed in twenty-eight crystals. Two spots were not used for the calculation of age, because of the elevated analytical errors, and thirteen were discarded due to the high degree of discordance. The other data used for the regression calculation and the upper intercept provided the age of 1990 ± 21 Ma, associated with the MSWD of 0.57 (Fig. 12c),

which is interpreted to be the age of crystallization of the sample.

Sample DEF 714 shows fine and slightly sericitized quartz-feldspathic matrix with localized hematite alteration. Two populations of zircon crystals were observed with subtle morphological differences. Population 1 shows zircons with short prism, little fractured, and similar to the zircon crystals of sample DEF 544. Population 2 shows subangular to subrounded crystals, without fractures or inclusions (Fig. 12 d, e). In BSE images, both populations have oscillatory zoning but no overgrowth. Twenty-eight spots were analyzed in nineteen crystals, six spots were discarded because of the high analytical error, five spots because of the high content of common lead and high degree of discordance, and two spots were not used for the calculation of age because of the high discordance. In the end, we used eight analyses for population 1, and seven analyses for population 2, which provided the ages of 1996 ± 21 Ma (MSWD = 0.72) and 1940 ± 19 Ma (MSWD = 0.82), respectively (Fig. 12 d, e). See the discussion section for the interpretation of the ages.

6. Lu–Hf in zircon

Hafnium isotope analyses were performed in concordant to nearly-concordant zircons from three samples dated by U–Pb in this study: one from the Vila Riozinho Formation - magnetic pyroclastic facies (CE-06), and two from the Serra Granite (CE-03A and SG-83). A fourth sample (EK-02 418,50), corresponding to a dacite porphyry of 2011 ± 6 Ma, which intruded the Castelo dos Sonhos Formation, and that was dated by Queiroz et al. (2015), was also analyzed, because this rock is

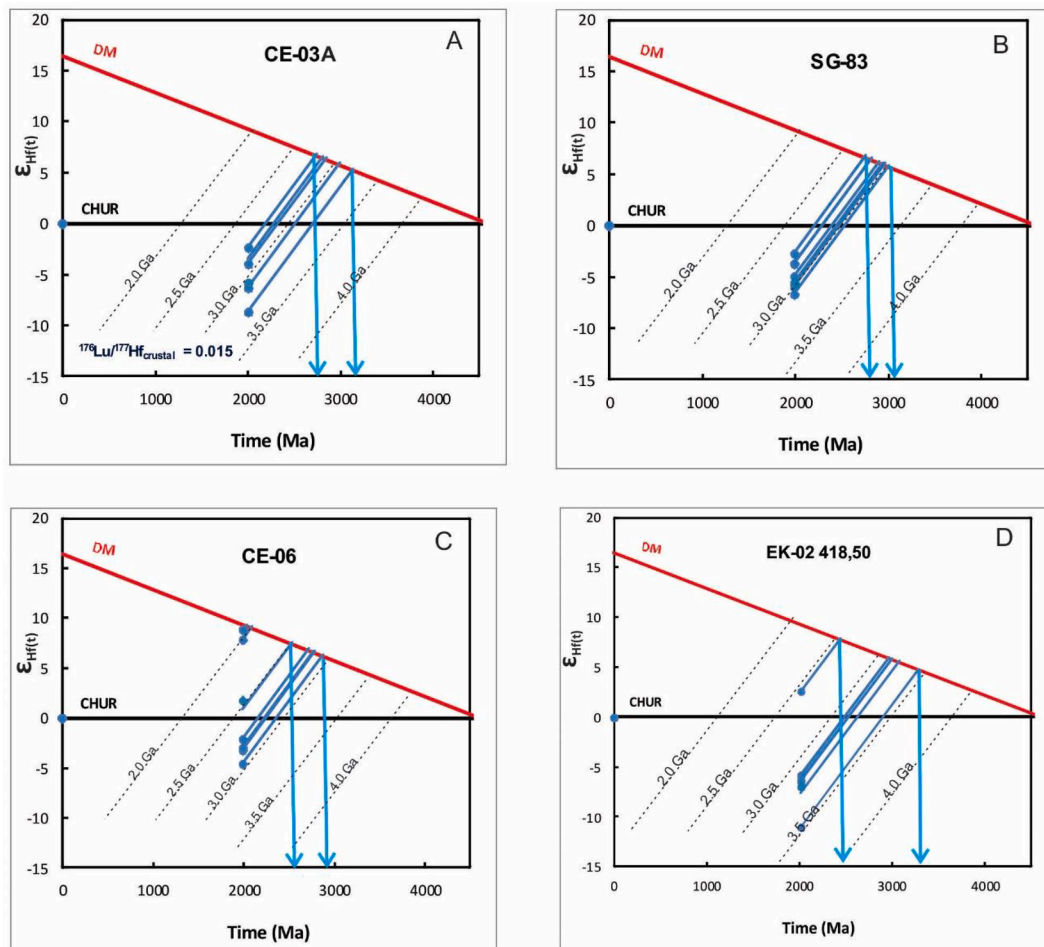


Fig. 13. Time versus $\epsilon_{\text{Hf}}(t)$ diagram for selected samples from Southeastern Tapajós Mineral Province. Sample CE-06 from the Vila Riozinho Formation (magnetic pyroclastic facies) and CE-03 and SG-83 from the Serra Alkali Feldspar Granite.

among the oldest ones found in the southeast Tapajós Mineral Province. The analyses were performed on the same zircon domains that have previously been analyzed by the U–Pb technique, and the results are presented in [Appendix 3](#) and [Fig. 13](#).

The two samples of the Serra Granite present zircons with similar Hf depleted mantle model ages varying from 2.74 to 3.13 Ga, and $\epsilon\text{Hf}(t)$ values ranging from -2.36 to -8.64 ([Fig. 13](#)). These moderate to strongly negative values, along with the old model ages indicate melting of older continental crust or OIB sources for the magmas. Considering the whole geological setting the melting of continental crust and interaction with mafic magmas is the more likely process in the petrogenesis of the Serra Granite (see also the discussion section).

Zircons from the Vila Riozinho Formation - magnetic pyroclastic facies (sample CE-06) present model ages in the range of 2.03–2.78 Ga, and $\epsilon\text{Hf}(t)$ values of $+8.81$ to -4.61 ([Fig. 13](#)). These model ages and $\epsilon\text{Hf}(t)$ values indicate melting of older continental crust and juvenile input in the genesis of the parental magma of the Vila Riozinho Formation. Juvenile magmas are those produced by melting of the depleted mantle or by remelting of material recently extracted from the mantle (e.g., [Belousova et al., 2010](#)).

The dacite porphyry sample (EK-02 418,50) present zircons with model ages varying from 2.44 to 3.08, and $\epsilon\text{Hf}(t)$ values of -5.81 to -11.01 , with one positive value of $+2.54$. These patterns of negative values with old model ages can indicate melting of older continental crust, as observed in the Serra Granite samples. [Queiroz et al. \(2015\)](#) observed geochemical similarities with the subalkaline granitoids of the Creporizão Intrusive Suite, although correlated the dacite porphyry with the Comandante Arara Formation.

7. Whole-rock Sm–Nd

Nine samples were investigated for their Sm–Nd isotope compositions. Four samples of the Serra Granite, four volcanoclastic samples attributed to Vila Riozinho Formation – Magnetic Pyroclastic Facies, and one sample of monzogranite from the Maloquinha Intrusive Suite. The results are presented in [Table 1](#). Most of the samples show $^{147}\text{Sm}/^{144}\text{Nd}$ ratios and $f\text{Sm–Nd}$ values within the normal range for the rock type.

Samples from Serra Granite presented $^{147}\text{Sm}/^{144}\text{Nd} = 0.0920$ to 0.1321 , TDM from 2.27 to 3.15 Ga, and $\epsilon\text{Nd}(t)$ values ranging from $+0.1$ to -8.0 , indicating predominance of crustal sources in magma genesis. The samples from the magnetic facies of the Vila Riozinho Formation show $^{147}\text{Sm}/^{144}\text{Nd} = 0.0960$ to 0.0880 , and TDM between 2.38 and 2.42 Ga, with $\epsilon\text{Nd}(t)$ values of -2.1 to -3.2 . The Maloquinha Suite monzogranite has of $^{147}\text{Sm}/^{144}\text{Nd} = 0.1102$ and a TDM of 2.50 Ga, with $\epsilon\text{Nd}(t)$ value of -0.17 .

In the Nd evolution diagram, all samples show similar behavior

([Fig. 14](#)), and all also show negative epsilon values. The SG123 sample, in spite of the abnormal parameters, has evolution identical to the other samples from VRF. The SG83 sample from Serra Granite differs in evolution pattern if compared to others, but it is still considered suitable for Tapajós Domain according to [Vasquez et al., \(2008a, 2008b, 2017\)](#), and [Fernandes et al. \(2011\)](#) ([Fig. 14](#)).

8. Discussions

8.1. Timing and types of magmatism in the southeastern Tapajós Province

The magmatic rocks of the Southeastern Tapajós Province comprise units already described elsewhere in the Province (Crepurizão, Parauari, and Maloquinha granitic suites, volcanic/volcanoclastic Vila Riozinho Formation – [Vasquez et al., 2008a, 2008b, 2017](#); [Lamarão et al., 2002](#)), in addition to units mapped and/or described more recently (Serra Alkali Feldspar Granite, Vila Riozinho Formation – magnetic pyroclastic facies, [Guimarães et al., 2015, 2019](#) - and concealed intrusions in the Castelo dos Sonhos Formation – [Queiroz et al., 2015](#)). These units can be grouped in the following order of formation and magmatic associations ([Table 2](#)).

8.1.1. Calc-alkaline dacites (>2.00 Ga)

The dacite porphyry of 2011 ± 6 Ma that intruded the sedimentary Castelo dos Sonhos Formation, was defined by [Queiroz et al. \(2015\)](#) as a calc-alkaline metaluminous rock, with chemical characteristics compatible with both volcanic arc and post-collisional suites. This dacite unit (even not cropping out) can be correlated with the Comandante Arara Formation and represents the oldest known magmatic unit in the southeastern Tapajós Mineral Province. From a chronological point of view, this magmatism is also coeval with the Cuiú-Cuiú Complex.

The Hf isotopes results with model ages varying from 2.44 to 3.08, and negative epsilon values can indicate melting of older continental crust, as observed in the Serra Granite samples (more detailed below).

8.1.2. High-K subalkaline granitoids (~2.00–1.96 Ga)

The Creporizão Intrusive Suite and the Serra Granite were formed within the same time interval. Creporizão presents a wide range of ages in the Tapajós Mineral Province, between 1987 and 1960 Ma (compiled by [Vasquez et al., 2017](#)), and Serra formed at 1998 to 1989 Ma (this work). Both Serra and Creporizão comprise high-K to shoshonitic and metaluminous to peraluminous granites ([Fig. 5](#)). As a whole, the chemical characteristics show features of both I-type and A-type granites ([Fig. 15](#)). The geochemical characteristics (including the REE) of the Serra Granite are in part similar to those presented by the Creporizão Suite rocks and consistent with those of orogenic I-type granites.

Table 1

Table of Nd isotope results data from southern Tapajós samples. t (Ga) = U–Pb ages in zircon obtained in this work.

Sample	Sm	Nd	Sm/Nd	$f\text{Sm/Nd}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_0$	$\epsilon(t)$	TDM (Ga)	Age (t)	Rock type	Unit
EK1A	9.75	61.43	0.15873	-0.51195	0.096	0.511212	-2.1	2.38	1989	Dacitic	Vila Riozinho Formation
EK4_76.75m	5.66	35.10	0.16112	-0.50483	0.0974	0.511175	-3.2	2.46	1989	Ignimbrite	Magnetic Pyroclastic Facies
SG75	6.173	38.885	0.15874	-0.51215	0.0960	0.511183	-2.6	2.42	1989	Ignimbrite	Vila Riozinho Formation
SG123	13.140	90.276	0.14555	-0.55271	0.0880	0.511066	-2.9	2.41	1989	Porphyry	Magnetic Pyroclastic Facies
EK124_120.30m	7.65	41.95	0.18234	-0.44026	0.1101	0.511507	0.1	2.27	1998	Andesite	Vila Riozinho Formation
SG83	4.31	19.74	0.21852	-0.32842	0.1321	0.511384	-8.0	3.15	1989	Welded ignimbrite	Magnetic Pyroclastic Facies
SG22	6.435	35.285	0.18237	-0.43956	0.1102	0.511359	-2.8	2.50	1974	Alkali Feldspar Granite	Serra Alkali Feldspar Granite
SG61A	2.484	16.319	0.15219	-0.53230	0.0920	0.511233	-0.6	2.27	1999	Alkali Feldspar Granite	Serra Alkali Feldspar Granite
SG57	12.869	81.020	0.15884	-0.51186	0.0960	0.511384	-0.17	2.15	1888	Monzogranite	Serra Alkali Feldspar Granite
										Monzogranite	Maloquinha Intrusive Suite

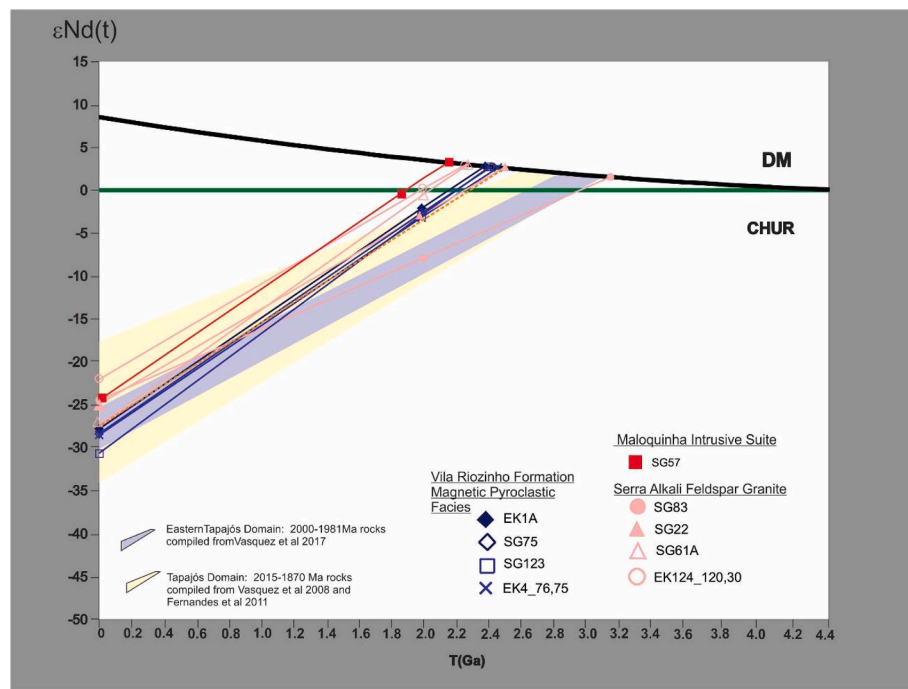


Fig. 14. Time versus ϵNd diagram for samples of granites and volcanic rocks from the Southeastern Tapajós Mineral Province.

However, the Serra Granite shows higher SiO_2 contents (>71 wt%), is typically ferroan and reduced and shows high Ga/Al ratios, which is akin to A-type granites (also Fig. 7).

It is interesting to observe that the chemical data of the Serra Granite and the Creporizão Suite form grossly a linear trend (Fig. 5A, C, 5D, 5E, and 7). Considering the range of silica and other geochemical parameters, as well as textural evidence, it is clear that feldspars have an important role in the magmatic evolution of the granites. Ba and Sr, elements that are strongly compatible in granitic systems, show large variation in the studied granites. The Rb, Sr, Ba, and Ni variations are useful in estimating the extent of fractionation of these minerals and whether magmatic evolution was controlled dominantly by fractional crystallization, partial melting, or more complex processes (Hanson, 1978; Cocherie, 1986). Accordingly, in the studied rocks, the crystallization of alkali feldspar can account for the observed variations, along with fractionation of biotite and amphibole (Fig. 16a, b, c). Fractional crystallization is also the magmatic process suggested by the Rb and Ni variations (Fig. 16d). Furthermore, ferroan granites with more than 70% SiO_2 form a subordinate part of Cordilleran (magnesian) granites (Frost et al., 2001).

Therefore, taking into account the chemical variations and the crystallization ages, we interpret the Serra Granite as the most evolved varieties of the Creporizão Intrusive Suite. Both belong to the high-K subalkaline association, and the “calc-alkaline like” signature of Creporizão may be attributed to crustal contamination (e.g., Le Maitre, 2002; Nardi, 2016), which is reflected in our Hf–Nd isotopic results. The ferroan character of the Serra Granite might be attributed to the magma source and petrogenetic process, which is interpreted to be the low-pressure melting of quartz-feldspathic/calc-alkaline crust (Patino Douce, 1997; Frost and Frost, 2013), and this magma has probably interacted with tholeiitic magmas (Nardi, 2016). These magmas might have been derived from sources modified by previous lithospheric subduction.

Nd and Hf isotopes for the Serra Granite show moderate to strongly negative values of the epsilon parameters, which along with the old model ages (2.27–3.15 Ga) indicate melting of older Paleoproterozoic and Archean crust in the petrogenesis of the Serra Granite. Nd isotopes for the Creporizão Suite also provide negative epsilon values, and model

ages of 2.49–2.25 Ma, (compiled from Lamarão et al., 2002, 2005; Vasquez et al., 2017), which indicate a moderate contribution of older Paleoproterozoic and Archean crustal sources for the parental magmas of these granitoids. So, the preliminary Serra Granite data suggest more contribution of Archean crust source than Creporizão Suite rocks, however more detailed studies (e.g., Hf isotopes) are necessary to confirm this interpretation.

This slightly older Paleoproterozoic crust resembles those found for the parental magmas of the contemporary igneous rocks of the Iri-Xingu Domain, whose component of Archean crust increases toward the tectonic domains to the east in the Amazonian Craton.

8.1.3. Calc-alkaline volcanic and pyroclastic rocks (~2.02–1.94 Ga)

Previous dating of the Vila Riozinho Formation indicates formation ages between 2002 ± 4 and 1990 ± 12 Ma (Vasquez et al., 2017 and references therein). In this study, two dated samples presented ages in the range of 1990 ± 21 to 1989 ± 12 Ma, which is in line with the literature data. Therefore, Vila Riozinho represents calc-alkaline magmatism coeval and spatially associated to the Creporizão and Serra granitoid units. However, one sample presented the age of 1940 ± 19 Ma for a zircon population along with an older population with age identical to those found in the two other samples. We interpret the younger age as a late pulse within the Vila Riozinho volcanic system. The predominant part of the formation shows a magnesian, calc-alkaline (alkali-calcic), and high-K to shoshonite affinity (Figs. 9 and 17).

As regards the magnetic pyroclastic facies, although resembling the REE patterns of the normal Vila Riozinho Formation rocks, the rocks grouped in this facies approach some chemical features of the Serra Granite, with which they are in contact despite the same age, it appears that the Serra granite is intrusive into the Vila Riozinho Formation (Fig. 3).

Nd–Hf isotopes from the magnetic facies of the Vila Riozinho Formation reveal model ages between 2.38 and 2.42 Ga, and epsilon values ranging from -2.1 to -3.2 , which is very similar to what was described by Lamarão et al. (2005) (Sm–Nd T_{DM} ages of 2.49 to 2.25 and epsilon values of -3.71 to -1.03) for the “normal” Vila Riozinho Formation.

Therefore, the Vila Riozinho Formation original magmas were not produced exclusively by the remelting of Archean sialic crust, but

Table 2

Available crystallization ages of magmatic rocks within the study area in the Southeastern Tapajós Mineral Province.

Sample	Rock type	Age (Ma)	Lithological Unit ^a	Reference
CO-69	Granite	2023 ± 30	Crepório Intrusive Suite	Tokashiki et al. (2015)
CE-03A	Alkali feldspar granite	1996 ± 6	Serra Alkali Feldspar Granite	this work
SG-83	Alkali feldspar granite	1989 ± 21	Serra Alkali Feldspar Granite	this work
SG-61	Alkali feldspar granite	1999 ± 25	Serra Alkali Feldspar Granite	this work
CO-59	Granite	1959 ± 5.5	Serra Alkali Feldspar Granite	Tokashiki et al. (2015)
CO-58	Granite	1980 ± 6.6	Serra Alkali Feldspar Granite	Tokashiki et al. (2015)
CO-44	Granite	1963 ± 15	Serra Alkali Feldspar Granite	Tokashiki et al. (2015)
CO-04	Granite	1959 ± 25	Serra Alkali Feldspar Granite	Tokashiki et al. (2015)
CO-37	Granite	1980 ± 15	Serra Alkali Feldspar Granite	Tokashiki et al. (2015)
CE-06	Rhyolitic ignimbrite	1989 ± 12	Vila Riozinho Formation – Magnetic Pyroclastic Facies	this work
SG-118	Ignimbrite	1994 ± 12	Vila Riozinho Formation – Magnetic Pyroclastic Facies	this work
DEF 544	Rhyolite	1990 ± 21	Vila Riozinho Formation – Magnetic Pyroclastic Facies	this work
DEF 714	Rhyolite	1996 ± 21	Vila Riozinho Formation – Magnetic Pyroclastic Facies	this work
		1940 ± 19		
CO-15	Rhyodacite	1967 ± 6.6	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Tokashiki et al. (2015)
CO-68	Rhyolite	1966 ± 22	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Tokashiki et al. (2015)
CO-47	Granodiorite	1955 ± 19	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Tokashiki et al. (2015)
CO-26	Rhyolite	1966 ± 6.3	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Tokashiki et al. (2015)
CO-17	Tuff	1975 ± 5.3	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Tokashiki et al. (2015)
CO-13	Rhyolite	1970 ± 20	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Tokashiki et al. (2015)
NP 183	Ignimbrite	1986 ± 8.2	Vila Riozinho Formation – Magnetic Pyroclastic Facies	Roverato et al., 2019
SG-69	Syenogranite	1888 ± 17	Maloquinha Intrusive Suite	this work

^a Lithological units according this work (Fig. 3).

predominantly by Paleoproterozoic sources. These may possibly be represented by subduction-related juvenile magmas (magmatic arc?), with magmas modified by interaction with older continental crust, or a post-to late-orogenic remelting of an older Paleoproterozoic juvenile arc with minimal contribution from the Archean crust, as proposed for Lamarão et al. (2005). In both cases, interaction with mafic magmas (previous lithospheric subduction) is envisaged.

8.1.4. Calc-alkaline granitoids (~1.89–1.88 Ga)

An intense calc-alkaline magmatic activity took place at ca. 1.89 to 1.87 Ga in the Tapajós Mineral Province, represented by the Parauari Intrusive Suite. In the study area, however, the Parauari Suite is quite subordinate, and in this work, we have not approached the suite with

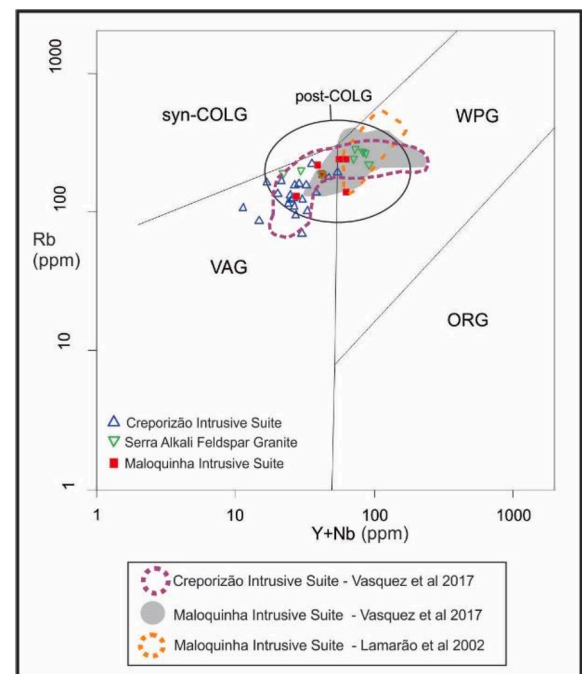


Fig. 15. Discriminant diagram of tectonic settings from Pearce et al. (1984) applied to the granites of the Southeastern Tapajós Mineral Province. VAG (volcanic arc granites), WPG (intraplate granites), syn-COLG (syn-collision granites), ORG (ocean ridge granites). The post-COLG (post-collision granites) field is after Pearce (1996).

petrological, chemical and geochronological studies. Its relation with the other units was taken from geophysical data associated with other regional works (e.g., Guimarães et al., 2019). For this suite, Echeverri Missas (2015) and Vasquez et al. (2017) obtained values of ϵ_{Nd} ranging from -3.2 to -1.3 , and T_{DM} ages of 2.3 and 2.2 Ga, suggesting that the isotopic signature represent a juvenile (Paleoproterozoic) mantle source less contaminated by older Paleoproterozoic to Archean crust. The high-K calc-alkaline affinity of the Parauari Suite was related to continental magmatic arcs (Santos et al., 2004), or to magmatism in post-collisional extensional setting (Vasquez et al., 2017).

8.1.5. Alkaline magmatism (~1.89–1.86 Ga)

The Maloquinha Intrusive Suite was dated here at 1883 ± 17 Ma, which is consistent with previous data in the range of 1864 ± 18 to 1880 ± 9 (Vasquez et al., 2017 and references therein). The suite shows alkali-calcic to alkalic, peraluminous to metaluminous and ferroan signature, along with trace-element distribution typical of granites which belong to the silica-saturated alkaline granites (A-type). These rocks are interpreted as formed by felsic magmatism, approximately coeval and geochemically similar to the volcanic rocks from the Iri Group and Moraes Almeida Formation (Santos et al., 2000; Lamarão et al., 2002).

The ϵ_{Nd} values of -0.72 to -1.62 and T_{DM} model ages of 2.23–2.24 Ga obtained by Lamarão et al. (2005) are in agreement with those obtained in this work, and indicate participation of crustal source, certainly rocks were derived from magmas formed by low degrees of partial melting (which explains the preservation of inherited zircon xenocrysts; e.g., Santos et al., 2004).

8.2. Crustal evolution and tectonic setting

One of the most difficult issues regarding the evolution of the Tapajós Mineral Province, as outlined early in the Introduction and Geological Context sections, is the tectonic evolution of the province, with models involving accretion of one, two or several magmatic arcs, and those that

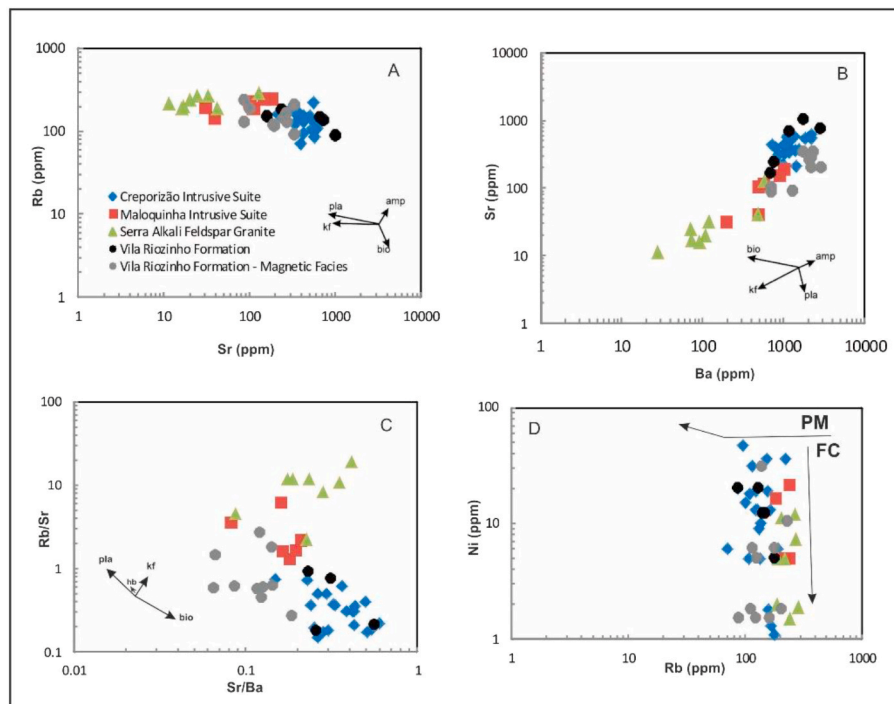


Fig. 16. A) Sr x Rb, B) Ba x Sr, C) Rb/Sr x Sr/Ba, D) Rb x Ni plots for samples from the Southeastern Tapajós Mineral Province. The vectors indicate the influence of fractionation of plagioclase (Pl), potassium feldspar (Kf), hornblende (Hb) and biotite (Bt) in the composition of the residual liquids. PM = partial melting, FC = fractional crystallization.

privilege extension-related magmatism (Vasquez et al., 2002, 2017; Lamarão et al., 2002, 2005; Santos et al., 2004; Juliani et al., 2013; Roverato et al., 2019), and, in consequence, the tectonic settings in which the different plutono-volcanic associations were formed.

There is a consensus that the Cuiú-Cuiú Complex represents an arc-related association (Santos et al., 2004; Vasquez et al., 2008a, 2008b). However, the tectonic meaning of the voluminous magmatism of the Creporizão Intrusive Suite and of the coeval Vila Riozinho Formation is highly controversial, whether representing post-collisional associations that followed the collision of the Cuiú-Cuiú island arc against an Archean block (Vasquez et al., 2002, 2017; Lamarão et al., 2002; Roverato et al., 2019), or a continental arc formed sequentially to the build-up of the Cuiú-Cuiú arc (Santos et al., 2004; Juliani et al., 2013). The main reason for this ambiguity comes from the similar trace-element geochemical signature presented by volcanic arc and post-collisional granites and felsic volcanic rocks, since both magmatic associations share similar sources and form by the melting of LILE-enriched mantle sources above the subduction zone, with more or less modification by lower crust melts (Pearce et al., 1984; Harris et al., 1986; Küster and Harms, 1998). Furthermore, both magmatic associations, show calc-alkaline signature in discriminant plots. While the calc-alkaline character is true for arc-related rocks, this character is acquired due to the effects of crustal assimilation in the post-collisional magmatism (e.g., Le Maitre, 2002; Nardi, 2016). This dual interpretation of the same geochemical characteristics commonly occurs elsewhere (e.g., Duarte et al., 2019; Santos et al., 2019). Therefore, the discrimination is done mostly on geological and temporal grounds, since post-collisional granites must follow the emplacement of pre-collisional volcanic arc and/or syn-collisional granites.

Post-collisional magmatism is characterized by potassic and high-K subalkaline with subordinate amount of shoshonitic rocks, with emplacement commonly linked to large horizontal movements along major shear zones. The source of the post-collisional magmatism is generated during the preceding subduction and collision periods, either within the crust or in the lithospheric/asthenospheric mantle.

Furthermore, this source commonly contains a large juvenile component, either mantle or newly-formed crust of igneous or sedimentary character (Liégeois et al., 1998; Küster and Harms, 1998; Nardi, 2016).

Abundant high-K calc-alkaline/subalkaline magmatism appears to be post-collisional and often shifts to shoshonitic or alkaline-peralkaline compositions in the final stages of orogeny. The post-collisional period differs from other settings by a propensity to generate large amounts of magma of various kinds mainly due large movements along shear zones, to the availability of modified, still hot sources generated by preceding subduction period and significant and rapid modifications of the lithospheric structure and temperature, among which high-K subalkaline magmatism is volumetrically the most prominent (Liégeois et al., 1998).

In the Tapajós Domain, the emplacement of the Creporizão Intrusive Suite was controlled by strike-slip shear zones, which have also been responsible for widespread transposition of the gneissic banding and local reorientation of the bodies of the Cuiú-Cuiú Complex (Santos et al., 2001; Klein et al., 2002; Santos and Coutinho, 2008). Therefore, we understand that the magmatism of the Creporizão Intrusive Suite and Vila Riozinho Formation may be chemically characterized as post-collisional, with a transition to alkaline magmatism (Maloquinha Intrusive Suite) at the end of the Orosirian orogeny, as already suggested elsewhere (Lamarão et al., 2002; Vasquez et al., 2002, 2017; Roverato et al., 2019). However, post-collisional magmatism requires a collisional event, and the existence of such an event is not consensual for the Tapajós Mineral Province (see also the next section).

8.3. Geological correlations and implications for the evolution the Tapajós Mineral Province

The extensive exposition of Orosirian felsic volcanic and plutonic rocks in the Tapajós Domain as an NW-SE belt extends throughout the central and northern portion of the Amazonian Craton (Fig. 1). These volcanic-plutonic belts are historically related to the Ventuari-Tapajós (Tassinari and Macambira, 1999) or Tapajós-Parima (Santos, 2003) geochronological provinces, and to the Central Amazonian Province.

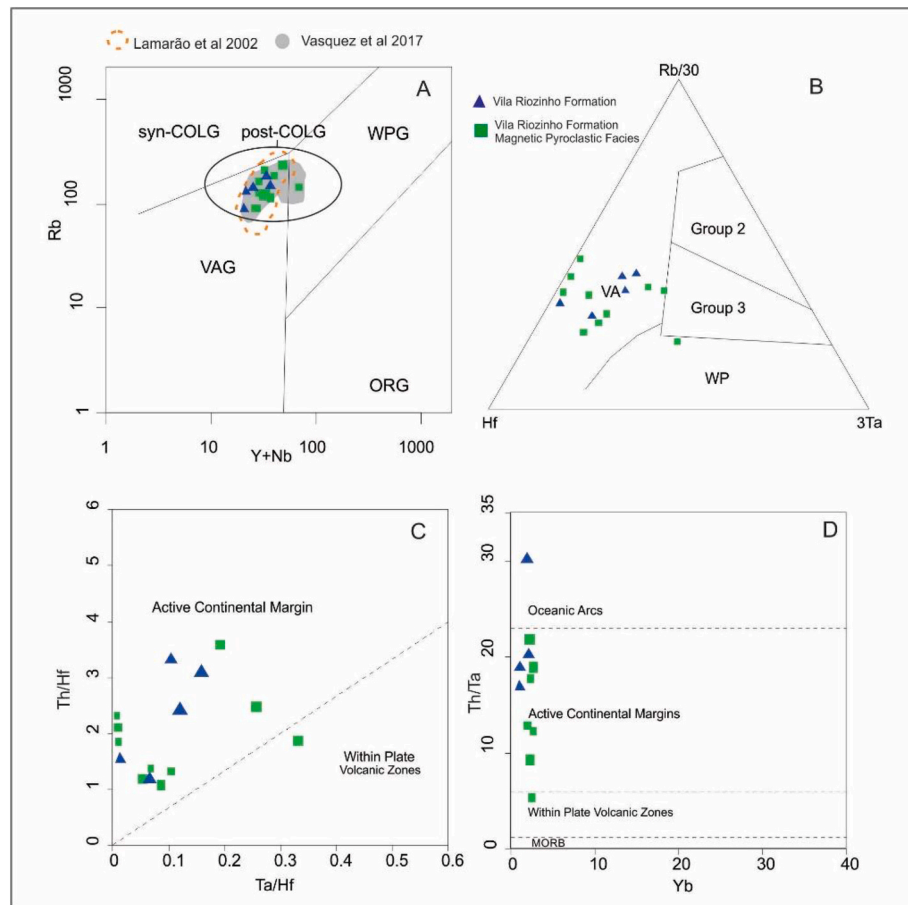


Fig. 17. A) Tectonic discriminant diagram of [Pearce et al. \(1984\)](#) for granites applied to the volcanic and pyroclastic rocks of the Vila Riozinho Formation. ORG = ocean ridge granite, VAG = volcanic arc granites, WPG = intraplate granites, and COLG = collision granites. The post-COLG (post-collision granites) field is from [Pearce \(1996\)](#), B) [Harris et al. \(1986\)](#) discrimination diagram, (C and D) tectonic setting of volcanism diagrams of [Schandl and Gorton \(2002\)](#).

Alternatively, these felsic rocks have been attributed to the Orocaima (2.00–1.96 Ga, orogenic) and Uatumã (1.90–1.86 Ga, extensional) magmatic events ([Reis et al., 2000](#); [Vasquez and Dreher, 2011](#); [Klein et al., 2012](#); [Fraga et al., 2017](#)), without taking into account the geochronological provinces approach.

In the Southeastern Tapajós Mineral Province, the felsic plutonic and volcanic rocks that host the Coringa Au–Ag deposit (Serra Alkali Feldspar Granite and Vila Riozinho Formation) and its surroundings (Crepurizão, Parauari, and Maloquinha intrusive suites, Iriri Group) bring information that can be related to these major events. The Orocaima igneous belt ([Reis et al., 2000](#); [Fraga et al., 2017](#)), which occurs in the northern portion of the Amazonian Craton ([Fig. 1](#)), shows pre-collisional assemblages coeval to the Cuiú-Cuiú Complex from the Tapajós Province. The collisional phase associated with the Orocaima igneous belt is defined by the medium-to high-grade (paragneisses) supracrustal rocks of the Cauarane-Coeroeni belt ([Fig. 1](#)), which underwent metamorphism at about 2020 Ma, associated with the amalgamation of Early Orosirian (2.04–2.03 Ga) magmatic arcs ([Fraga and Cordani, 2019](#)). A huge igneous belt was emplaced after the metamorphic peak (1.98–1.95 Ga) in a post-collisional setting ([Fig. 1](#)). The Crepurizão Intrusive Suite shares lithological, chemical, and isotopic characteristics with the coeval Pedra Pintada Suite ([Fraga et al., 2017, 2019](#)) that forms a major part of the igneous belt ([Fig. 1](#)). Assuming the continuity of the Orosirian terranes of the northern and southern portions of the Amazonian Craton (now disrupted in the two sides of the Amazon basin – [Fig. 1](#)), the Tapajós Mineral Province is part of this large Early Orosirian orogen. This way we can justify the interpretation of post-collisional setting for the Crepurizão Intrusive Suite (and the

associated Vila Riozinho Formation), in contrast to the interpretation of island arc, because this overcomes the lack of collisional assemblages within the present-day Tapajós Province.

After a gap of ca. 50 Ma, this orogenic event was followed by the extensional to intraplate Uatumã event (Uatumã SLIP), which produced large volume of felsic rocks. [Fraga et al. \(2017\)](#) stated that the continuous exposures of the Uatumã SLIP coincide approximately with the presence of remains of the Early-Orosirian crust. Probably, the Early-Orosirian orogenic processes contributed to the formation of hydrated and fertile sources at the base of the crust, allowing a large-scale crustal melting in an extensional environment with a thermal/underplating contribution of mantle magmas, controlling the development of the SLIP, and marking a particular period of evolution of the Amazonian craton.

A consequence of this evolution is that the basement of the Uatumã SLIP (i.e., the Iriri-Xingu Domain, [Fig. 1](#)) is unlikely composed of rocks different from those found in the Tapajós province and in Archean and Paleoproterozoic provinces of the Eastern Amazonian Craton (Rio Maria, Carajás, Bacajá etc. – [Fig. 1](#)), i.e., there is no need for the Central Amazonia Province as historically argued (e.g., [Tassinari and Macambira, 1999](#); [Santos, 2003](#)). The existence of this province to the north, in the Guiana Shield, has also been questioned by [Leal et al. \(2018\)](#).

9. Conclusions

According to data provided in this research, the following conclusions can be listed:

- The spatially associated Serra Alkali Feldspar Granite and Vila Riozinho Formation, which are the hosts of the Au-Ag (Cu-Pb-Zn) deposit, formed between 1968 and 2024 Ma, and 1969 and 2017 Ma, respectively, and are coeval to the Creporizão Intrusive Suite.

- Chemically, the Creporizão and Vila Riozinho units are composed of high-K, subalkaline, and magnesian rocks, whereas the Serra Granite and the magnetic pyroclastic facies of the Vila Riozinho Formation are predominantly ferroan rocks, and represent the more differentiated varieties of the Creporizão Suite and Vila Riozinho Formation, respectively. The three rock units form part of a single magmatic event and, as a whole, their chemical signature is compatible with both volcanic arc and post-collisional settings.

- A post-collisional setting is assumed here taking into account the whole Early-Orosirian orogenic belt, which straddles the limits of the Tapajós Mineral Province domains, having major counterparts to the north, in the Guiana Shield, where the collisional assemblages are well represented. Within the Tapajós Mineral Province, the existence of collisional rocks still needs to be proved.

- The stocks of A-type rocks formed at 1883 ± 17 Ma belong to the Maloquinha Intrusive Suite. These rocks were emplaced during a large-scale intraplate magmatic event (Uatuma SLIP), which probably covers significant parts of the Early-Orosirian orogenic belt. In consequence, the existence of the Central Amazonia Province must be reviewed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsames.2020.102726>.

References

- Aguiar-Bocanegra, M.A., 2013. Mineralizações epitermal low-sulfidation e do tipo pórfiro superpostas associadas ao magmatismo félsico de 1,88 Ga na parte norte da Província Mineral do Tapajós (PA). Dissertação de Mestrado, Instituto de Geociências, Universidade de São Paulo, p. 235p.
- Assunção, R.F.S., Klein, E.L., 2014. The Moreira Gomes deposit of the Cuiú-Cuiú goldfield: fluid inclusions and stable isotope constraints and implications for the genesis of granite-hosted gold mineralization in the Tapajós Gold Province, Brazil. *J. S. Am. Earth Sci.* 49, 85–105.
- Belousova, E.A., Kostitsyn, Y.A., Griffin, W.L., Begg, G.C., O'Reilly, S.Y., Pearson, N.J., 2010. The growth of the continental crust: constraints from zircon Hf-isotope data. *Lithos* 119, 457–466.
- Biondi, J.C., Borgo, A., Chauvet, A., Monié, P., Bruguier, O., Ocampo, R., 2018. Structural, mineralogical, geochemical and geochronological constraints on ore genesis of the goldonly Tocantinzinho deposit (Para State, Brazil). *Ore Geol. Rev.* 102, 154–194.
- Borgo, A., Biondi, J.C., Chauvet, A., Bruguier, O., Monié, P., Baker, T., Ocampo, R., Friedman, R., Mortensen, J., 2017. Geochronological, geochemical and petrographic constraints on Paleoproterozoic Tocantinzinho deposit (Tapajós Gold Province, Brazil): implications for timing, regional evolution and deformation style of its host rocks. *J. S. Am. Earth Sci.* 75, 92–115. <https://doi.org/10.1016/j.jsames.2017.02.003>.
- Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu-Hf and Sm-Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth Planet Sci. Lett.* 273 (1–2), 48–57.
- Boynnton, W.V., 1984. Cosmochemistry of the rare earth elements: meteorite studies. In: Henderson, P. (Ed.), *Rare Earth Element Geochemistry*. Elsevier, Amsterdam, pp. 63–114.
- Buhn, B., Pimentel, M.M., Matteini, M., Dantas, E.L., 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-IC-MS). *An Acad. Bras Ciências* 81 (1), 99–114.
- Carneiro, C.C., Juliani, C., Carreiro-Araujo, S.A., Monteiro, L.V., Crôsta, A.P., Fernandes, M.D., 2019. New Crustal Framework in the Amazon Craton based on geophysical data: evidences of deep east-west trending suture zones. *IEEE Geosciences and Remote Sensing Letters* 16, n°1.
- Chauvel, C., Blichert-Toft, J.E., 2001. A hafnium isotope and trace element perspective on melting of the depleted mantle. *Earth Planet Sci. Lett.* 190, 137–151.
- Chu, N.C., Taylor, R.N., Chavagnac, V., Nesbitt, R.W., Boella, R.M., Milton, J.A., German, C.R., Bayon, G., Burton, K., 2002. Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: an evaluation of isobaric interference corrections. *Journal of Analytical Atomic Spectrometry* 17, 1567–1574.
- Cocherie, A., 1986. Systematic use of trace element distribution patterns in log-log diagrams for plutonic suites. *Geochem. Cosmochim. Acta* 50, 2517–2522.
- Corrêa-Lima, R.G., Klein, E.L., 2020. Hydrothermal alteration, mineralization and fluid inclusions in the Pista and Fofão prospects: implications for the genetic model of the Coringa polymetallic deposit, SE Tapajós Mineral Province, Amazonian Craton, Brazil. *J. Geol. Surv. Brazil*. <https://doi.org/10.29396/jgsb.2020.v3.n1.3>.
- Costa, I.S.L., Rocha, M.P., Klein, E.L., Vazquez, M.L., 2020. Lithospheric structure of the southern Amazonian Craton from multiple-frequency seismic tomography: preliminary insights on tectonic and metallogenic implications. *J. S. Am. Earth Sci.* 101, 102608. <https://doi.org/10.1016/j.jsames.2020.102608>.
- Dall'Agnol, R., Oliveira, D.C., 2007. Oxidized, magnetite-series, rapakivi-type granites of Carajás, Brazil: implications for classification and petrogenesis of A-type granites. *Lithos* 93, 215–233.
- De La Roche, H., Leterrier, J., Grandclaude, P., Marchal, M., 1980. A classification of volcanic and plutonic rocks using R1-R2 diagrams and major element analyses - its relationships with current nomenclature. *Chem. Geol.* 29, 183–210. [https://doi.org/10.1016/0009-2541\(80\)90020-0](https://doi.org/10.1016/0009-2541(80)90020-0).
- De Paolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth Planet Sci. Lett.* 53, 189–202. [https://doi.org/10.1016/0012-821X\(81\)90153-9](https://doi.org/10.1016/0012-821X(81)90153-9).
- Duarte, T.B., Xavier, R.P., Rodrigues, J.B., 2019. A review of the geodynamic setting of the Volcanic Domain in the Juruena Magmatic Arc, southwestern Amazon Craton, Brazil, based on geochemical, U-Pb and Sm-Nd data. *Journal of the Geological Survey of Brazil* 2 (1), 37–73. <https://doi.org/10.29396/jgsb.2019.v2.n1.4>.
- Echeverri Missas, C.M., 2015. Geologia e alteração hidrotermal nas rochas vulcânicas e plutônicas paleoproterozoicas na porção Sul da Província Mineral do Tapajós (PA). Tesis. Universidade de São Paulo (USP). <http://www.teses.usp.br/teses/disponiveis/44/44141/tde-27082015-101343/>.
- Fernandes, C.M.D., Juliani, C., Monteiro, L.V.S., Lagler, B., Echeverri Missas, C.M., 2011. High-K calc-alkaline to A-type fissure-controlled volcano-plutonism of the São Félix do Xingu region, Amazonian craton, Brazil: exclusively crustal sources or only mixed Nd model ages? *J. S. Am. Earth Sci.* 30, 1–18.
- Fraga, L.M., Vasquez, M.L., Dreher, A.M., 2017. A influência da Orogenia Eo-orosiana na formação da SLIP Uatuma, parte central do Cráton Amazônico. *Anais do 15º Simpósio de Geologia da Amazônia*, pp. 405–408. Belém.
- Fraga, L.M.B., Cordani, U., 2019. Early Orosirian tectonic evolution of the Central Guiana Shield: insights from new U-Pb SHRIMP data. 11th Inter Guiana Geological Conference: Tectonics and Metallogenesis of NE South America, pp. 59–62. Proceedings.
- Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. *J. Petrol.* 42, 2033–2048.
- Frost, C.D., Frost, B.R., 2013. Proterozoic ferroan feldspathic magmatism. *Precambrian Res.* 228, 151–163.
- Gioia, S.M.C.L., Pimentel, M.M., 2000. The Sm-Nd isotopic method in the Geochronology Laboratory of the University of Brasília. *Anais da Academia Brasileira de Ciências* 72 (2), 219–245.
- Guimarães, S.B., Klein, E.L., Chaves, C.L., Souza, S.M., Castro, J.M.R., Queiroz, J.D.S., Feio, J.V.B., Lima, R.G.C., 2015. Metalogenia das Províncias Minerais do Brasil: Área sudeste do Tapajós, Estado do Pará. 1. CPRM - Serviço Geológico do Brasil, Brasília, 2016. v. 1. 61pp.
- Guimarães, S.B., Klein, E.L., Correa, R.T., 2019. Reassessment of the geology of the southeastern Tapajós Gold Province, Amazonian Craton, Brazil, based on field, petrographic, and airborne geophysical data. *Journal of the Geological Survey of Brazil* 2 (1), 1–16. <https://doi.org/10.29396/jgsb.2019.v2.n1.1>. April 2019.
- Hanson, G.N., 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planet Sci. Lett.* 38, 26–43.
- Harris, N.B.W., Pearce, J.A., Tindle, A.G., 1986. Geochemical characteristics of collision zone magmatism. In: Coward, M.P., Ries, A.C. (Eds.), *Collision Tectonics*, vol. 19. Geological Society of London Special Publication, pp. 67–81. <https://doi.org/10.1144/GSL.SP.1986.019.01.04>.
- Janousek, V., Farrow, C.M., Erban, V., 2006. Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). *J. Petrol.* 47, 1255–1259.

- Juliani, C., Fernandes, C.M.D., 2010. Well-preserved, late paleoproterozoic volcanic centers in the São Félix, do Xingu region, Amazonian craton, Brazil. *J. Volcanol. Geoth. Res.* 191, 167–179.
- Juliani, C., Carneiro, C.C., Carneiro-Araújo, S.A., Fernandes, C.M.D., Monteiro, L.V.S., Crósta, A.P., 2013. Estruturação dos arcos magmáticos paleoproterozoicos na porção sul do Cráton Amazônico: implicações geotectônicas e metalogenéticas. *Anais do 13º Simpósio de Geologia da Amazônia*, pp. 157–160. Belém.
- Klein, E.L., Almeida, M.E., Rosa-Costa, L.T., 2012. The 1.89–1.87 Ga Uatuma silicic large igneous province, northern south America. *International Association of Volcanology and Chemistry of the Earth's Interior, Large Igneous Province Commission, November 2012 LIP of the Month*.
- Klein, E.L., Guimarães, S.B., Rodrigues, J.B., Chaves, C.L., Souza-Gaia, S.M., Lopes, E.C.S., Castro, J.M.R., 2018. The Novo Progresso Formation, Tapajós Gold Province, Amazonian Craton: zircon U-Pb and Lu-Hf constraints on the maximum depositional age, reconnaissance provenance study, and tectonic implications. *Journal of the Geological Survey of Brazil (JGSB)* 1 (1), 31–42. <https://doi.org/10.29396/jgsb.2018.v1.n1.3>.
- Klein, E.L., Rodrigues, J.B., Queiroz, J.D.S., Oliveira, R.G., Guimarães, S.B., Chaves, C.L., 2017. Deposition and tectonic setting of the paleoproterozoic Castelo dos Sonhos metasedimentary formation, Tapajós gold province, Amazonian craton, Brazil: age and isotopic constraints. *Int. Geol. Rev.* 59 (7), 864–883.
- Klein, E.L., Vasquez, M.L., Rosa-Costa, L.T., Carvalho, J.M.A., 2002. Geology of paleoproterozoic gneiss- and granitoid-hosted gold mineralization in southern Tapajós gold province, Amazonian craton, Brazil. *Int. Geol. Rev.* 44, 544–558.
- Kroonenberg, S.B., Roeber, E.W.F., Fraga, L.M., Reis, N.J., Faraco, T., Lafon, J.-M., Cordani, U., Wong, T.E., 2016. Paleoproterozoic evolution of the Guiana Shield in Suriname: a revised model. *Netherlands Journal of Geosciences* 95, 491–522. <https://doi.org/10.1017/njg.2016.10>.
- Küster, D., Harms, U., 1998. Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African Orogen: a review. *Lithos* 45, 177–195.
- Lamarão, C.N., Dall'Agnol, R., Lafon, J.M., Lima, E.F., 2002. Geology, geochemistry, and Pb–Pb zircon geochronology of the paleoproterozoic magmatism of Vila Riozinho, Tapajós gold province Amazonian craton, Brazil. *Precambrian Res.* 119, 189–23.
- Lamarão, C.N., Dall'Agnol, R., Pimentel, M.M., 2005. Nd isotopic composition of Paleoproterozoic volcanic and granitoid rocks of Vila Riozinho: implications for the crustal evolution of the Tapajós gold province, Amazonian craton. *J. S. Am. Earth Sci.* 18, 277–292.
- Leal, R.E., Lafon, J.M., Rosa-Costa, L.T., Dantas, E.L., 2018. Orosirian magmatic episodes in the Erepecuru-Trombetas domain (southeastern Guyana shield): implications for the crustal evolution of the Amazonian craton. *J. S. Am. Earth Sci.* 85, 278–297. <https://doi.org/10.1016/j.jsames.2018.04.011>.
- Le Maitre, R.W., 2002. *Igneous Rocks - A Classification and Glossary of Terms*. Cambridge University Press, Cambridge, p. 236pp.
- Liégeois, J.P., Navez, J., Hertogen, J., Black, R., 1998. Contrasting origin of post-collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline granitoids. The use of sliding normalization. *Lithos* 45, 1–28.
- Ludwig, K.R., 2003. *Isoplot 3.00 – A Geochronological Toolkit for Microsoft Excel*. Berkeley Geochronology Center, Special Publication. No 4.
- Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. *GSA Bulletin* 101, 635–643.
- Matteini, M., Dantas, E.L., Pimentel, M.M., Buhn, B., 2010. Combined U-Pb and Lu-Hf isotope analyses by laser ablation MC-ICP-MS: methodology and applications. *An Acad. Bras. Ciências* 82 (2), 479–491.
- Milhomem Neto, J.M., Lafon, J.M., Galarza, M.A., 2017. Lu-Hf em zircão por LA-MC-ICP-MS no laboratório Pará-Iso (UFPa): metodologia e primeiro exemplo de aplicação na porção sudeste do Escudo das Guianas. *Contribuições à Geologia da Amazônia* 10, 195–208.
- Nardi, L.V.S., 2016. Granitoides e séries magmáticas: o estudo contextualizado dos granitoides. *Pesqui. em Geociências* 43 (1), 85–99.
- Nardi, L.V.S., Bitencourt, M.F., 2009. A-type granitoids in post-collisional settings from southernmost Brazil: their classification and relationship with magmatic series. *Can. Mineral.* 47 (6), 1493–1504.
- Patiño Douce, A.E., 1997. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. *Geology* 25, 743–746.
- Pearce, J.A., 1996. Source and settings of granitic rocks. *Episodes* 19 (4), 120–125.
- Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* 25, 956–983.
- Prenn, N., Peralta, E., Breckenridge, L., Sim, R., Davis, B.M., Smith, M., Michel, R., King, N., Fisher, B., 2017. Coringa gold project, Brazil. Feasibility study NI 43-101 technical report access on March 23 2019. <https://www.serabigold.com/wp-content/uploads/2018/02/Coringa-FS-43-101.pdf>.
- Queiroz, J.D.S., Klein, E.L., 2018. The Paleoproterozoic metaconglomerate-hosted Castelo dos Sonhos gold deposit, Tapajós Gold Province, Amazonian Craton: a modified paleoplacer origin. *J. Geol. Surv. Brazil* 1. <https://doi.org/10.29396/jgsb.2018.v1.n2.3>.
- Queiroz, J.D.S., Klein, E.L., Rodrigues, J.B., 2015. Rochas intrusivas na bacia paleoproterozoica Castelo dos Sonhos, Cráton Amazônico: geocronologia, aspectos geoquímicos e implicações para litoestratigrafia, limite entre os domínios Tapajós e Iriri-Xingu e idade da mineralização no depósito aurífero Castelo de Sonhos. *Boletim Paraense Emílio Goeldi. Ciências Naturais*.
- Reis, N.J.R., Faria, M.S.G., Fraga, L.M., Haddad, R.C., 2000. Orosirian calc-alkaline volcanism and the Oroaima event in the northern Amazonian craton, eastern roraima state, Brazil. *Rev. Bras. Geociências* 30 (3), 380–383.
- Roverato, M., Giordano, D., Giovanardi, T., Giuliani, C., Polo, L., 2019. The 2.0–1.88 Ga Paleoproterozoic evolution of the southern Amazonian Craton (Brazil): an interpretation inferred by lithofaciological, geochemical and geochronological data. *Gondwana Res.* 70, 1–24.
- Santos, J.O.S., 2003. Geotectônica do Escudo das Guianas e Brasil-Central. In: Bizzi, L.A., et al. (Eds.), *Geologia, tectônica e recursos minerais do Brasil: texto, mapas e SIG*. Brasília: CPRM – Serviço Geológico do Brasil, pp. 169–226.
- Santos, R.A., Coutinho, M.G.N., 2008. *Geologia estrutural*. In: Coutinho, M.G.N. (Ed.), *Provincia Mineral do Tapajós: geologia, metalogenia e mapa provisional para ouro em SIG*. CPRM-Serviço Geológico do Brasil, Rio de Janeiro, pp. 97–135.
- Santos, J.O.S., Groves, D.L., Hartmann, L.A., Moura, M.A., McNaughton, N.J., 2001. Gold deposits of the Tapajós and alta floresta domains, Tapajós – parima orogenic belt, Amazon craton, Brazil. *Miner. Deposita* 6, 279–299.
- Santos, J.O.S., Van Breemen, O.B., Groves, D., Hartmann, L.A., Almeida, A.M.E., McNaughton, N.J., Fletcher, I.R., 2004. Timing and evolution of multiple paleoproterozoic magmatic arcs in the Tapajós Domain, Amazon Craton: constraints from SHRIMP and TIMS zircon, baddeleyite and titanite U-Pb geochronology. *Precambrian Res.* 131, 73–109.
- Santos, J.O.S., Hartmann, L.A., Gaudette, H.E., Groves, D.L., McNaughton, N.J., Fletcher, I.R., 2000. New understanding of the Amazon Craton provinces, based on fieldwork and radiogenic isotope data. *Gondwana Res.* 3, 453–488.
- Santos, E.A., Sommer, C.A., Waichel, B.L., Haag, M.B., 2019. Ediacaran post-collisional high-silica volcanism associated to the Florianópolis Batholith, Dom Feliciano belt, southernmost Brazil: lithofacies analysis and petrology. *J. S. Am. Earth Sci.* <https://doi.org/10.1016/j.jsames.2019.102299>.
- Schandel, E.S., Gorton, M.P., 2002. Applications of high field strength elements to discriminate tectonic setting in VMS environments. *Econ. Geol.* 97, 629–642.
- Scherer, E., Munker, C., Mezger, K., 2001. Calibration of the lutetium-hafnium clock. *Science* 293, 683–687.
- Tassinari, C.C.G., Macambira, M.J.B., 1999. Geochronological provinces of the Amazonian craton. *Episodes* 22, 174–18.
- Taylor, S.R., McLennan, S.M., 1985. *The Continental Crust: its Composition and Evolution*. Blackwell, Oxford, p. 312.
- Tokashiki, C.C., Giuliani, C., Monteiro, L.V.S., Echeverri-Missas, C.M., Aguiar, M.A., Arrais, L.B., 2015. Eventos vulcânicos de 1,97 Ga com mineralizações de ouro epitermais low- e intermediate sulfidation na porção sul da Província Mineral Tapajós (PA). *Contribuições à Geologia da Amazônia* 9.
- Valério, C.S., Macambira, J.B., Souza, V.S., Dantas, E.L., Nardi, L.V.S., 2018. 1.88 Ga São Gabriel AMCG association in the southernmost Uatuma-Anauá domain: petrological implications for post-collisional A-type magmatism in the Amazonian craton. *Lithos* 300, 291–313.
- Vasquez, M.L., Chaves, C.L., Moura, E.M., Oliveira, J.K.M., 2017. Geologia e Recursos Minerais das Folhas São Domingos - SB.21-Z-A-II e Jardim do Ouro - SB.21-Z-A-III, Estado do Pará, Escala 1:100.000. CPRM - Serviço Geológico do Brasil, Belém, p. 305.
- Vasquez, M.L., Dreher, A.M., 2011. Uma avaliação da estratigrafia dos eventos magmáticos de 1900–1860 Ma do Cráton Amazônico. *Anais do 12º Simpósio de Geologia da Amazônia Boa Vista- Roraima*.
- Vasquez, M.L., Klein, E.L., Ricci, P.S.F., 2002. Granitoides pós-colisionais da porção leste da Província Tapajós. In: Klein, E.L., Vasquez, M.L., Rosa-Costa, L.T. (Eds.), *Contribuições à Geologia da Amazônia*, vol. 3, pp. 67–84. Belém.
- Vasquez, M.L., Rosa-Costa, L.T., Silva, C.M.G., Klein, E.L., 2008a. Compartimentação tectônica. In: Vasquez, M.L., Rosa-Costa, L.T., orgs (Eds.), *Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará*. Escala 1:1.000.000. Belém: CPRM, pp. 39–112.
- Vasquez, M.L., Rosa-Costa, L.T., orgs, 2008b. *Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará*. Escala 1:1.000.000. Belém: CPRM 39–112. *Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará*. Escala 1:1.000.000.
- Villas, R.N.N., Santiago, E.S.B., Castilho, M.P., 2013. Contexto geológico, estudos isotópicos (C, O e Pb) e associação metálica do depósito aurífero Tocantinzinho, domínio Tapajós, Província Tapajós-Parima. *Geol. Usp. Série Científica* 13, 119–138.
- Wedepohl, K.H., 1995. The compositions of the continental crust. *Geochem. Cosmochim. Acta* 59, 1217–1232.
- Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol.* 20, 325–343. [https://doi.org/10.1016/0009-2541\(77\)90057-2](https://doi.org/10.1016/0009-2541(77)90057-2).
- Wood, D.A., Joron, J.L., Treuil, M., Norry, M.J., Tarney, J., 1979. Elemental and Sr isotope variations in basic lavas from Iceland and the surrounding ocean floor. *Contrib. Mineral. Petrol.* 70, 319–339.

4. METALLOGENESIS OF THE OROSIRIAN EPITHERMAL CORINGA GOLD-SILVER (CU-PB-ZN) DEPOSIT, SOUTHEASTERN TAPAJÓS MINERAL PROVINCE, AMAZONIAN CRATON, BRAZIL

Artigo submetido ao periódico Ore Geology Reviews

Data submissão: 12/04/2020

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Metallogenesis of the Orosirian epithermal Coringa gold-silver (Cu-Pb-Zn) deposit, Southeastern Tapajós Mineral Province, Amazonian craton, Brazil

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Abstract

The Coringa gold-silver (Cu-Pb-Zn) deposit, in southeastern of Tapajós Mineral Province, is hosted in felsic volcanic rocks the Vila Riozinho Formation (1996 ± 21 Ma) and in the Serra Alkali Feldspar Granite (1999 ± 25 Ma), interpreted to have formed in a post-collisional volcano-plutonic setting. The mineralized shear-vein system follows the NNW-SSE trend of the main regional structures, and is coincident with a magnetic trend that can represent a crustal discontinuity at the boundary zone between a magnetic pyroclastic facies of the Vila Riozinho Formation and the pluton of the Serra Alkali Feldspar Granite. The hydrothermal alteration stages comprise: (a) proximal chlorite-hematite alteration, (b) intermediate-proximal sericite-pyrite alteration, with estimated temperature of 400°C (white mica chemistry), and (c) late, distal Mn-carbonate-chlorite-epidote alteration, with average temperature of 234°C (chlorite chemistry). There are discontinuous massive barren quartz veins (veins type 1), and two types of quartz-sulfide veins (veins types 2 and 3). The veins type 2 are sulfide-poor, gold-bearing, open-space filling veins with pyrite, galena, and hematite, with average temperature formation of 243°C (fluid inclusions in quartz). The veins type 3 are sulfide-rich, and gold-bearing quartz veins with sulfide phases represented by pyrite, galena, sphalerite, and chalcopyrite and presented a minimum temperature of 340°C (fluid inclusions in quartz). Chemical analyses detected in the sulfides significant contents of Mo, Bi, Ni, and Co, with decreasing contents according to the crystallization sequence of the

sulfide phases (pyrite-chalcopyrite-sphalerite-galena-gold). The mineralizing fluids are H₂O-rich and CO₂-poor, low salinity, and the stable isotope compositions of the alteration minerals are mostly consistent with a magmatic source that mixed with a diluted and colder meteoric fluid. The geological setting, the timing of mineralization being nearly contemporaneous with the host rocks (given by previous works), the genetic characteristics, and the local presence of adularia and Mn-carbonate led us to classify Coringa as formed by an intermediate-sulfidation epithermal system.

Keywords: epithermal, intermediate sulfidation, stable isotopes, mineral chemistry, fluid inclusions

1. Introduction

The Tapajós Mineral Province (TMP), in the central portion of Amazonian Craton (Fig. 1), is one of the main metallogenic provinces in Brazil. A significant part of the province comprises felsic volcanic, and volcanoclastic rocks and granitoids. These rocks formed predominantly in two-time intervals, (i) 2.02 to 1.95 Ga, (ii) 1.91 to 1.87 Ga, and are grouped in several stratigraphic and lithodemic units (Fig. 4.1, Vasquez et al., 2017; Guimarães et al., 2019, and references therein). These volcano-plutonic units are the primary hosts for gold mineralization in the province, which contains over 340 t of estimated gold and subordinate copper and silver resources (Table 4.1).

In the last two decades, there has been a significant increase in the geological and metallogenic knowledge of the TMP at regional and local scales. However, issues such as tectonic settings of several geological units, geological-genetic models, and timing of gold mineralization are still debatable. A regional approach focused on geological events in the province involved the cartography of lithostratigraphic units, structural, geochronological, and isotopic studies (Santos et al. 2004; Lamarão et al., 2002, 2005; Klein et al. 2002, 2012, 2018; Vasquez et al. 2008, 2017; Guimarães et al., 2015, 2019; Guimarães and Klein, 2020). Nevertheless, the evolution of the TMP and its continuation to the east, into the Iriri-Xingu Domain, is a matter of debate. The controversy involves whether TMP is associated with continental magmatic arcs or extensional environment, the existence of subduction towards northeast or north, operation or not of continental collision, petrogenetic processes, and

crustal versus mantle sources (Vasquez et al., 2019; Guimarães and Klein, 2020 and references therein).

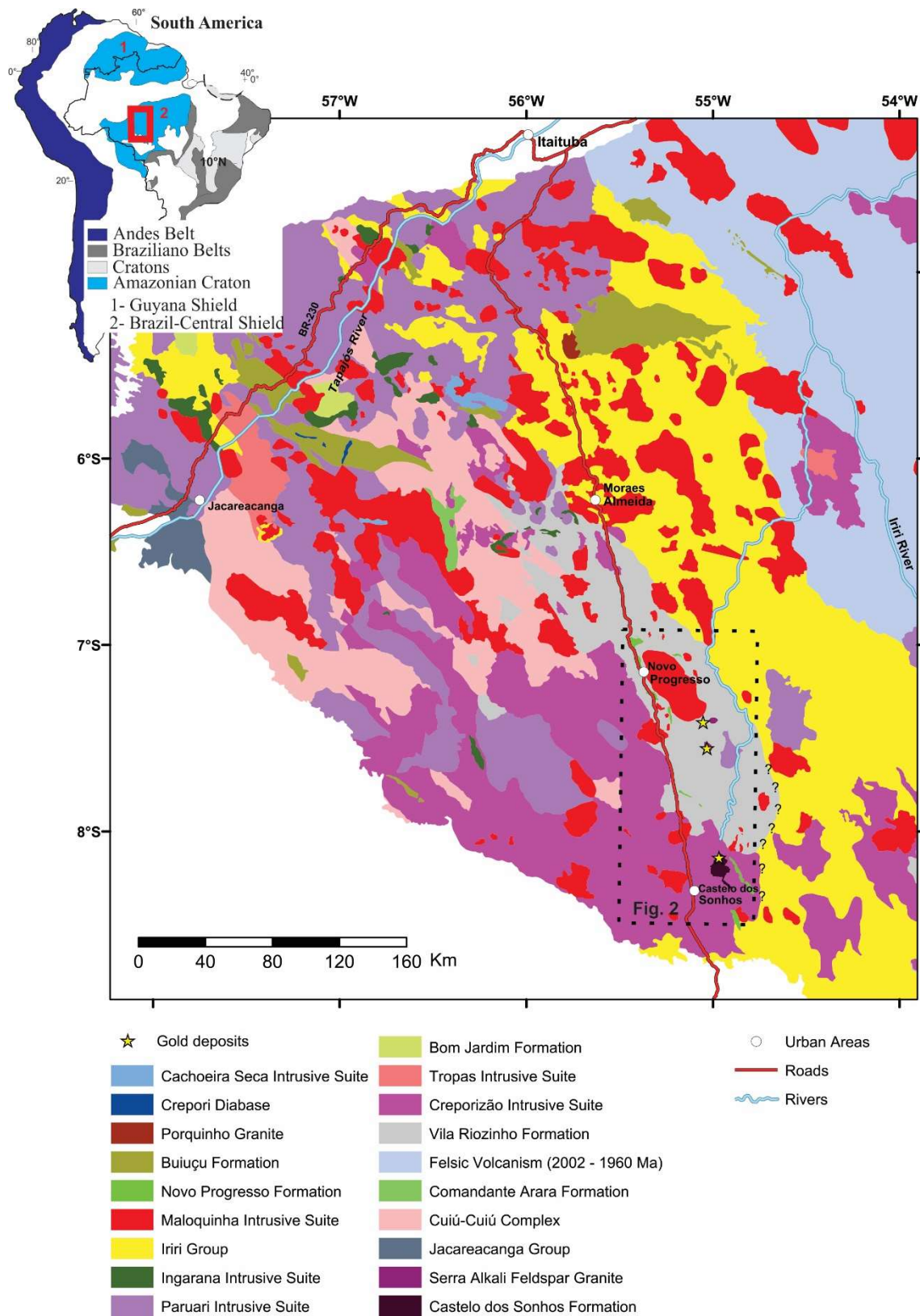


Figure 4.1 - Geological map of the Tapajós Mineral Province (modified from Vasquez et al., 2017 and Guimarães et al., 2019), with the location of the study area.

Table 4.1 – Summary of characteristics of the mineral systems (deposit classes) proposed for the Tapajós Mineral Province.

Mineral system	Example	Host rocks/ stratigraphic unit	Age of the host rock (Ma)	Main features	Hydrothermal alteration	Ore mineralogy	Metal association	Mineral Resources (t)	Estimated age (Ma)	Refs
Epithermal - high sulfidation	V3/Botica	Felsic volcanic, volcanoclastic/ Iriri Group	1888a	Brittle-style, calderacomplex, hydrothermal breccia, silica cap, vuggy silica,	Argillic, advanced argillic, sericitic, propylitic	py	Au-Ag (Cu-Zn-Mo)	30 (Au)	1876 -1869c	1,2
	V6/Chapéu do Sol	Felsic volcanic, volcanoclastic/ Iriri Group	1888a	Brittle-style, volcanic complex, associated with porphyries, breccia	Potassic, sericite-adularia, propylitic, argillic	py, cpy, mo, gal, sph	Cu (Mo-Au-Ag)	nd	nd	1,3
Epithermal - low sulfidation	Coringa	Felsic volcanic-volcanoclastic/ Vila Riozinho Formation. Alkali-feldspar granite/ Serra Granite	1998b	dextral strike-slip brittle shear zones. Veins system	Albitization, sericitization, carbonatization, silicification	py, gal,cpy, sph	Au-Ag-Pb-Zn	Au (28.30)	<1998	13,16
	São Domingos	Granite, granodiorite/ Parauari Intrusive Suite	1888a		silicification, phyllic, propylitic	py, cpy, gal, esf, hem	Au	4.20 (Au)	<1888	14
Porphyry	Palito	Granito Palito, Granito Rio Novo, Granodiorito Fofóquina	1883a	Brittle-style, red colored granite, dome-shaped, significant Cu content	Potassic, propylitic, sericitic, silicification, chloritization (late)	cpy,py,sph,gal, po, cs, bi, tell-sel	Au-Cu	22 (Au), 12.5 (Ag), 9 (Cu)	1794d	3,4,5
Intrusion related	Tocantinzinho	Monzogranite / Creporizão Intrusive Suite	1982a	Brittle-style, nd probably > 1950 underformed host rock low base metal contents	Potassic, chloritic, sericitic, silicification, carbonatization	py-cpy-gal-sph	Au-Cu-Pb-Zn (As,Bi, Mo, Te)	61 (Au)	nd	6,7,14
	Cuiú-cuiú	Granodiorite and tonalite / Creporizão Intrusive Suite	1997b	E-W trending shear zones. NNE-SSW and ESSE-WNW veinlets	Sericitization, chloritization, sulfidation, silicification, carbonatization, epidotization	au, py, cpy, sph, gal, hess-bis	Au	21.7 (Au)	1997a	12
	São Chico	Granite and granodiorite/ Suite Intrusiva Parauari	1851, 1861a, 1886d	trending sinistral shear zones. Transcurrent faults sinistral N80°W	Potassic, chloritization, sericitization	py, cpy, gal, esf	Au-Ag	30.21 (Au)	<1886	14
Orogenic	São Jorge	Monzogranite/ Tropas Intrusive Suite	1891a	Brittle-style sheeted veins, stockwork, dissemination	chloritic, sericitic, carbonatization	py	Au	54.34 (Au)	nd	8
	Ouro Roxo	Granodiorite/ Tropas intrusive Suite	1897b	Ductile-, ductile-brittle-style, quartz veins, low sulfide contents	Silicification, phyllic, carbonatization	py-cpy-bis-(po-gal-cob)	Au-Cu-Bi	7.8 (Au)	1880	9,1
	Patinhas	Gneiss/ Cuiú-cuiú Complex	2003, 2015b		Silicification	py (cpy)	Au (Cu)	nd	nd, probably > 1950	11
Paleoplacer	Castelo dos Sonhos	Quartzite, metaconglomerate / Castelo dos Sonhos	2011-2050b	Stratification NNW/ NE. Subvertical foliation	Silicification	au, hm, py, cpy, po	Au	8.71	<3713	15

		Formation								
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*Key to references: 1- Jacobi (1999); 2 - Juliani et al (2005); 3- Juliani et al (2012); 4 - Echeverri-Missas et al (2013); 5 - Santos et al (2013); 6 -Villas et al (2013); 7 -Santiago et al (2013); 8 - Borges et al (2009); 9- Veloso and Santos (2013); 10- Coutinho (2008); 11-Klein et al (2004), 12-Assunção and Klein (2014), 13- Guimarães et al, 2019, 14- Vasquez et al. (2017), 15-Queiroz et al (2015), 16 - Correa-Lima and Klein (2020) *Geochemical technique: a) single zircon Pb-evaporation; b)U-Pb zircon; c) 40Ar/39Ar; d) Pb-Pb sulfide

*Abbreviations: Au- gold, Cu-copper, Pb- lead, Zn- zinc, Py-pyrite, Cpy- chalcopyrite, Mo-molibdenite, Gal- galena, Sph- sphalerite, Ag- silver, Tell-sel- telluride and selenide, Bis-bismuthinite, Po-pyrhotite, Cob-cobaltite, Cs- calcosite, hess-bis -hessite and bismuthinite, hem- hematit

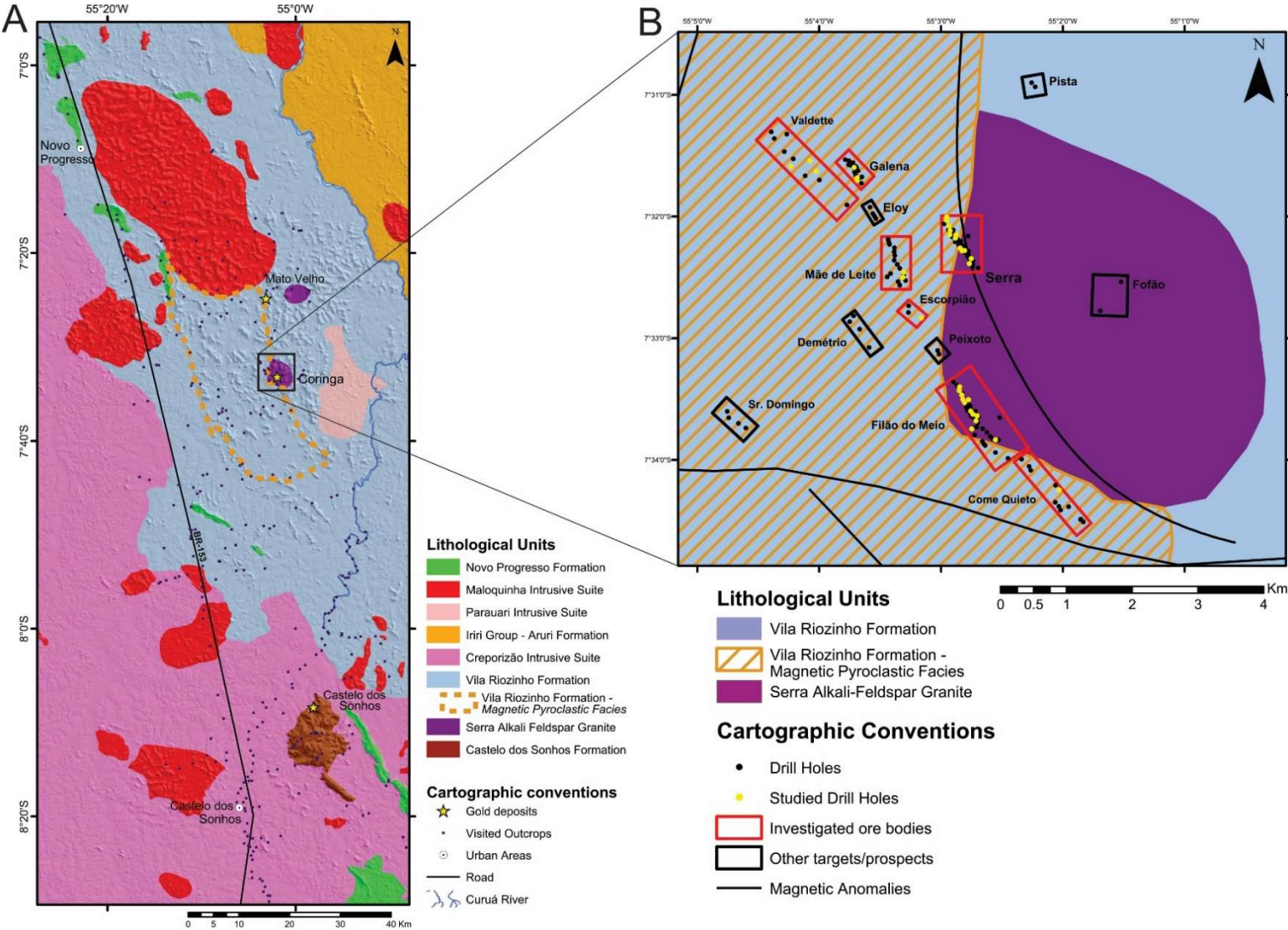


Figure 4.2 – A) Geological map of the Southeastern Tapajós Mineral Province (adapted from Guimarães et al. 2019), with the location of outcrops visited during this study.B) Geological and location map of the targets and drill holes performed in the Coringa deposit area (modified from Gunesh, 2002)

At the local scale, several authors have focused on the characterization of individual deposits, and suggested different styles or classes of deposits, described as orogenic (Klein et al., 2001, 2004; Santos et al., 2001; Coutinho, 2008; Veloso and Santos et al, 2013), intrusion-related/magmatic-hydrothermal (Santos et al., 2001; Borges et al., 2009; Santiago et al., 2013; Villas et al., 2013; Assunção and Klein, 2014; Borgo et al. 2017; Cassini et al. 2017; Biondi et al. 2018, 2019), porphyry (Jacobi, 1999; Juliani et al., 2002; Echeverri-Misas, 2010; Lopes and Moura, 2019), epithermal (Dreher et al., 1998; Juliani et al., 2005; Aguja-Bocanegra, 2013, Tokashiki et al., 2015, Guimarães et al., 2015; Corrêa-Lima and Klein, 2020), and paleoplacer (Queiroz and Klein, 2018). The principal characteristics of each class are reported in Table 1.

The Coringa gold-silver (Cu-Pb-Zn) deposit, in southeastern TMP, started in the 1970s as artisanal gold mining in alluvial and subordinate hypogene occurrences, which produced about 10 t of gold (Dzick, 2015). More recently, exploration has led to the discovery of the polymetallic mineralization in tens of discontinuous veins (Fig.4 2), with resources of ~12 t Au and ~19 t Ag, and variable amounts of Cu-Pb-Zn (Prenn et al., 2017). The mineralization is hosted in felsic volcanic rocks and granite, which have been dated and attributed to the Vila Riozinho Formation (1996 ± 21 Ma) and Serra Alkali Feldspar Granite (1999 ± 25 Ma) units, respectively (Guimarães et al., 2019; Guimarães and Klein, 2020).

Lately, some attempts have been made to improve the understanding of the genesis of the Coringa deposit, with works suggesting an epithermal model (Tokashiki et al., 2015; Corrêa-Lima and Klein, 2020). However, these works addressed only veins peripheral to the main ore bodies (Fig. 4.2), which have not been used in resource estimation to date, and a thorough characterization of the whole hydrothermal system that produced the deposit has not been achieved.

Therefore, in this work, we aim to contribute to the solving of some of the genetic issues concerning the Au-Ag mineralization in the Coringa deposit by studying its main ore bodies, which were used to delimit the present-day minable mineralization (Fig. 4.2b). In this regard, we provide a better characterization of the hydrothermal alteration stages and mineralization through petrographic, mineral chemistry, fluid inclusion, and stable isotope studies on ore and gangue minerals. The results allow us to discuss the physicochemical characteristics of mineralization (T-P-X-pH- fO_2), the nature, and source of the ore-forming fluids, and to establish the geological and genetic models for the Coringa deposit.

Furthermore, we discuss the implications of our results to the understanding of the regional-scale magmatic-hydrothermal mineral system of the Tapajós Mineral Province.

2. Geological setting

In the Tapajós Mineral Province (or Tapajós Domain, in the sense of Santos et al., 2001, and Vasquez et al., 2008), there is an extensive exposition of volcanic and plutonic rocks in an NW-SE belt, which extends throughout the central portion of the Amazonian Craton (Fig. 4.1), and has been attributed to the Uatumã and Orocaima magmatic events (Klein et al., 2012; Fraga et al., 2017; Vasquez et al., 2017, and references therein).

The basement associations are represented by the supracrustal rocks of the Jacareacanga Group, granites and orthogneisses of the Cuiú-Cuiú Complex (2003-2005 Ma), and the volcanic and volcanoclastic rocks of Comandante Arara Formation, which are concentrated in the central, southeastern, and eastern portions of TMP (Fig. 1). These sequences are related to a slightly evolved magmatic arc associated with the subduction of the oceanic lithosphere, possibly an island arc setting and related to arc collision against an Archean continent, named Cuiú-Cuiú Arc (Vasquez et al., 2002).

The events that succeeded the formation of the Cuiú-Cuiú Arc, during the Orosirian period, produced the volcanic rocks of the Vila Riozinho Formation, and granitoids of the Creporizão Intrusive Suite (Fig. 4.1) (Lamarão et al. 2002; Vasquez et al. 2002; Santos et al. 2004; Guimarães and Klein, 2020), both units marked by a high-K calc-alkaline and shoshonitic signature. The Serra Alkali Feldspar Granite (1999 ± 25 to 1989 ± 21 Ma) is interpreted as a differentiated and evolved variety of the Creporizão Intrusive Suite, and shows evidence of emplacement in the upper levels of the crust (Guimarães et al., 2015, 2019). This granite is probably intrusive in the Vila Riozinho Formation (1996 ± 21 to 1989 ± 12 Ma). Guimarães et al. (2019) also described a magnetic pyroclastic facies from the Vila Riozinho Formation (Fig. 4.2), which comprises the most magnetic rocks in southeastern TMP.

A high K calc-alkaline magmatism occurred between 1907 and 1864 Ma originating the São Jorge Jovem Granite, which was succeeded by the high-K calcic and alkalic magmatic events that produced the Parauari Intrusive Suite, and the basic to intermediate rocks of the Ingarana Intrusive Suite. Simultaneously, acidic, alkaline magmatism was emplaced and is represented by the Maloquinha Intrusive Suite granitoids and its extrusive equivalents of the Moraes Almeida Formation and Iriri Group. The NW-SE trending transcurrent faults

controlled most of the igneous bodies from this phase, but the E-W and NE-SW direction components, which mark the transition to extensional tectonics, controlled some mafic bodies (Vasquez et al., 2017).

The youngest magmatic events in the region are diabase dikes correlated to the Jurassic period, tholeiitic magmatism of the Penatecaua event (Vasquez and Rosa-Costa 2008). These dikes clearly show a magnetometric signature and are oriented according to the E-W and NE-SW directions (Guimarães et al., 2019).

In the southeast portion of the TMP, close to the border with the Iriri-Xingu Domain (Fig. 4.1), there are sedimentary sequences related to different geological events. The Castelo dos Sonhos Formation, the oldest unit of the TGP, is composed of auriferous metaconglomerates and metasandstones deposited by fan and fluvial systems between 2011 and 2050 Ma (Queiroz et al., 2015; Klein et al., 2017). The Castelo de Sonhos Formation was considered a relic of a larger foreland basin, whose basement in the southeast of Tapajós is still unknown because all the volcanic and granitic rocks of the adjacent areas are younger than this formation.

The sedimentary Novo Progresso Formation is represented by NNW-SSE-trending elongated and discontinuous hills and composed of sandstones and siltstones with volcanic contribution (Guimarães et al., 2015; Klein et al., 2018). Reconnaissance detrital zircon U-Pb LA-ICP-MS data indicate maximum depositional age around 1840 Ma, whereas structural relationships suggest a minimum age of 1780 Ma (Klein et al., 2018).

Some authors established a geological evolution to TMP as the addition of several magmatic arcs from southwest to northeast between 2040 and 1870 Ma, which was followed by post-orogenic magmatism from 1890 to 1870 Ma, during the Uatumã event, and finally an anorogenic granitic event at ca. 1780 Ma (e.g., Santos et al., 2004). However, Juliani et al. (2013) suggested magmatic arcs oriented to the east-west direction, with subduction from south to north. In contrast to the model of successive magmatic arcs, Vasquez et al. (2017) proposed the collision of a single arc, the Cuiú-Cuiú Arc (2.03 to 2.05 Ga), against an Archean continent to the east. Vasquez et al. (2017) also suggested that this subduction-collision event was followed by a transcurrent post-collision magmatic event of ca. 2.0 to 1.96 Ga, and then by extensional events of 1.90 to 1.87 Ga. This post-collision magmatic event includes the volcanic rocks and granites that host the Au-Ag mineralization in the Coringa deposit (Guimarães et al., 2020, and as we discuss in the following sections). A problem with this interpretation is the lack of known unequivocal collisional assemblages in the TMP.

However, the Tapajós Domain must be taken in a largest context which includes its continuation to the north, in the Guiana Shield. There, collisional assemblages are clearly defined by the medium- to high-grade supracrustal rocks of the Cauarane-Coeroeni belt, which underwent metamorphism at about 2020 Ma, associated with the amalgamation of Early Orosirian (2.04-2.03 Ga) magmatic arcs (Fraga and Cordani, 2019). These arcs are coeval to the Cuiú-Cuiú arc.

3. Previous works on the Coringa deposit and surroundings areas

The Coringa deposit is located 70 km southeast from the town of Novo Progresso, Pará State, Brazil, in the southeastern part of the Tapajós Mineral Province (Fig. 4.2). In the surroundings of the deposit, Guimarães et al. (2015, 2019) characterized volcanic and felsic volcanoclastic rocks belonging to the magnetic pyroclastic facies of the Vila Riozinho Formation (MPF) and intrusive granite bodies defined as the Serra Alkali Feldspar Granite (SAFG). These units have been dated at 1989 ± 12 to 1994 ± 12 Ma (MPF), and 1989 ± 21 to 1998 ± 6 Ma, and interpreted to be formed in a post-collisional setting of the Orosirian orogeny (Guimarães and Klein, 2020).

The main regional structures trend to northwest and north-northwest and follow, in general, magnetic discontinuities. These structures correspond to dextral strike-slip brittle shear zones, which correspond to a Riedel system (Guimarães et al., 2019). The mineralized Coringa shear-vein system is coincident with the north-northwest trend (Fig. 4.2) and dips 70° to 90° to the northeast (Prenn et al., 2017).

Several discontinuous ore bodies have been defined as forming the Coringa deposit, each composed of mineralized quartz-sulfide veins (Fig. 4.2, Prenn et al., 2017). The mineralized vein system has variable widths ranging from a few centimeters to over 14 meters and has been defined at least to depths of 250 meters (Prenn et al., 2017). Subordinate stockworks zones, as well as sulfide dissemination in host rocks, also occur (Tokashiki et al., 2015; Guimarães et al., 2015). The main ore bodies, which have been used to define the mineral reserves and resources, are Serra, Valdetete, Galena, Mãe de Leite, Escorpião, Meio, and Come Quietto. These bodies occur broadly aligned for c. 7 km along the central shear zone. Other peripheral mineralized bodies, parallel to the main mineralized structure, include the Demetrio, Fofão, Pista, and Sr. Domingos targets (Fig.4.2b).

Studies on some of the peripheral veins and alteration zones described hydrothermal alteration with adularia and sericite, manganese carbonate, argillic alteration zones, and base metals in the mineralization. These features and the spatial association between mineralization and brittle structures in supposed rhyolite domes were interpreted as compatible with a low- to intermediate sulfidation epithermal deposit, genetically linked to magmatic-hydrothermal systems with age close to 1.97 Ga (Tokashiki et al., 2015). A more detailed study was performed in the polymetallic mineralization of the Pista and Fofão targets (Fig. 4.2b) hosted in the Serra Alkali Feldspar Granite, which is associated with coeval volcanic rocks (Corrêa-Lima and Klein, 2020). The authors described albitization and potassic metasomatism as a post-magmatic stage, followed by silicified-brecciated zones, sericitization, and carbonatization of wall-rocks as ore-related alterations. The post-ore hydrothermal stages include distal propylitic and supergene alterations. The mineralization occurs as dissemination and filling fissure veinlets containing gold, Au-Ag tellurides, and Bi-Ag selenides, and is part of a magmatic-hydrothermal mineralized system with characteristics compatible with those of low- to intermediate-sulfidation epithermal systems.

In addition to Coringa, the Mato Velho prospect, which occurs to the north (Fig. 4.2a), shares several characteristics with Coringa, and both might be associated with the same hydrothermal system or mineralizing event. Feio (2014) identified three types of host rocks: rhyolite, dacite, and magmatic-hydrothermal (volcanic) breccia. The ore-related hydrothermal alteration that overprinted the primary characteristics of the host rocks was of the pervasive and fissure-filling types. Six alteration types have been identified: sericitic, argillic, chloritic, sulfidation, silicification, and carbonatization, without the establishment of a temporal sequence. The mineralization at Mato Velho occurs in two ways: 1) disseminated and low grade, associated with millimeter-wide swarms of quartz-chlorite-carbonate-sulfide veins, oriented according to NW-SE and NE-SW. The sulfide contents are between 1 and 2%, mainly sphalerite, with subordinate galena and chalcopyrite; and 2) free gold in high-grade quartz-sulfide multiple-vein arrangements (Dzick, 2015). A Pb-Pb model age of 1974 Ma in ore-related pyrite crystals from quartz veins hosted in dacite, suggesting contemporaneity between the mineralization and the host volcanic rock (Feio, 2014).

4. Analytical procedures and geophysical interpretation

In order to better constrain the structural context of the mineralized bodies in the Coringa deposit we used a regional 3D unconstrained magnetization vector inversion model (Ellis et al., 2012). The model can invert the magnetization vector straight, mitigating the low latitudes and remanent magnetization effects (Johnson and Aisengart, 2014). The subsurface was discretized in $184 \times 210 \times 26$, establishing a 3D model with 1,004,640 cells. The unconstrained model recovered susceptibilities down to 7,500 m, with amplitudes ranging from 0.1×10^{-3} SI to 117.6×10^{-3} SI. Concerning to improve the visualization, we suppressed anomalies with less than 0.01×10^{-3} SI and changed the susceptibility anomaly by the depth values.

For petrographic, chemical, fluid inclusion and isotopic studies, most of the samples used in this work come from drill cores from seven of the main ore bodies that make up the Coringa deposit: Serra, Meio, Come Quietto, Galena, Mãe de Leite, Escorpião, and Valdetete (Fig. 2). Some other samples come from outcrops of the country rocks.

We investigated about 270 polished sections using conventional and Scanning Electronic Microscope (SEM) associated with backscattering images and Energy Dispersive Spectroscopy (EDS). The SEM analyses were conducted in laboratories of the Geological Survey of Brazil located in Brasília (FEI Quanta 450) and Belém (Zeiss LS15). The chemical compositions of selected minerals (silicates, sulfide, gold) were determined by Electron Microprobe Analysis (EPMA) on thirty polished sections at the University of Brasília Microprobe Laboratory. This laboratory houses a JEOL JXA-8230 equipment, operating with an acceleration voltage of 20 kV and 40 atm. The analysis time varied from 10 to 30 seconds, according to the expected abundance of each element in the mineral.

For fluid inclusions studies, thirty-six double-polished sections of veins were petrographically investigated, but only ten samples presented satisfactory fluid inclusions to obtain the microthermometric data. Microthermometric analyses were carried out using a Linkam heating-freezing stage THMSG 600 housed at the Laboratório de Microanálises of the Geological Survey of Brazil, in Brasília, following procedures described by Roedder, 1984, and Shepherd et al., 1985. The equipment was calibrated with synthetic samples of fluid inclusions (CSCO₂). The data are reproducible to ± 0.5 °C for the freezing runs down to -180 °C and ± 5 °C for heating runs to the appropriate temperature of total homogenization.

The salinities of the NaCl–H₂O aqueous inclusions were calculated according to the ice melting temperature and using the equation provided by Bodnar (1993). Salinities of CO₂–

NaCl–H₂O inclusions were calculated using the final melting temperatures of CO₂–clathrate (Collins, 1979).

Stable isotopes analyses of hydrothermal and magmatic minerals were obtained in different laboratories. Pure mineral concentrates were obtained after sample crushing by handpicking using a binocular microscope. The results are presented in per thousand (‰) using the delta (δ) notation and referred to the V-PDB standard (Vienna Pee Dee Belemnite) for carbon, V-SMOW (Vienna Standard Mean Ocean Water) for oxygen and hydrogen, and V-CDT (Canyon Diablo Troilite) for sulfur, standards.

Sulfur isotope data were obtained for galena and pyrite from a total of eighteen samples. The analyses were carried out at the Stable Isotope Laboratory of the University of Brasília, Brazil. For sulfur analysis, the SO₂ produced by combustion of about 0.5 mg of sample was loaded onto tin capsules reacting at 1080°C. The combusted gases were carried in a stream and reduced by contact with high-purity copper wires and the SO₂ were separated by gas chromatography. Analyses were performed by the EA-IRMS (Elemental Analysis and Isotope Ratio Mass Spectrometry) using a Flash Elemental Analyzer and ThermoFisher MAT 253 mass spectrometer. Uncertainties are estimated at 0.2‰.

Three carbonate samples were analyzed for carbon and oxygen isotopes at the Stable Isotope Laboratory of the University of São Paulo, Brazil. The results were obtained using an isotopic ratio mass spectrometer Delta V Advantage, coupled to a Gas-Bench II Thermo Finnigan equipment and a CT-Analysis GC-PAL autosampler. This equipment measures the carbon and oxygen isotopic ratios with the initial extraction of CO₂ by reaction with 100% phosphoric acid (H₃PO₄) at 72°C. After extraction, the gas is analyzed on the mass spectrometer calibrated to international standards and from laboratory internal references. Uncertainties are 0.03‰.

Oxygen isotope analyses were performed at the Laboratório de Estudos Isotópicos of the Federal University of Pernambuco (UFPE), Recife, Brazil (quartz, n=10), and at the Stable Isotope Laboratory of the University of Cape Town (UCT), South Africa (quartz, n=11, muscovite, n=2), using Thermo Finnigan Delta V Advantage and Finnigan Delta XP mass spectrometers, respectively. Both laboratories use similar analytical protocols and the laser fluorination method (Clayton and Mayeda, 1963; Harris and Vogeli, 2010). Accordingly, oxygen was released by reaction with BrF₅ using CO₂ laser as a heat source and converted to CO₂ by reaction with graphite at 750°C (UFPE), or O₂ was collected on a

molecular sieve and analyzes as O₂ (UCT). Uncertainties for $\delta^{18}\text{O}$ were better than 0.1‰ (UFPE) and 0.16 ‰ (UCT), based on the long-term difference of in-house standard runs.

Hydrogen isotope data were also produced at UCT using the technique of Vennemann and O'Neil (1993) with a reduction by “Low-blank Indiana Zinc” (Schimmelmann and DeNiro, 1993). The internal water standards CTMP2010 (Cape Town Millipore Water 2010, D=−7.4‰) and RMW (Rocky Mountain Water, D=−131.4‰) were used to convert raw data to the Standard Mean Ocean water (SMOW) scale. The precision for δD was $\pm 2\text{‰}$.

5. The Coringa deposit

5.1. Geophysical constraints on the localization of mineralized bodies

In the southeastern Tapajós Mineral Province, Guimarães et al. (2019) described the magnetic pyroclastic facies from the Vila Riozinho Formation (MPF) as having high concentrations of radiometric elements associated with unusual high magnetic anomalies. Here we use a regional 3D unconstrained magnetization vector inversion model (MVI) concerning to understand the relationships, if any, between the MPF and the location of the Coringa deposit. This approach built a 3D magnetic relief of the MPF and surroundings (Fig. 4.3a). The 3D model shows the MPF as several minor magnetic anomalies down to 2,500 m. These anomalies can also be seen in the MVI susceptibility cross-section A-A' extracted crossing the Coringa deposit (Fig. 4.3b). In this cross-section, the Coringa deposit seems to correlate with a major crustal discontinuity east of the magnetic pyroclastic facies, and at the contact between this facies and the pluton of the Serra Alkali Feldspar Granite.

5.2. Host rocks

The investigation of the drill core and outcrop samples from the Serra, Meio, Come Quietto, Galena, Mãe de Leite, Escorpião, and Valdette ore bodies, allowed us to describe the host rocks, their hydrothermal alteration halos and paragenetic evolution, some contact relationships, and mineralization. The host rocks are volcanic and pyroclastic rocks of the Magnetic Pyroclastic Facies (MPF) from the Vila Riozinho Formation (ignimbrites, tuffs, and breccia), and the Serra Alkali Feldspar Granite, with a predominance of the supracrustal rocks (Fig. 4.4). In some samples, we observed intercalation between ignimbrites and tuffs. The breccias are associated with areas with intense cataclasis and show abrupt contacts with ignimbrites and tuffs.

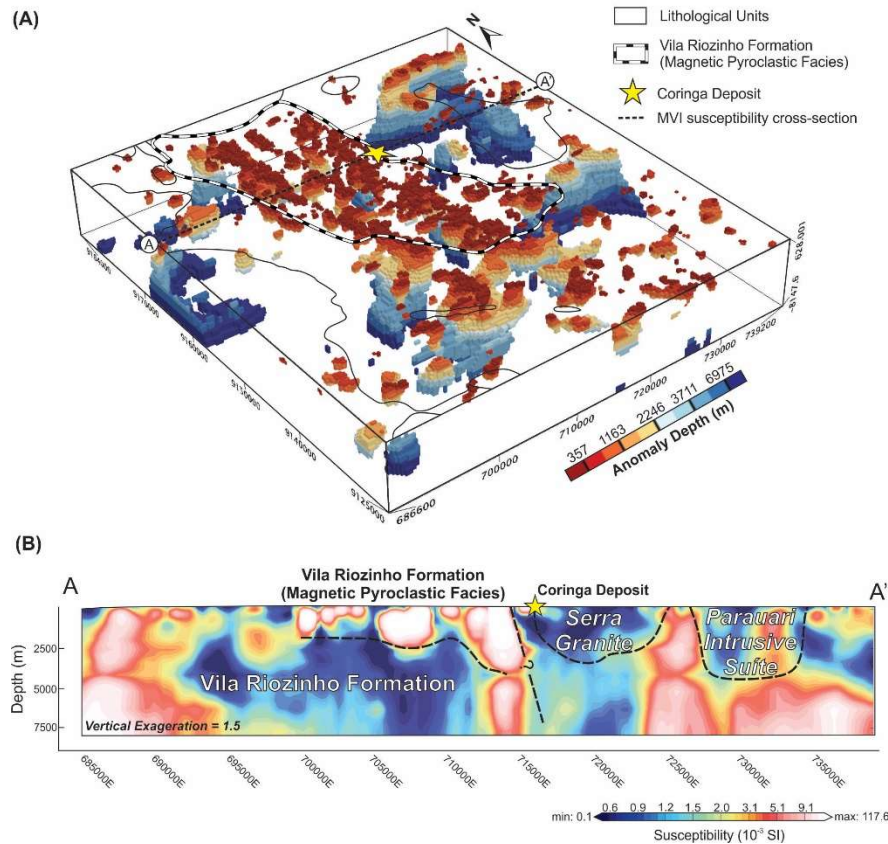


Figure 4.3 - A) The regional 3D magnetic relief of the magnetic pyroclastic facies (MPF) of the Vila Riozinho Formation for anomalies with susceptibility higher than 0.01×10^{-3} SI. B) The MVI susceptibility cross-section A-A' over the Coringa deposit.

The rhyolitic ignimbrites have an aphanitic matrix and sub-angular phenocrysts (quartz and K-feldspar) and locally show porphyritic texture. Lithic fragments are also present, with many preserved volcanic structures. There are also dacitic ignimbrites with porphyritic texture, and thin to aphanitic gray matrix. The ignimbrites maintain some primary features such as devitrified pumices, shards, spherulites, and devitrified flow structures (Figs. 4.4e, f). Crystals of quartz and K-feldspar and lithic fragments are sub-angular to sub-rounded, and are set in a brownish aphanitic quartz-feldspathic matrix also composed of titanite, apatite, chlorite, magnetite, and ilmenite. Disseminated hematite occurs in the matrix and gives the reddish color to the rock (Fig. 4.4e).

Ash-tuff and lapilli-tuff are composed of a grayish aphanitic and strongly recrystallized matrix, with sub-angular to sub-rounded clasts of quartz and rare K-feldspar. Locally, flow structures can be observed in the matrix (Fig. 4.4h,i).

Strongly silicified zones in tuffs and ignimbrites are represented by brecciated rocks formed by quartz crystals (jigsaw-textured quartz) associated with microcrystalline quartz. The breccias show fragments (1 to 2 cm) of ignimbrite cemented by micro to cryptocrystalline quartz grains, locally by carbonate (Fig. 4g). Breccias are more common in the Valdette ore body, where brittle tectonics appears to be more intense.

The alkali feldspar granite hosting mineralization is observed only in the Serra ore body (Fig. 4a). There, the pinkish alkali feldspar granite is equigranular and very fine-grained with granophyric and micrographic textures (Fig. 4.4d). The granite is weakly fractured (Fig. 4.4b) and occurs in abrupt (intrusive) contact with ignimbrites, and tuffs. Dissemination of biotite, hematite, and magnetite is locally observed.

Only in the Come Quietto ore body we have observed the occurrence of altered diabase dike. The dike occurs in abrupt (intrusive?) contact with the rhyolitic ignimbrites and is also altered, with carbonate-chlorite-epidote occurring as alteration of plagioclase and dissemination of magnetite.

5.3. *Hydrothermal alteration and veining*

The hydrothermal system that produced the mineralization in the Coringa deposit developed zones of pervasive and fissural hydrothermal alteration. Based on cross-cutting relationships, mineralogy, and location about the orebodies, the alteration associations were subdivided into three groups, according to their spatial distribution along with the veined ore zone: (a) a distal carbonate-chlorite-epidote (propylitic) alteration, (b) an intermediate to proximal sericite-pyrite alteration, (c) a proximal chlorite-hematite alteration. These alteration types affected the volcanic sequence and granite that host the mineralization and are present to more or less extent in all studied ore bodies. A few differences between the various bodies are highlighted below. The veined ore zone is characterized by intense quartz-sulfide veining (silicification-sulfidation) (Fig.4.5).

The carbonate-chlorite-epidote or propylitic alteration, forms the outermost halo, involving the other halos, and is more frequently observed in the peripheral targets. This alteration is common in rhyolitic ignimbrites and tuffs (Fig. 4.5a, b), texturally retentive, and pervasive selective, affecting only feldspar crystals, which may be partially or completely replaced (Fig. 4.6a, b). Subordinate mineral phases are magnetite, titanite, and apatite.

The sericite-pyrite alteration imparts a pale green color to the host rocks, and affects all lithotypes (ignimbrites, tuffs, and granite), and may be pervasive to selective pervasive

(Fig. 4.5c). The paragenesis is formed by sericite, pyrite, quartz, rare chalcopyrite, and locally adularia (Fig. 4.6d). The main effect is the texture obliterated by the replacement of feldspars

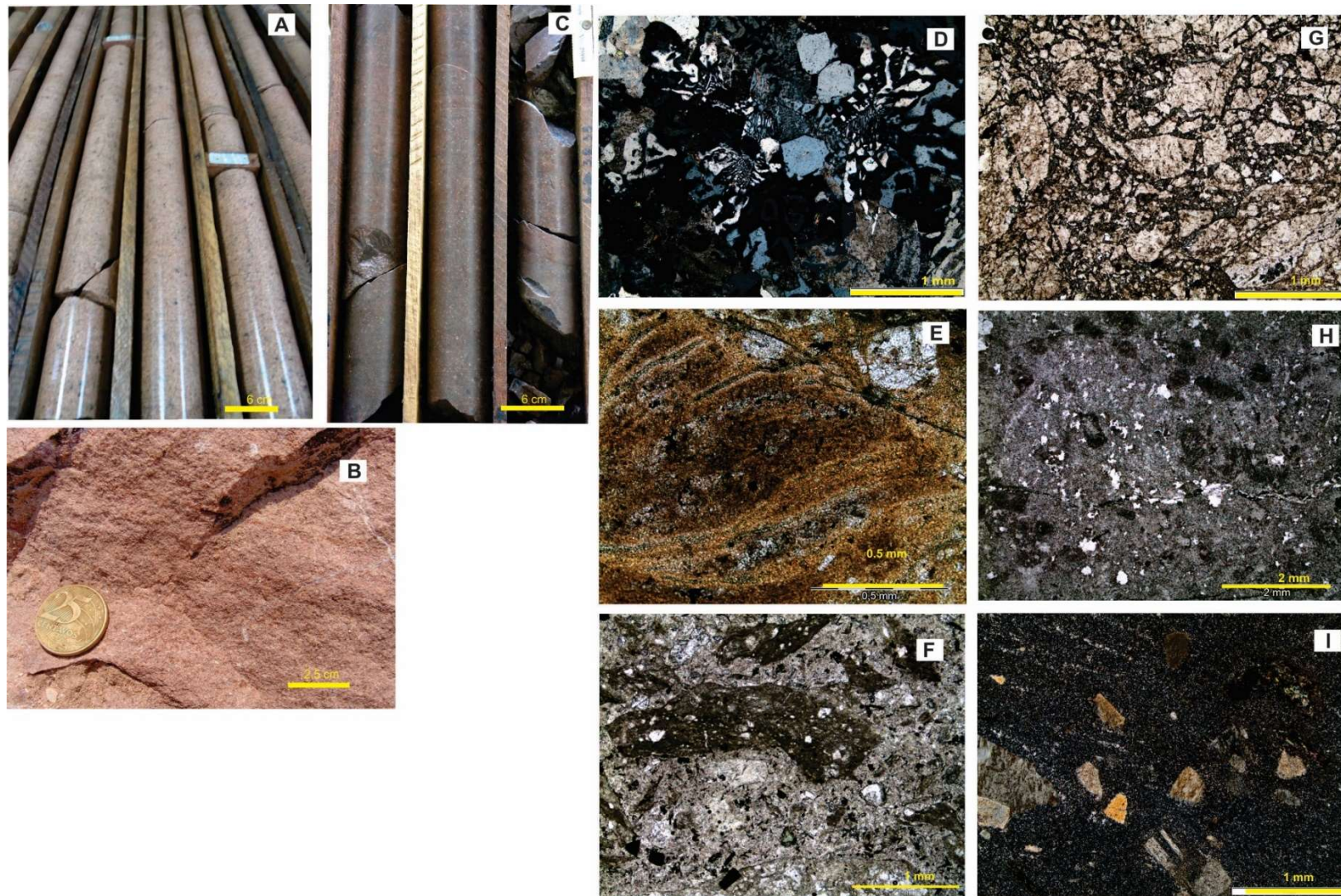


Figure 4.4 – Mesoscopic and microscopic aspects of host rocks. A) Drillhole alkali feldspar granite samples; B) Alkali feldspar granite sample; C) Drillhole rhyolitic ignimbrite sample; D) Photomicrography of alkali feldspar granite showing granophyric texture; E) Photomicrography of ignimbrite with flow structure in a matrix with chlorite-hematite alteration; F) Photomicrography of ignimbrite rhyolitic showing pumices in ignimbrite; G) Photomicrography brecciated ignimbrite; H) Photomicrography lapilli-tuff; I) Photomicrography ash-tuff.

by sericite, accompanied by the dissemination of fine-grained pyrite crystals, and locally by quartz and adularia. The adularia crystals were observed only in volcanic lithotypes in the Come Quieto and Valdetto ore bodies (Fig. 4.6e). Sometimes the sericite-pyrite alteration may occur along with quartz-sulfide veins due to intercalation with the chlorite-hematite alteration.

The proximal chlorite-hematite alteration forms discrete reddish to completely red halo involving the quartz-sulfide veins (Fig. 4.5d, e). This alteration is observed in ignimbrites, that become reddish due to fine hematite grains disseminated in the matrix with small chlorite lamellae (Fig. 4.6f). It is a texturally non-destructive alteration, non-pervasive, but always in contact with quartz-sulfide veins.

A different type of alteration was observed only in the Valdetto target. It is represented by intense carbonate alteration composed of spartaite, a variety of Mn-bearing calcite (Fig. 4.6c). The pervasive form of this alteration style is recorded in the hydrothermal-tectonic breccias crosscutting ignimbrites and tuffs.

The silicification-sulfidation process is fissural (Fig. 4.5f, g), and marked by the development of several generations of mono to polyminerallic quartz veins, hosted in ignimbrites, tuffs, and granite in all investigated ore bodies. These veins are composed of microcrystalline quartz (massive and jigsaw-textured quartz) associated with sulfides and other minerals like chlorite, carbonate, hematite, and sericite.

Three types of quartz-rich veins were identified. However, no temporal relationship among them was defined due to the lack of crosscutting evidence. The type 1 veins comprise thin (0.2 mm to 0.5 cm) and discontinuous massive quartz veins lacking sulfides (Fig. 7a), and barren. The type 2 veins are medium thickness (0.5 to 1.0 cm), sulfide-poor, gold-bearing, open-space filling veins (Fig. 4.7b, c). The pseudo-hexagonal quartz crystals may show jigsaw texture with pyrite, galena, and hematite. The type 3 veins are thick thickness (1 cm to 4 cm), sulfide-rich, and gold-bearing quartz veins. The coarse-grained subhedral quartz crystals may form comb texture (Fig. 4.7d), but also present fine-grained subhedral milky quartz (Fig. 4.7e). The sulfide phases are represented by pyrite, galena, sphalerite, and chalcopyrite. Occasionally, sericite, hematite, chlorite, and Mn-calcite are observed.

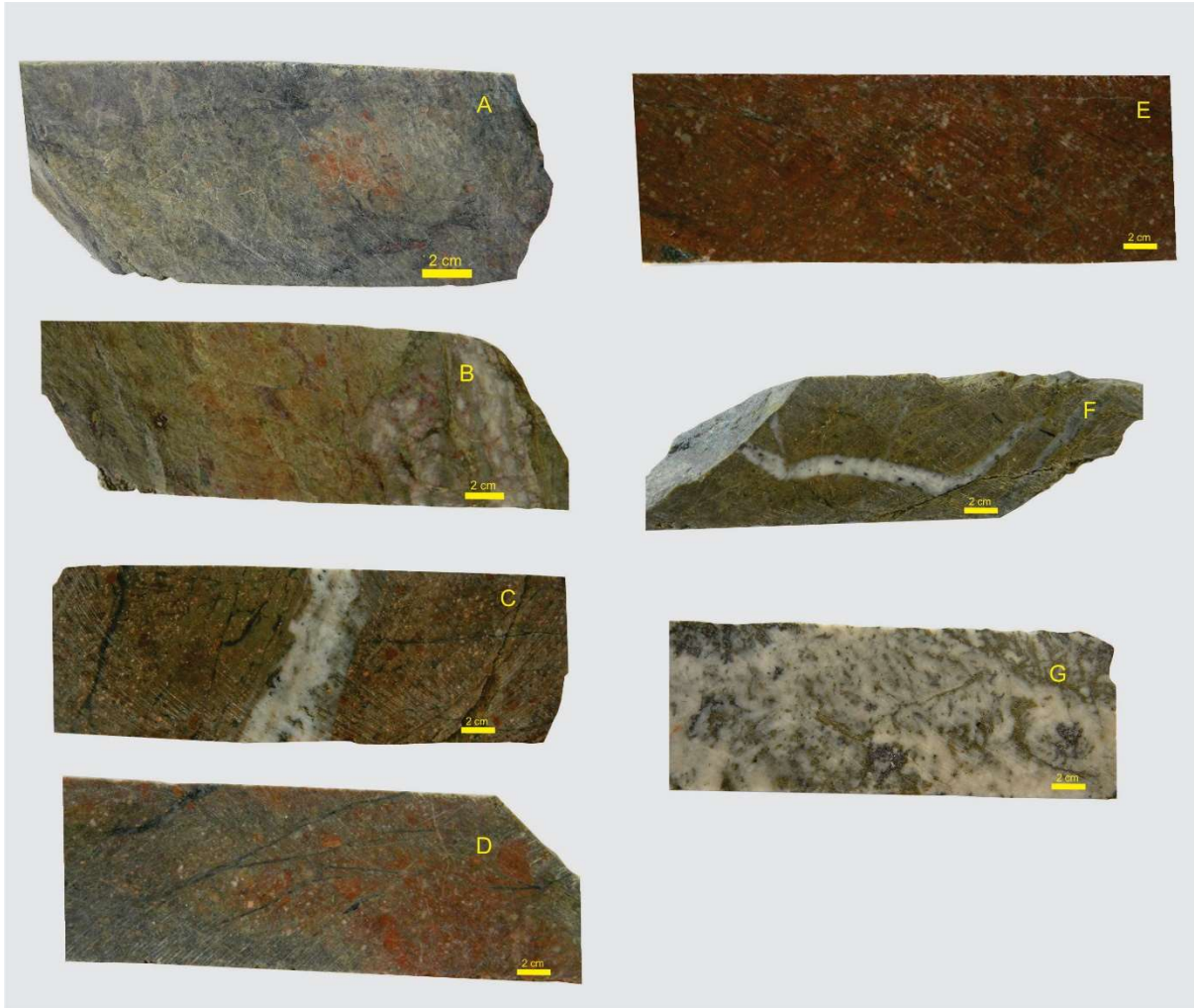


Figure 4.5 - Macroscopic aspects from drill holes host rocks samples and their hydrothermal alterations. A) Rhyolitic ignimbrite with carbonate-chlorite-epidote alteration; B) Rhyolitic ignimbrite with carbonate-epidote alteration; C) Sericite-pyrite alteration in ignimbrite; D) Chlorite-hematite alteration in ignimbrite; E) Hematite rich alteration in ignimbrite; F) Quartz veining in ignimbrite with sericite-pyrite alteration; G) Quartz-sulfide vein.

5.4. Gold-silver (Cu-Pb) mineralization

The gold-silver (Cu-Pb) mineralization is nearly all associated with quartz-sulfide veining (types 2 and 3). In addition to gold-silver, the mineralogical association consists of pyrite, galena, sphalerite, chalcopyrite, and hematite. The sulfides also occur as disseminations in all host rocks.

Pyrite is the most abundant sulfide mineral, not only in the veins but also disseminated in the host rocks, forming two generations. The pyrite A is euhedral (cubic) to subhedral, showing few unfilled fractures and occurs as dissemination in the host rocks, and related to the sericitic alteration (Figs. 4.7e, 4.8a). The pyrite B is subhedral to rounded, often fractured, and occurs in quartz-sulfide veins of types 2 and 3. The fractures are filled by one

or more phases including, in decreasing abundance, galena, chalcopyrite, sphalerite, and gold. Inclusions of the same minerals were also observed (Fig. 4.8b). Galena occurs as subhedral grains in veins and filling fractures in pyrite and chalcopyrite (Fig. 4.8d, e). Chalcopyrite occurs as subhedral grains in veins, as inclusions in pyrite and sphalerite, and filling fractures in pyrite B (Fig. 4.8c, d). Sphalerite occurs as semi-opaque anhedral crystals in veins, as inclusions in galena, and commonly contains chalcopyrite inclusions (Figs. 4.8d, e, f).

Gold grains occurs typically as rounded inclusions in pyrite (Fig. 4.8g) from quartz-sulfide veins, and also occupy fractures within pyrite grains (Fig. 4.8h).

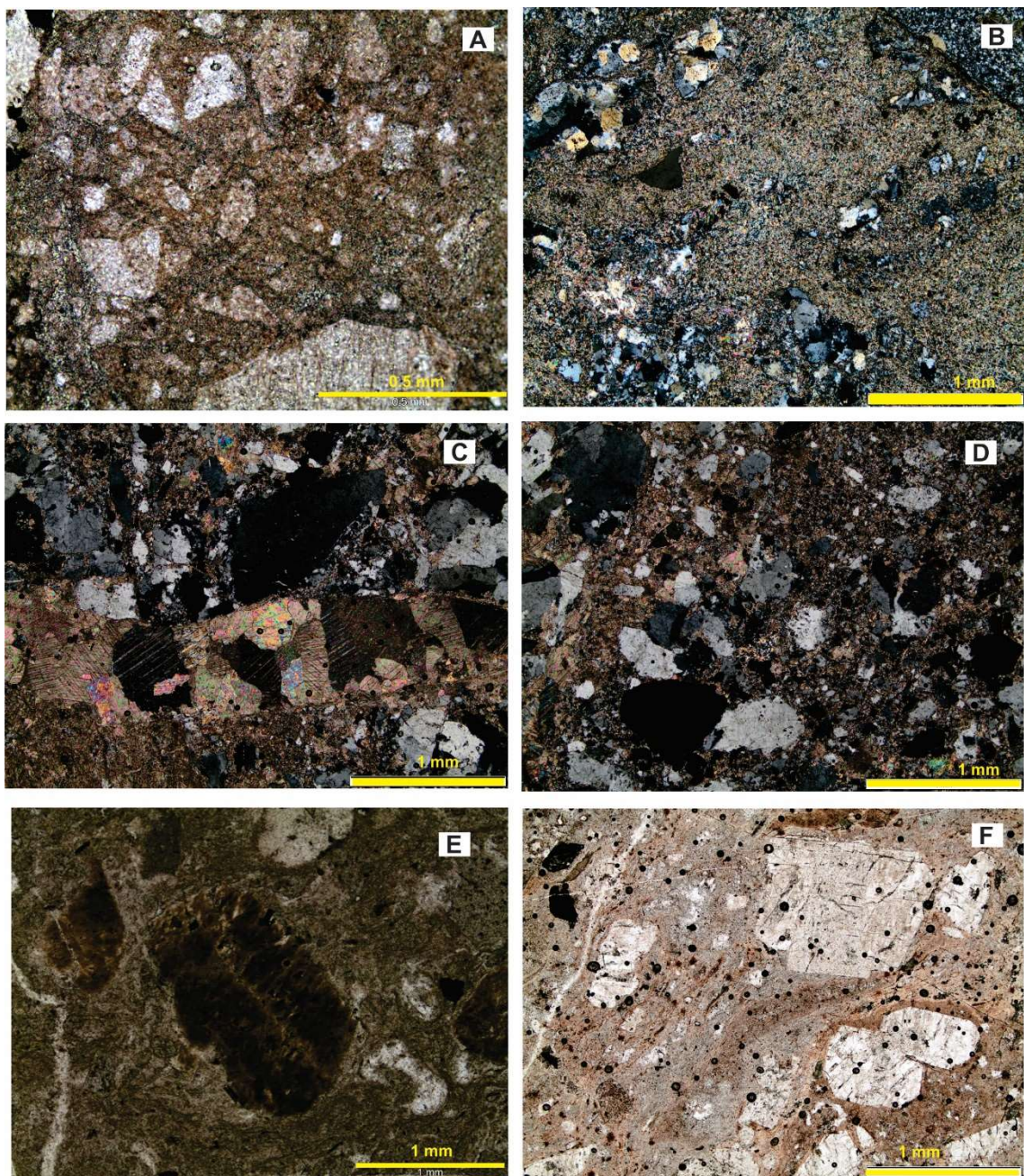


Figure 4.6 – Microscopic features of hydrothermal alterations in host rocks. A) A chlorite-epidote alteration (matrix) in rhyolitic ignimbrite; B) A carbonate-chlorite-epidote alteration in lapilli tuff; C) Intense carbonate alteration with carbonate vein in ignimbrite; D) Sericitic alteration in ignimbrite with pyrite crystals; E) Adularia crystals in ignimbrite; F) The reddish ignimbrite matrix with disseminated with small chlorite lamella and hematite grains (chlorite-hematite alteration).

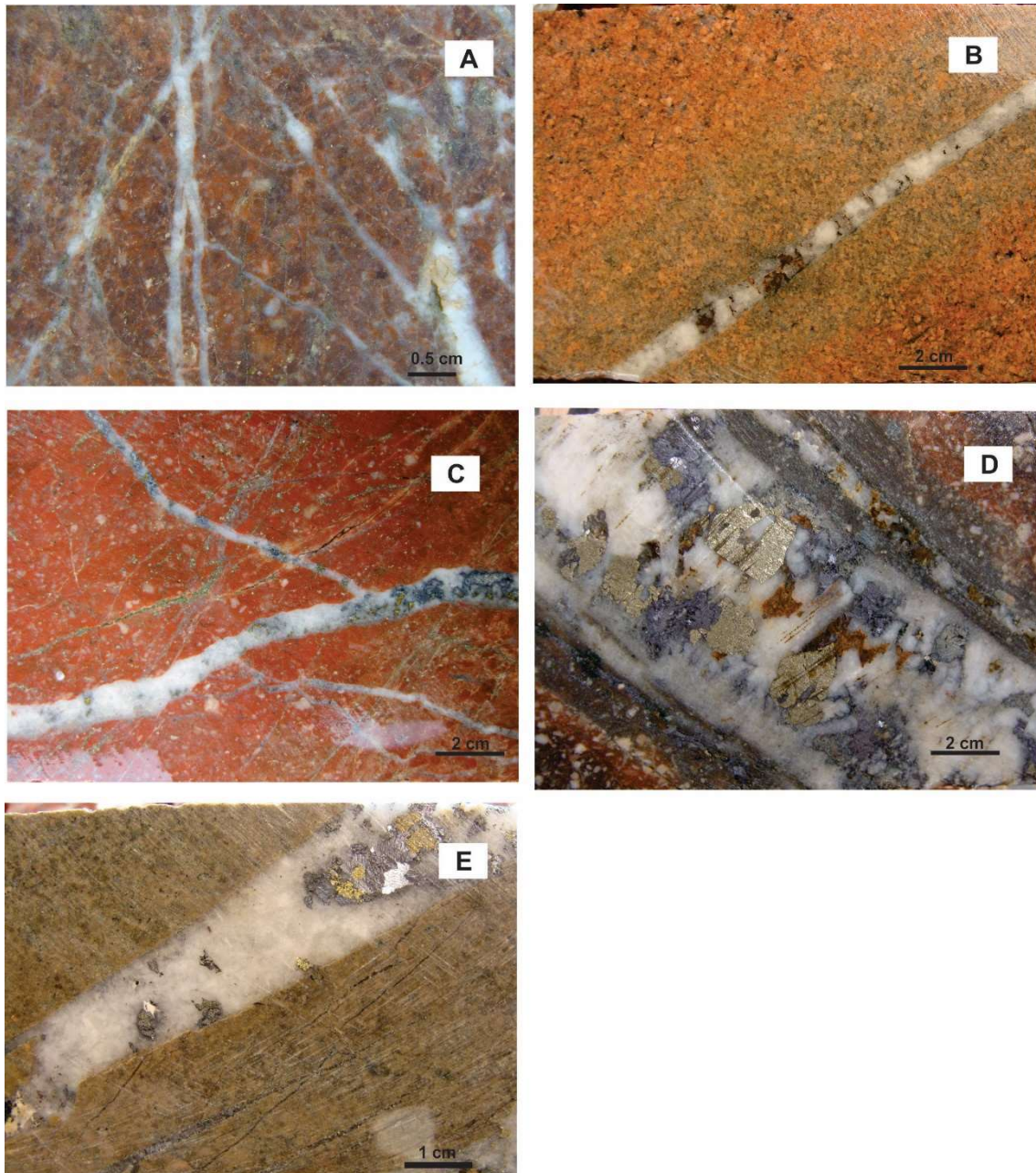


Figure 4.7 - Types of quartz veining. A) Veins type 1 -thin quartz veins lacking sulfides; B) Veins type 2 - sulfide-poor quartz vein hosted in alkali feldspar granite; C) Veins type 2 sulfide-poor quartz veins hosted in rhyolite with chlorite-hematite alteration; D) Veins type 3 – sulfide-rich quartz veins with comb texture in rhyolite; E) Veins type 3 -sulfide-rich quartz vein in ignimbrite enveloped by a sericite-pyrite alteration halo.

6. Mineral chemistry

6.1. Sulfides and gold

Electronic probe microanalyses (EPMA) in pyrite crystals (types A and B) in the different host rocks and ore bodies/targets show no significant differences in their chemical composition (Appendix 2). One exception is the pyrite disseminated in tuffs (type A) from the Escorpião target, which can reach 0.46% Pb, while in other occurrences Pb averages 0.14%. Galena EPMA results show small amounts of gold (0.01 - 0.04%) and silver (0.01 - 2.0%) in almost all ore bodies/targets. Relatively significant amounts of other elements include Mo (~0.87%), Bi (0.68%), and Te (0.03%). Chemically, the different occurrences of chalcopyrite (inclusions and fractures) do not differ from each other, with very low contents of Ag (0.01%), Co (0.03%), Ni (0.01%), Zn (0.02-2.5%), Mo (0.05%), and Pb (0.10%). The chemical analysis of sphalerite revealed a small amount of gold in only in the Mãe de Leite orebody, hosted in ignimbrite veins. Very small amounts of Fe (<1.5%), Co (0.01%), Ni (0.01%), and Pb (0.10%) were also evidenced.

The EPMA analyses of gold particles from veins in tuffs of the Serra ore body revealed the predominance of electrum with 27 to 30% Ag. The SEM-EDS analysis (Appendix 1) still revealed significant amounts of Au in sulfides (0.8 to 4.5%) at Serra, Galena, Mãe de Leite, and Valdetete, although no gold inclusion is visible, and other elements such as Pt, Pd, Bi, Ni, Co also show relatively significant contents (0.1 - 3.0 %). However, EPMA results confirmed only the presence of Ni and Co (0.01 – 0.07%) in pyrite, galena, chalcopyrite, and sphalerite grains.

The EPMA analyses also allowed the identification of other mineral phases, such as covellite (CuS), which occurs at the edges of chalcopyrite, and is of secondary origin and associated with oxidation of chalcopyrite. We have also found the bismuth-bearing sulfide phase aikinite (PbCuBiS₃) in the veins of the Serra ore body.

The petrography study with SEM support of mineralized veins indicated a spatial association of chalcopyrite, sphalerite, galena, and gold, which are all late regarding pyrite B.

Chemically, using EPMA data, the chronological relationship between the sulfide phases can also be shown in the Co x Ni graph (Fig. 4.9). Pyrite B, possibly the first mineral phase to crystallize, and more Co enriched, is followed by chalcopyrite, which is very common as inclusions and fractures in pyrite. Then, sphalerite + galena, marked by inclusions of sphalerite in galena and pyrite and galena included and in fractures in pyrite, in addition to

the abundance of galena. Finally, gold (+ galena) that occurs together in fractures and inclusions in pyrite.

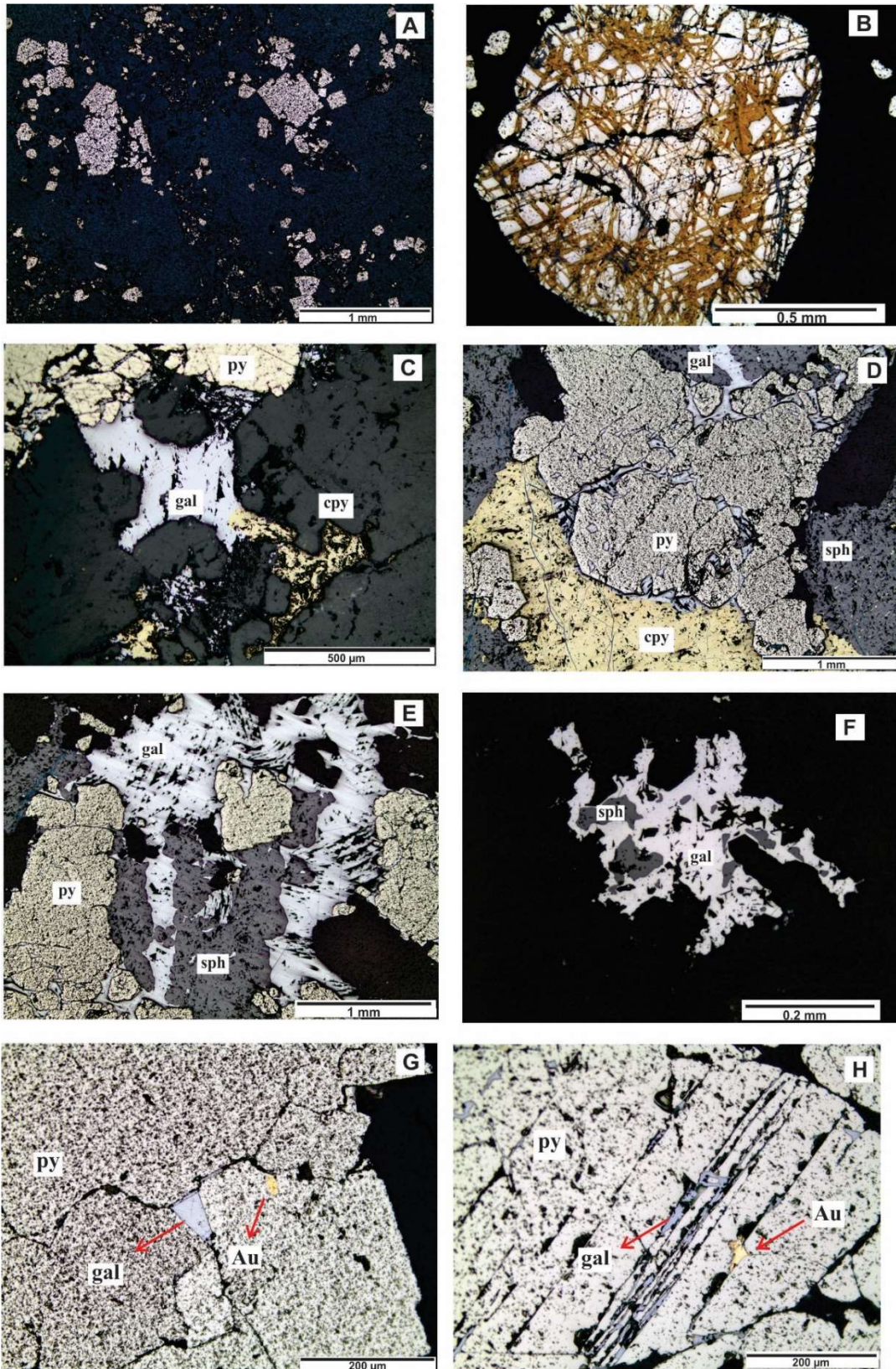


Figure 4.8 - Microscopic features of the sulfides in the Coringa deposit. A) Cubic-euhedral pyrite crystals disseminated; B) Fractured pyrite crystal filled by chalcopyrite; C) A quartz-pyrite-galena-chalcopyrite vein in ignimbrite from Galena target; D) Quartz-pyrite-sphalerite-chalcopyrite-galena in ignimbrite from Meio target. Chalcopyrite inclusions in sphalerite

6.2. Chlorite chemistry and thermometry

The variation of chemical composition in chlorite is useful to obtain information on the physicochemical conditions of the formation and estimating the temperature of hydrothermal systems (Cathelineau and Nieva, 1985). In the present study, we examined chlorites from the distal carbonate-chlorite-epidote (propylitic) alteration in the Serra Alkali Feldspar Granite. The chlorite is a product of hydrothermal alteration of primary biotite. The chlorites show pleochroism from olive green to pale green and low birefringence colors.

The average from microprobe analytical results performed on 26 chlorite grains are presented in Table 2, and show significant compositional variations. These chemical characteristics permit the chlorites to be classified as daphnite, pycnochlorite, and brunsvigite according to Hey (1954). This variation of types can be partially justified by the incomplete substitution of the primary biotite by chlorite, as observed in petrography.

Different empirical geothermometers related to chlorite composition were estimated using three equations for calibration (Cathelineau and Nieva (1985), Kranidiotis and MacLean (1987), and Zang and Fyfe (1995)) (Table 4.2). Each author applied corrections based on their observations that use $\text{Fe}/(\text{Fe}+\text{Mg})$ ratio, number of atoms of Si, and Al^{iv} per formula unit (a.p.f.u.) as parameters directly involved. For the studied samples the $\text{Fe}/(\text{Fe}+\text{Mg})$ ratio varies from 0.42 to 0.83. The Si/Al ratio shows little variability, from 1.03 to 1.40. The Si atoms vary between 5.45 and 5.98 a.p.f.u. and the Al^{iv} ranges from 2.02 to 2.55 a.p.f.u. These values are following those used by Zang and Fyfe (1995) to calibrate their geothermometer. As such, temperatures calculated using this calibration yielded values ranging from 224 to 241°C, which are interpreted as the temperature of the distal chlorite-carbonate-epidote alteration (Table 4.2, Fig. 4.10).

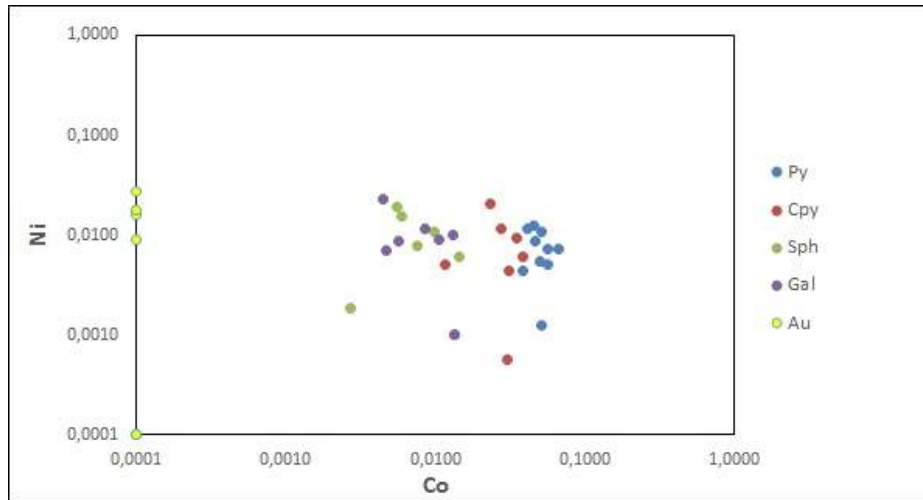


Figure 4.9 – Distribution Ni x Co of EPMA results from Coringa deposit sulfide and gold.

6.3. White mica (*Sericite*).

A compositional identification study of white mica was performed in one sample from the Serra Alkali Feldspar Granite and one sample from Vila Riozinho Formation, which was petrographically interpreted as hydrothermal. The EPMA results are presented in Appendix 3. The analyses revealed a relatively homogeneous composition in both samples, only with slightly higher Al_2O_3 , MgO , and Na_2O contents in the Serra granite sample.

According to the classification of Monier and Robert (1986), the analyzed samples belong to muscovite end member (Fig. 4.11a). However, a biotite substitution trend is also defined by the composition (Fig. 4.11b). According to these authors, the proximity to muscovite end member is an agreement with high-temperature, thus magmatic origin; and low-temperatures (300-400°C) typically represents a hydrothermal contribution to this rock, like observed in Coringa analyzed samples.

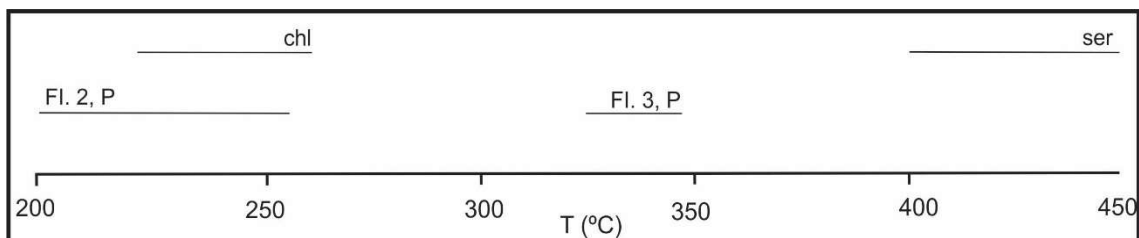


Figure 4.10 – Range of chlorite formation temperatures, calculated according to Zang and Fyfe (1995) (ZF), and primary fluid inclusion homogenization temperature from types FI. 2 and FI.3.

Table 4.2 - Averages of EPMA results for chlorite to Serra Alkali Feldspar Granite

Unit	SAFG	SAFG	SAFG
Sample	DDH 01-31.70	SG-38	SG-62
SiO ₂	24.70	29.96	27.87
TiO ₂	0.06	0.32	1.99
Al ₂ O ₃	20.29	17.94	18.04
FeO	38.38	22.02	29.12
MnO	2.01	0.74	0.59
MgO	4.51	17.49	11.67
CaO	0.11	0.09	1.60
Na ₂ O	0.09	0.01	0.05
K ₂ O	0.42	2.04	0.85
BaO	0.03	0.13	0.10
F	0.04	0.40	0.09
Cl	0.01	0.01	0.00
V ₂ O ₃	0.02	0.04	0.05
(OH)	9.36	8.99	8.02
Total	100.00	100.00	100.00
Si	5.45	5.98	5.73
Al iv	2.55	2.02	2.27
Al vi	2.75	2.25	2.13
Ti	0.01	0.05	0.31
Cr	0.00	0.00	0.00
Fe ³⁺	0.05	0.00	0.16
Fe ²⁺	7.03	3.71	4.85
Mn	0.38	0.13	0.10
Mg	1.48	5.21	3.58
Ni	0.00	0.00	0.00
Zn	0.00	0.00	0.00
Ca	0.03	0.02	0.35
Na	0.08	0.01	0.04
K	0.24	1.04	0.45
Ba	0.00	0.02	0.02
Rb	0.00	0.00	0.00
F	0.00	0.00	0.00
Cl	0.00	0.00	0.00
OH*	16.00	16.00	16.00
Total	36.05	36.43	35.98
Variety	daphnite	pycnchlorite	brunsvigite
Fe/Fe+Mg	0.03	0.13	0.10
Si/Al	0.00	0.00	0.00
T (°C)			
CAT	220.86	161.78	190.03
KM	349.41	262.52	301.91

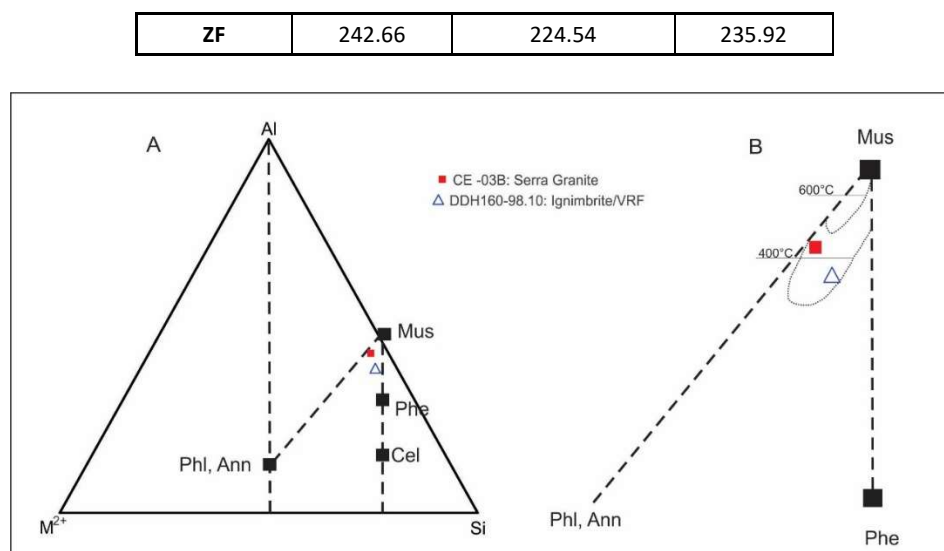


Figure 4.11 – A) Diagram Al-M²⁺-Si (atomic proportions) of Monier and Robert (1986) for white mica grains from Coringa deposit, where M²⁺ corresponds to divalent Fe and Mg; B) Detail of the Al-M²⁺-Si diagram, indicating biotite substitution trend. Phl: phlogopite, Ann: annite, cel: celadonite, phe: phengite, mus: muscovite.

7. Fluid inclusions

7.1. Types and distribution

The fluid inclusion studies were carried out in quartz from mineralized quartz-sulfide veins (types 2 and 3) of five investigated ore bodies (Serra, Meio, Galena, Come Quietto, and Mãe de Leite), using the Fluid Inclusion Assemblage (FIA) criteria of Goldstein and Reynolds (1994). Based on the number of phases present at room and sub-zero temperatures, phase transitions upon heating, and mode of occurrence, four types of fluid inclusions have been identified. The inclusions show the variable distribution in the different ore bodies, and two types of fluid inclusion (types FI.3 and FI.4) were only observed in samples from Serra, Galena, and Meio. Growth zonation in quartz is lacking, and no cross-cutting relationships could be observed between the four types since they occur in parallel or mixed trails (Fig. 12a), and therefore, a temporal relationship between them could not be established. However, inclusions occurring in clusters are considered as primary individuals, which are probably coeval with pseudo-secondary inclusions, and both have been trapped before the secondary type.

The type FI.1 comprises monophasic aqueous inclusions - H₂O (l). These are scarce and rounded inclusions, with less than 10 µm in size. This type occurs spatially associated

with type FI.2 as essentially dispersed between the trails (Fig. 4.12b, d), being probably primary in origin.

The type FI.2 are two-phase aqueous inclusions - H_2O (l) + H_2O (v), the most abundant type. The inclusions are elongated to irregular occurring in clusters (primary inclusions), pseudo-secondary and secondary trails in all orebodies (Table 3). In both modes of occurrence, the inclusions range from 20 to 50 μm in size, and in most of the samples, the vapor phase occupies 10 to 40% of the cavities. However, in some samples from Come Quietto and Mãe de Leite, liquid-rich inclusions (80 to 95 vol.% $\text{H}_2\text{O}_{\text{liq}}$) coexist with vapor-rich inclusions (50 to 80 vol.% $\text{H}_2\text{O}_{\text{vap}}$) (Fig. 4.12b, c, d).

The type FI.3 consists of three-phase aqueous-carbonic inclusions - H_2O (l) + CO_2 (l) + CO_2 (v). These inclusions are subordinate and occur in primary clusters and pseudo-secondary trails with ellipsoidal to irregular shapes, and sizes ranging from 20 to 50 μm (Fig. 4.12e, f). The volume of the carbonic phase ranges from 10 to 40 % of the total volume of the cavities. The inclusions FI.3 and FI.4 were observed only in veins from the Meio, Galena, and Serra ore bodies, where they coexist with the FI.1 and FI.2 types.

The type FI.4 are two-phase carbonic inclusions - CO_2 (l) + CO_2 (v), which are rare, occur in clusters and pseudo-secondary trails, and are 10 to 40 μm in size. Liquid-rich (80 to 90 vol. % $\text{CO}_{2\text{liq}}$) and vapor-rich inclusions (80 to 90 vol.% $\text{CO}_{2\text{gas}}$) coexist in the same trail (Fig. 4.12e, f). The FI.4 inclusions were only observed in one sample from Meio orebody, where inclusions of types FI.2 and FI.3 were also observed.

7.2. Microthermometric results

About 160 fluid individual inclusions in 38 microscopic domains of the host quartz have been analyzed by the microthermometric work. For type FI.1 fluid inclusions we have not acquired thermometric data due to the small size of the inclusions.

In clusters of type FI.2 primary inclusions, the final ice melting occurred between -0.9° to 0°C , corresponding to salinities of up to 1.6 wt. % NaCl equiv. The final homogenization to the liquid phase occurred between 190° and 252°C . In pseudo-secondary inclusions, the final ice melting occurred between -2.8° and -0.1°C , corresponding to a salinity of 0.2 to 4.5 wt. % NaCl equiv., and the final homogenization to the liquid phase ranged from 170° to 274°C . In secondary trails, the final ice melting temperature varied from -3.7 to -0.2°C , resulting in a salinity range from 0.2 to 5.7 wt. % NaCl equiv., and homogenization temperatures to the liquid phase occurred between 177° to 320°C (Fig. 13 a, b).

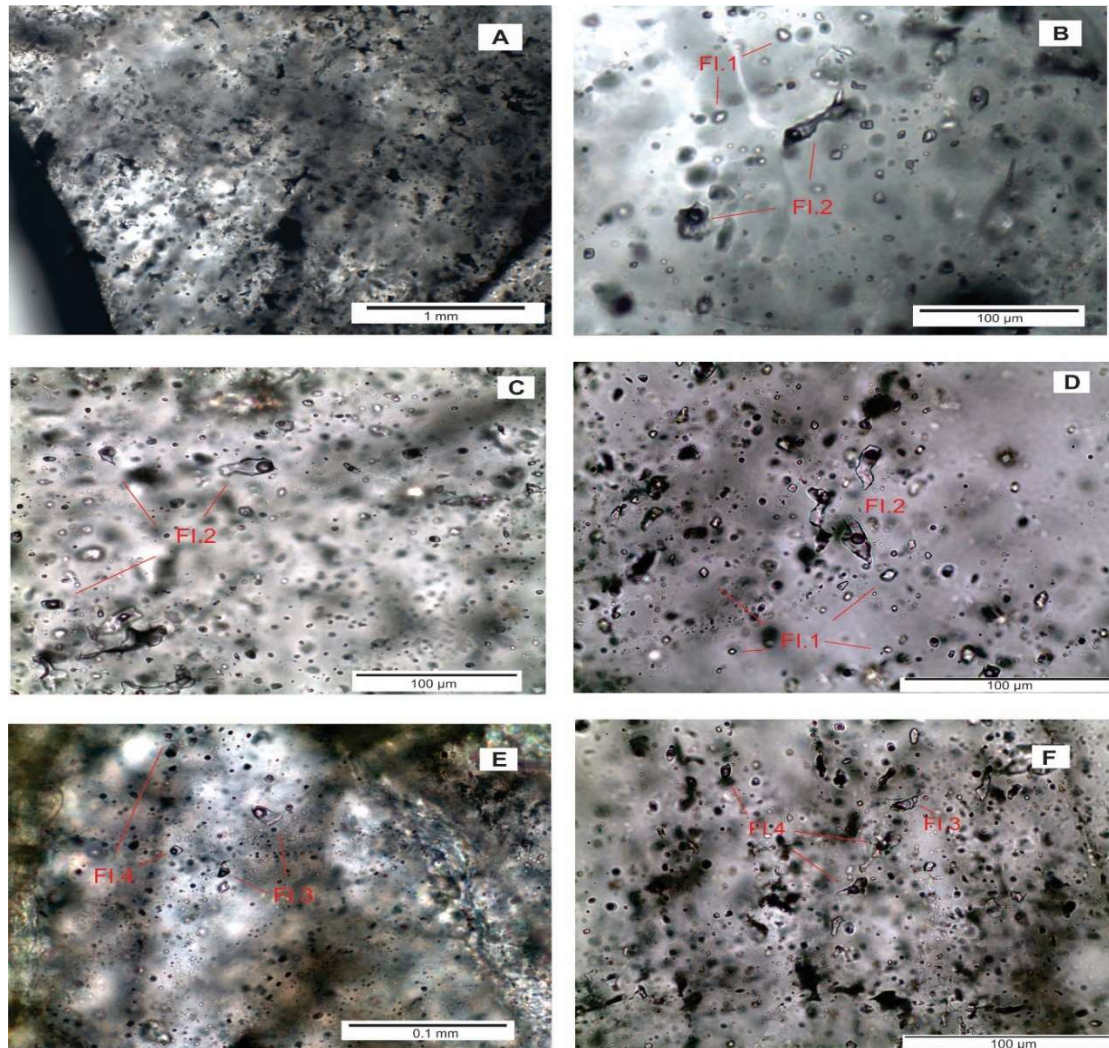


Figure 4.12 – Fluid inclusions types. A) Mixed and parallel fluid inclusions trails; B) Aqueous fluid inclusions, monophasic (type FI.1) and two-phase (FI.2); C) Two-phase aqueous fluid inclusions (FI.2), liquid-rich inclusions coexist with vapor rich inclusions; D) Monophasic (FI.1) and two-phase (FI.2) aqueous fluid inclusions; E) Primary three-phase aqueous carbonic inclusions (FI.3) and two-phase carbonic inclusions (FI.4); F) three-phase aqueous carbonic inclusions (FI.3) and intragranular trail vapor-rich and liquid-rich two-phase carbonic inclusions (FI.4).

The primary and pseudo-secondary aqueous-carbonic fluid inclusions (Type FI.3) presented the melting temperature of CO₂ between -56.7 to 56.6°C, which may be considered as pure CO₂. Clathrate dissociation occurred between 6.0 and 9.0 °C, resulting in the salinity ranging from 2.0 to 7.4 wt.% NaCl equiv., in different clusters or trails. The partial homogenization of CO₂ occurred in both liquid and gaseous states, between 26 and 31°C. The temperature of the total homogenization into the liquid state ranges from 315 to 355°C in different clusters or trails (Fig. 4.13c, d). The only significant difference is observed in the

Galena ore body, where the primary inclusions show salinity quite lower (~2%) than that presented by the pseudo-secondary varieties (~6%). This salinity variation is observed in different samples (Fig. 4.14).

The type FI.4 displays values of melting of CO₂ between -58.9 to -56.6°C, and differently from the aqueous-carbonic inclusions, a greater contribution from other volatiles (CH₄ and/or N₂) mixed with CO₂ is expected. These inclusions with the calculated densities ranging from 0.65 to 0.89 g/cm³ have partial (ThCO₂) between 28 to 31°C (Fig. 4.13c, d).

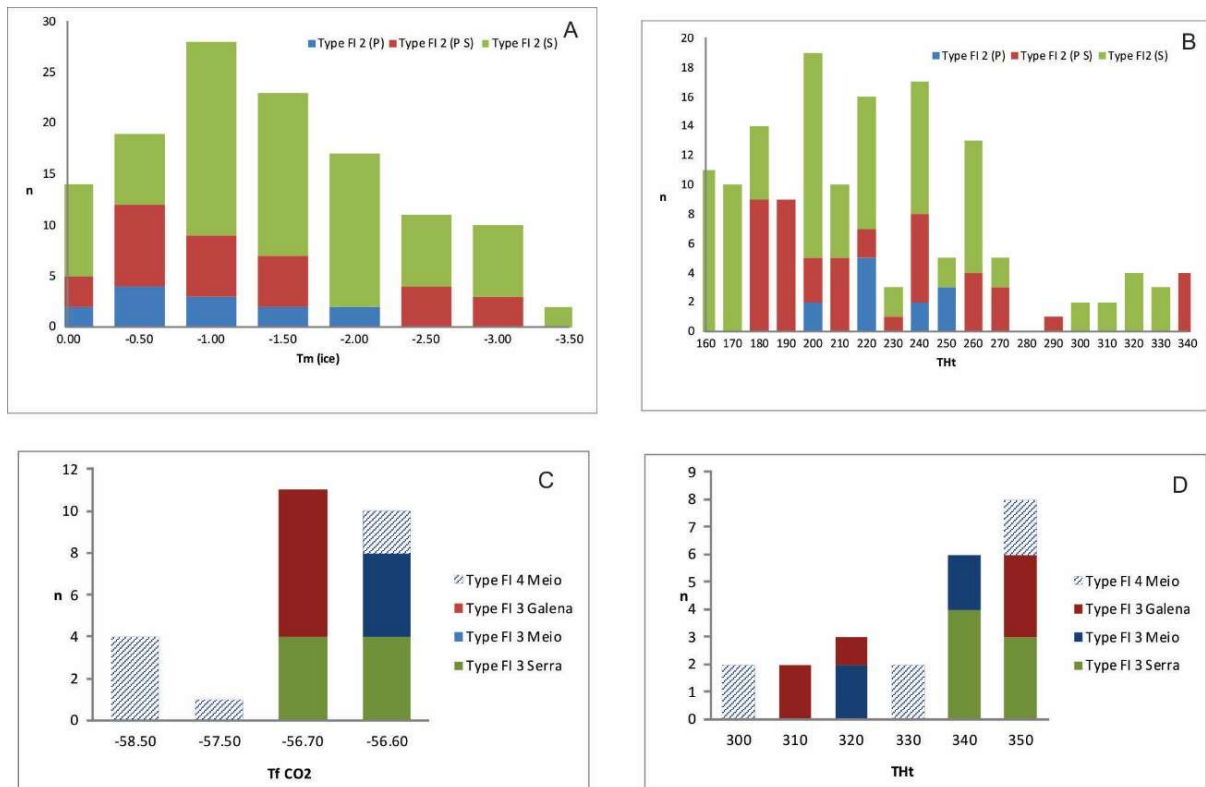


Figure 4.13 – Fluid inclusions microthermometric histograms. A) final ice melting (T_{mice}) for FI. 2 type B) total homogenization temperatures (Tht) for FI.2 type inclusions; C) final CO₂ melting (T_mCO₂) for FI. 3 and FI.4 types, D) total homogenization temperatures (Tht) for FI.3 and FI.4 types.

Table 4.3 - Summary of thermometric data of fluid inclusions from Coringa orebodies.

Orebody	FI type	T _m ice (°C)	T _m CO ₂ (°C)	T _m cla (°C)	T _h CO ₂ (°C)	T _h (°C)	wt % NaCl	d (g/cm ³)
Serra	2	-2.8 to -0.1				177 to 252	0.4 to 4.6	0.72 to 0.90
	3	-2.0 to -0.5	-56.6 to -56.7	7.0 to 8.5	26 to 30	340 to 345	3.0 to 5.7	0.93 to 0.99
Meio	2	-0.2 to 0.0				197 to 274	0.0 to 0.4	0.74 to 0.87
	3	-2.0 to -0.1	-56.6	6.0 to 7.4	30	320 to 343	5.0 to 7.4	0.92 to 0.93
	4		-58.9 to -56.5		28 to 31			0.65 to 0.89
Galena	2	-1.4 to -1.8				254 to 270	2.4 to 3.1	0.79 to 0.81
	3	-3.5 to -1.5	-56.6 to -56.7	7.0 to 9.0	26 to 30	315 to 355	2.0 to 5.7	0.93 to 0.95
Mãe de Leite	2	-3.7 to -0.6				160 to 245	1.1 to 6.0	0.86 to 0.92
Come Quietto	2	-1.4 to -0.1				166 to 336	0.4 to 2.4	0.78 to 0.91

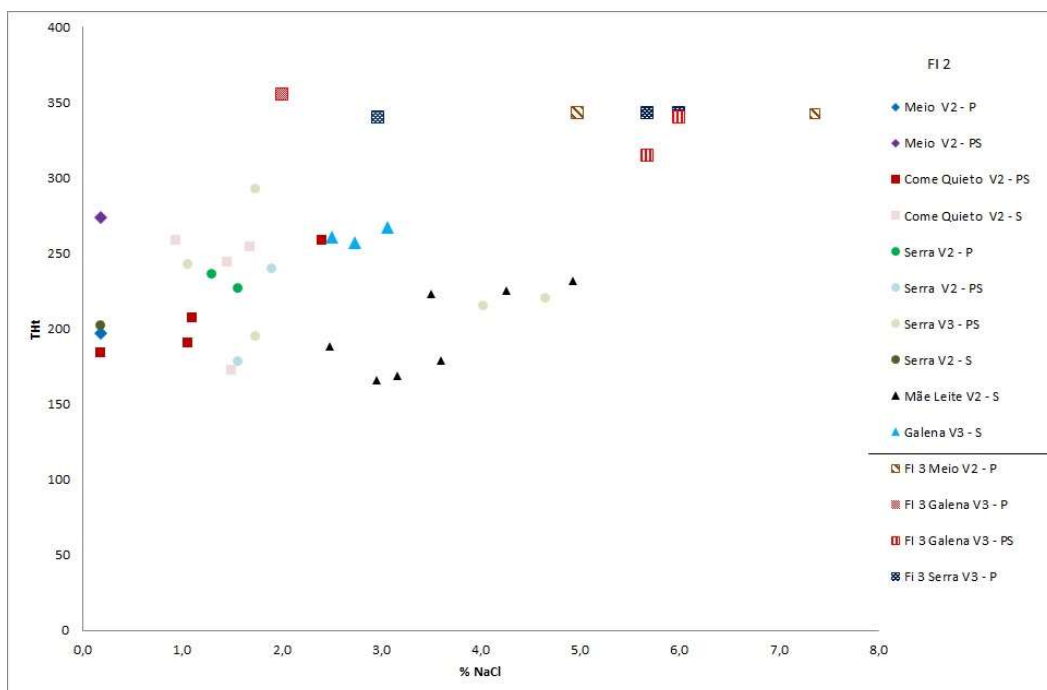


Figure 4.14 – Diagram Salinity (%NaCl) x total homogenization temperatures (Tht) for fluid inclusions from Coringa Deposit

8. Stable isotopes results

Stable isotope analyses (oxygen, hydrogen, carbon, and sulfur) were performed at Coringa and might reveal possible fluid sources. The $\delta^{18}\text{O}$ values were determined in the

primary quartz from regional granitic rocks, magmatic and hydrothermal quartz, and muscovite from veinlets in the Galena, Serra, Meio, and Valdetete ore bodies (Table 4.4).

The isotopic data for the magmatic quartz from regional granites show differences for the Maloquinha Intrusive Suite ($\delta^{18}\text{O} = +7.5$ to $+10.3\text{‰}$), Creporizão Intrusive Suite ($\delta^{18}\text{O} = +6.8$ to $+8.3\text{‰}$) and Serra Alkali Feldspar Granite ($\delta^{18}\text{O} = +4.6$ to $+6.3\text{‰}$). The quartz from the Vila Riozinho Formation shows $\delta^{18}\text{O}$ values of $+9.7\text{‰}$ in at Galena and $+10.3$ to $+11.8\text{‰}$ at Valdetete (Fig. 4.15).

The $\delta^{18}\text{O}$ values of the hydrothermal quartz from veinlets in different ore bodies range widely from $+7.9$ to $+15.8\text{‰}$, and this whole variation is observed in the Type 2 veins of the Meio ore body. The Type 3 veins at Meio show a narrower, but still significant, range of values ($+10.2$ to 13.8‰). At Galena, the $\delta^{18}\text{O}$ values are nearly constant ($+10.1$ to 10.2‰), and little variable at Serra ($+10.9$ to 11.4‰), irrespective of the vein type (Types 2 and 3). The muscovite from alteration zones shows $\delta^{18}\text{O}$ and δD values of $+6.2$ and -122‰ at Serra and a $\delta^{18}\text{O}$ value of $+9.8\text{‰}$ at Valdetete (Table 4.4).

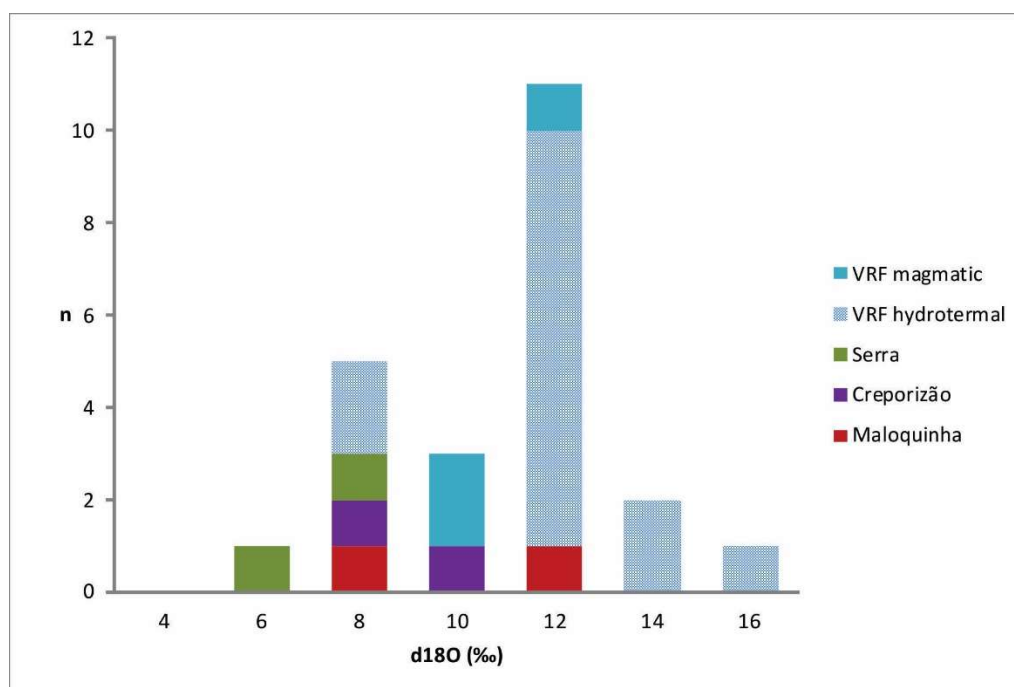


Figure 4.15 – Distribution histogram of $\delta^{18}\text{O}$ values from Coringa Deposit samples.

The isotope compositions of oxygen were also determined combined with carbon isotope composition in three Mn-calcite (spartaite) samples from Valdetete. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are -1.5 and -1.4‰ , and $+6.9$ and $+6.8\text{‰}$, respectively, in the disseminated calcite from distal alteration zone, and -0.7‰ and $+6.9\text{‰}$ in the calcite present in a Type 2 vein (Table 4).

For sulfides extracted from Types 2 and 3 quartz veins, the $\delta^{34}\text{S}$ values of galena range from -6.7 to -1.4‰ at Galena, and -6.6 to -2.5‰ in the Meio orebody, and no differences is observed between the vein types. In the same veins, pyrite B shows $\delta^{34}\text{S}$ values of -0.1 to +0.1‰ at Galena (Type 2 vein), -2.6 to +1.2‰ (Type 2 vein), and -4.5 to +1.8‰ (Type 3 vein) in the Meio ore body. One sample from a Type 2 vein from Valdetete shows the extreme value of -10.9‰. Pyrite A, from the intermediate/proximal alteration zone at Valdetete, has $\delta^{34}\text{S}$ values varying from -2.4 to -0.5‰.

Table 4.4 - Stable isotope data of magmatic and hydrothermal minerals from the Coringa deposit.

Location	Sample	Mineral	Style or stage	$\delta^{18}\text{O}$ (‰)	δD (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{34}\text{S}$ (‰)	Host unit
Regional rocks	SG57	Qtz	Magmatic	10.3				MIS
	SG11A	Qtz	Magmatic	7.6				MIS
	SG112	Qtz	Magmatic	6.8				CIS
	SG26	Qtz	Magmatic	8.3				CIS
	SG83	Qtz	Magmatic	6.3				SAFG
	SG38	Qtz	Magmatic	4.6				SAFG
Galena	EK 30/51.70	Qtz	Magmatic	9.7				VRF
Valdetete	EK 110/148.80	Qtz	Magmatic	11.8				VRF
	EK 114/202.30	Qtz	Magmatic	10.3				VRF
Galena	EK 3/35.30	Qtz	Vein type 2	10.1				VRF
		Gal					-6.7	
		Py B					0.1	
	EK 30/ 53.45	Gal	Vein type 2				-1.4	VRF
		Py B					-0.1	
	EK1C	Qtz	Vein type 3	10.2				VRF
	EK1D	Qtz	Vein type 3	10.1				VRF
Meio	SG 65/114-114.20	Qtz	Vein type 2	15.8				VRF
		Gal					-5.4	
		Py B					-2.0	
	SG 90/74.5	Py B	Vein type 2				-2.6	VRF
	EK 137/164.4-164.7	Qtz	Vein type 2	7.9				VRF
		Py B					0.7	
	SG137/166.10	Py B	Vein type 2				1.2	VRF
	SG 137/165.7	Qtz	Vein type 2	13.7				VRF
	SG 156/165.40	Qtz	Vein type 2	11.4				VRF
		Gal					-6.6	
		Py B					-0.3	
	CE06B	Gal	Vein type 3				-2.5	VRF
		Py B					-1.9	
	SG 65/117.15-117.45	Qtz	Vein type 3	10.2				VRF
		Gal					-4.2	
		Py B					-4.5	

	SG 95/64.90-65.15	Qtz	Vein type 3	13.8				VRF
		Py B					1.8	
Serra	SG 37/73.40-73.53	Qtz	Vein type 2	11.4				VRF
		Py B					1.3	
	EK 145/211.95	Qtz	Vein type 3	10.9				SAFG
		Py B					0.1	
	EK 20/39.40	Py B	Vein type 3				-2.8	VRF
	EK 160/98.10	Ser	Intermediate/proximal	6.2	-122			VRF
Valdette	EK 114/208.20	Cal	Distal	6.9		-0.7		VRF
		Py B	Vein type 2				-10.9	
	EK 114/202.30	Py A	Intermediate/proximal				-2.4	VRF
	EK 114/203.40	Py A	Intermediate/proximal				-0.9	VRF
	EK 110/146.85	Cal	Distal	6.8		-1.4		VRF
	EK 114/193.65	Cal	Distal	6.9		-1.5		VRF
	EK114/194.70	Py A	Intermediate/proximal				-0.5	VRF
	EK110/153.60	Py A	Intermediate/proximal				-1.9	VRF
	EK 110/148.80	Ser	Intermediate/proximal	9.8				VRF

9. Discussion

9.1. Tectonic setting of the host rocks and timing of mineralization

The hydrothermal alteration and the Au-Ag (Cu-Pb-Zn) mineralization at Coringa are hosted in volcanic and pyroclastic rocks of the Vila Riozinho Formation (ca. 1989-1996 Ma), and in the Serra Alkali Feldspar Granite (ca. 1989-1999 Ma), which shows evidence of emplacement in shallow depths (Guimarães et al., 2019; Guimarães and Klein, 2020, and references therein). Both host units are part of a major calc-alkaline volcano-plutonic event formed in a post-collisional setting, following the agglutination of one or more Orosirian magmatic arcs to older blocks (Rhyacian to Archean) during an Orosirian orogeny (Santos et al., 2004; Lamarão et al., 2005; Vasquez et al., 2017; Fraga and Cordani, 2019; Guimarães and Klein, 2020).

No robust information about the age of the mineralizing event is available for Coringa. However, the Pb-Pb model age of 1974 Ma (Feio, 2014) obtained in ore-related pyrite crystals from quartz veins hosted in dacite in the Mato Velho prospect, located north of Coringa (Fig. 4.2), suggests contemporaneity between the mineralization and the host

volcanic rock, which belong to the Vila Riozinho Formation. Given this and the similarities of the mineralization constitution and alteration at Coringa and Mato Velho, we can infer contemporaneity of the mineralization.

9.2. Mineralization controls and hydrothermal zoning

The mineralization at Coringa occurs in a sequence of NNW-SSE-trending quartz-sulfide veins hosted in a right-lateral strike-slip brittle shear zone. This structure is oriented according to the majority of the mineralized structures found in the Tapajós Mineral Province and, in the study region, follows magnetic discontinuities. According to our interpretation, this magnetic discontinuity appears to correlate with a major crustal discontinuity at the boundary zone between the magnetic pyroclastic facies of the Vila Riozinho Formation and the pluton of the Serra Alkali Feldspar Granite (Fig. 4.3).

Studies performed on the main ore bodies that form the Coringa deposit, such as mineralogical and textural observations of magmatic and hydrothermal features, the relationships of the host rocks with the alteration and mineralization phases, and temperatures derived from fluid inclusion, and the chlorite and white mica chemical composition enable to propose the sequence alteration and paragenetic sequence for the deposit (Fig. 4.19). This sequence is common to all the studied ore bodies, with minor local differences, as we presented in section 5.3 (hydrothermal alteration and veining). Accordingly, the intermediate to proximal stages that formed the sericite-pyrite alteration with minor and local adularia formed at about 400°C, as estimated by the white mica chemistry (Fig. 4.11). This stage was followed by the precipitation of two stages of Au-bearing veins: (i) the sulfide-rich Vein type 3 at about 340°C (total range of 315-355°C), as determined by fluid inclusion homogenization temperatures, and (ii) sulfide-poor Vein type 2 at ca. 243°C (fluid inclusion homogenization temperatures, total range of 170-274°C). Post-mineralization stages are characterized by the formation of chlorite-hematite alteration, and the late and distal carbonate-chlorite-epidote alteration at 234°C (estimated through chlorite chemistry), and locally by the carbonate alteration.

Some differences have been observed in peripheral ore bodies of the Pista and Fofão targets (Fig. 4.2), such as the post-magmatic albite and potassic alteration and the presence of Au-Ag tellurides and Bi-Ag selenides (Corrêa-Lima and Klein, 2020), which have not been

observed in the main ore bodies, and that can be ascribed to local effects or variations in the fluid chemistry.

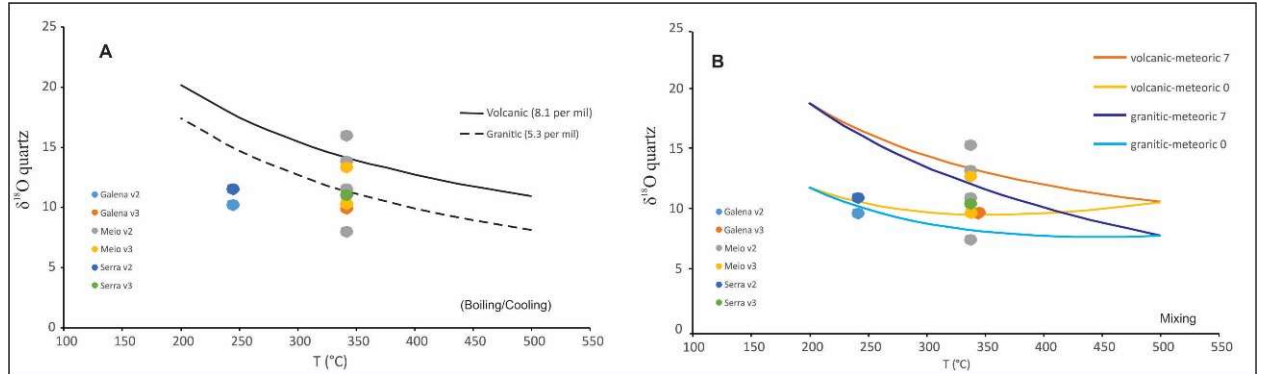


Figure 4.16 –Temperature versus $\delta^{18}\text{O}$ modeling diagrams. A) cooling model curves from granite and volcanic host rocks, B) Mixing model curves for magmatic and meteoric fluids.

9.3. Fluid composition, and sources

To estimate the O- and H-isotope compositions of the fluids that precipitated quartz, muscovite, and calcite, we used the relevant temperatures defined above and the following relevant fractionation factors: quartz- H_2O (Fekete et al., 2016, for oxygen), calcite- H_2O (Friedman and O’Neil, 1977, for oxygen), muscovite- H_2O (O’Neil and Taylor, 1969, for oxygen; Suzuoki and Epstein, 1976, for hydrogen), calcite- CO_2 (Ohmoto and Rye, 1979, for carbon), pyrite/galena- H_2S (Ohmoto and Rye, 1979, for sulfur).

The calculated isotopic composition of the hydrothermal water ($\delta^{18}\text{O}_{\text{H}_2\text{O}}$) shows relatively large variation between different stages, but is more constant for individual ore bodies, except in the case of the Meio ore body, where variations are more expressive in Type 2 (-1.8 to +6.1‰) and Type 3 (+4.1 to +7.7‰) veins. In the distal and intermediate-proximal stages, the $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values are respectively -1.0 to -1.1‰ and +4.8 to +9.8‰ (Table 4.5 and Fig. 4.18). Considering the geological setting in which formed the Coringa hydrothermal system, the $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values between about +5 and +10‰ most likely reflect a magmatic source (e.g., Sheppard, 1986). The lower values might have been produced by mixing or other processes (see also the section “evolution of the hydrothermal system”, below). We have only one $\delta\text{D}_{\text{H}_2\text{O}}$ value of -92‰ for the intermediate-proximal stages, which is lower than magmatic values (Sheppard, 1986). This low δD value is unlikely to reflect the influx of meteoric water, because the study region was not in very high latitude in the Paleoproterozoic, but

close to the equator, as suggested by Juliani et al. (2005). Instead, this low value may suggest vapor influence or extensive magma degassing (De Hoog et al., 2009).

The $\delta^{13}\text{C}_{\text{CO}_2}$ values are relatively similar in the distal (-0.4 to -0.5‰) and Vein type 2 (+0.5‰) stages of the Valdetete ore body. These values are compatible with a magmatic ($\pm$ mantle) source, with calcite precipitation from an HCO_3^- -bearing fluid associated with CO_2 degassing or with fluid-rock interaction (Zheng and Hoefs, 1993). Except for one outlier (-12.4‰), the $\delta^{34}\text{S}$ values of sulfides of veins types 2 and 3 show a similar range of -5.6 to +1.2‰, with sulfides from the intermediate-proximal stage having a lesser range of -3.3 to -1.4‰ (Table 4.5, Fig.4.17). The majority of values are consistent with a reduced magmatic source (Lambert et al., 1984; Kerrich, 1987).

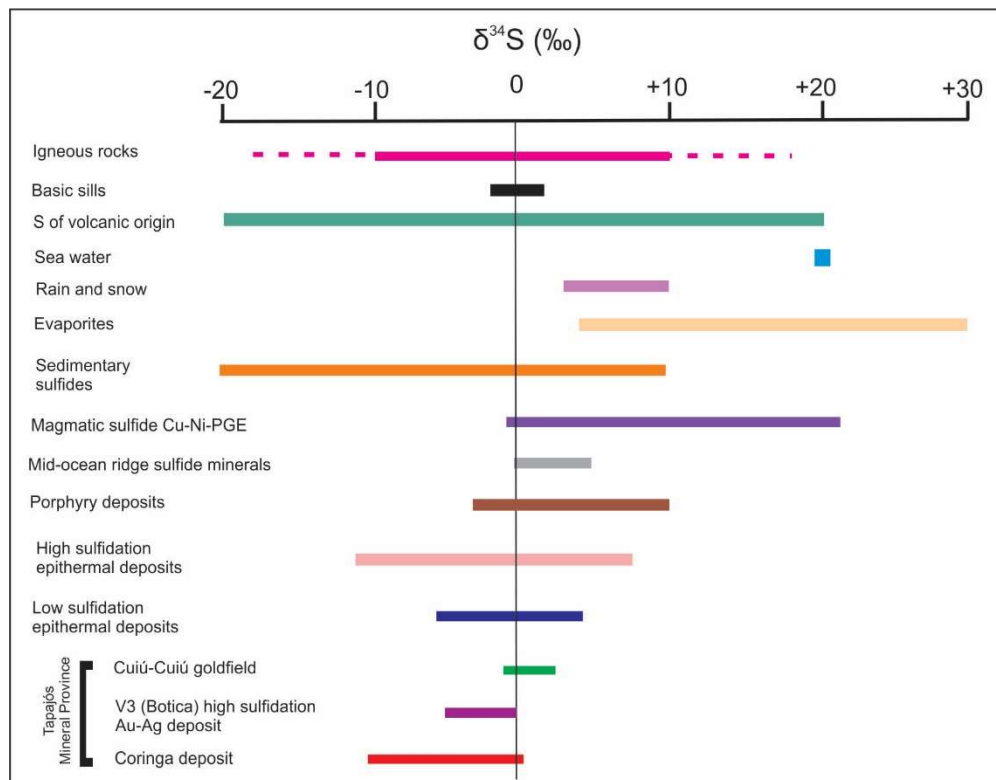


Figure 4.17 – Sulfur isotope values ($\delta^{34}\text{S}$ ‰ CDT) from different systems/deposits compared to $\delta^{34}\text{S}$ values of sulfide minerals from Coringa Deposit. References: Chmielewski et al., 2002 and references therein (igneous rocks, basic sills, seawater, rain, and snow, evaporates, sedimentary sulfides, volcanic origin), Arribas, 1995 (High- sulfidation); Field and Fifarek, 1985 (low-sulfidation); Juliani et al., 2005 (V3/Botica); Assunção and Klein, 2014; Silva Junior and Klein, 2015 (Cuiú-Cuiú goldfield), Shanks, 2001 (magmatic and mid-ocean sulfide minerals), Cooke et al., 2002 (porphyry deposits).

Table 4.5 – Summary table of calculated isotopic values of some stages from Coringa deposit.

Stage	Orebody	T (°C)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	$\delta\text{D}_{\text{H}_2\text{O}}$	$\delta^{13}\text{C}_{\text{CO}_2}$	$\delta^{34}\text{S}_{\text{H}_2\text{S}}$
Distal	Valdette	234	-1.1 to -1.0		-0.4 to -0.5	-
Intermediate /Proximal	Valdette	400	+ 9.8			-3.3 to -1.4
	Serra		+ 4.8	-92.0		-
V2	Meio	243	-1.7 to 6.1			-4.2 to +1.2
	Galena		+ 0.4			-4.3 to +1
	Serra		+ 1.7			-0.2
	Valdette		-0.7		+ 0.5	-12.4
V3	Meio	340	+ 4.1 to 7.7			0.7 to -5.6
	Galena		+ 4.0 to 4.1			-
	Serra		+ 4.8			-1.0 to -3.9

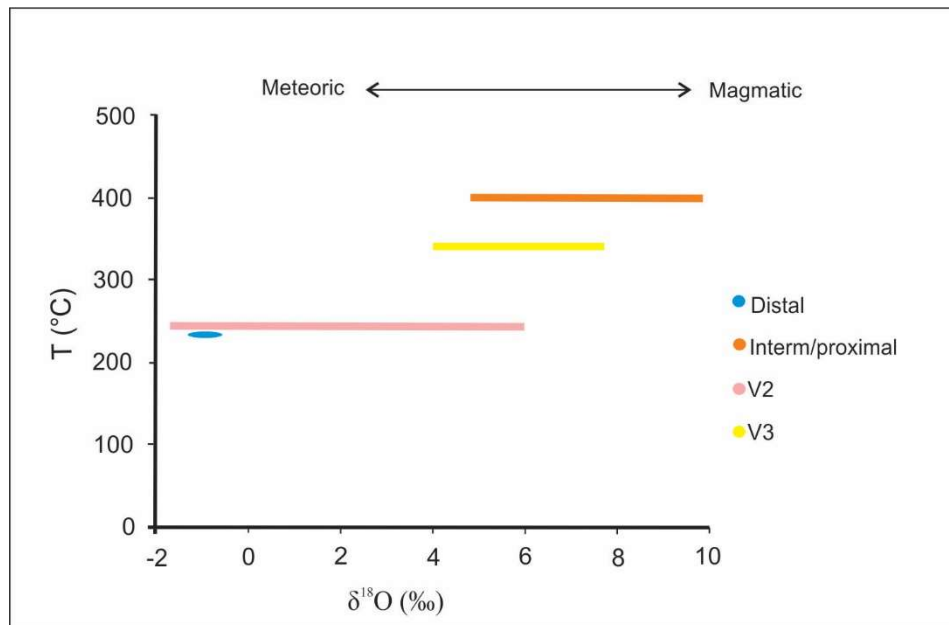


Figure 4.18 – Oxygen isotope modeling values versus temperature from some stages in Coringa deposit

9.4. Evolution of the hydrothermal system

There are some possibilities of fluid processes for ore formation in the Coringa deposit that include the reaction of the ore-forming fluids with the host rocks, boiling, mixing of the ore-bearing fluids with fluids from different compositions, or a combination of some of the above (Heinrich, 1995). We interpret that fluid-rock interaction might have been responsible for the distal hydrothermal alteration halos in, but have not necessarily influenced ore formation.

The boiling models for low-salinity fluids can be expected because that would produce a progressive increase in mineral $\delta^{18}\text{O}$ values (Wagner et al., 2005). This would be the consequence of preferential partitioning of the lighter ^{16}O isotope into the vapor phase, yielding an increasingly ^{18}O -rich residual brine (Wagner et al., 2005). However, vapor-rich fluid inclusions in Coringa are scarce, only observed in the aqueous type (FI.2) in two peripheral targets (Come Quietto and Mãe Leite), and in carbonic type (FI.4) in the Meio orebody. On the other hand, adularia is present in the intermediate/proximal stage of the hydrothermal alteration and might indicate boiling (e.g., Canet et al., 2011).

We have modeled boiling of a magmatic-hydrothermal fluid, based on the average $\delta^{18}\text{O}$ values of the magmatic quartz from the Creporizão Suite and Serra Granite (+5.3‰), and Vila Riozinho Formation (+8.1‰) (Table 5). According to Wagner et al. (2005), the boiling process is similar to that of the cooling of the fluid. Assuming the 500 to 200°C temperature interval, the resulting curves were compared with the compositions of hydrothermal quartz from different vein types (2 and 3) and temperatures (Fig. 16a). The composition of quartz from vein-type 2 from Serra and Galena (c. 230°C) does not match with the boiling process, whereas the composition from vein-type 3 (c. 340°C) is too much variable, and no clear conclusion can be drawn. Thus, if boiling occurred during the main ore-forming event, it was a limited extent.

We have then modeled the mixing of fluids. The end-members are a magmatic-hydrothermal fluid (granitic and volcanic, the same isotopic composition used above for boiling) at 500°C and a meteoric fluid at 200°C. We considered two different $\delta^{18}\text{O}$ values for this meteoric water: a) $\delta^{18}\text{O} = +7\text{‰}$, as estimated by Juliani et al. (2005) for the Tapajós Mineral Province in the Paleoproterozoic, and b) and a generic $\delta^{18}\text{O} = 0\text{‰}$ (Fig. 16b). A linear relationship between the temperature and composition of the fluid mixture was assumed as well as the mineral-water fractionation factors that were assumed to be salinity independent (e.g Wagner et al, 2009). Comparing the composition of the hydrothermal quartz from vein types 2 and 3, we observe that the vein-type 2 from Serra and Galena is compatible with the mixing of the magmatic fluid (either volcanic or granitic) with the “generic” meteoric fluid of $\delta^{18}\text{O} = 0\text{‰}$ (Fig. 16b). Again, because of the large variation in the $\delta^{18}\text{O}$ values of quartz from vein-type 3, the result is equivocal for mixing.

Then, we can assume that aqueous-carbonic fluid inclusions came from the magmatic origin, probably related to magma emplacement at high levels of the crust, and the main trapping occurred at 320-345°C (total homogenization temperature of FI type 3). On the other

hand, the aqueous fluid inclusion is probably from meteoric origin, whose entry was favored by fracturing, presented low salinities and trapping temperatures, 160 to 330°C (FI type 2 homogenization temperature). The chlorite from the late and distal carbonate-chlorite-epidote alteration was mainly formed at this stage (224 to 241°C), consistent with temperature of type 2 fluid inclusions, and petrographic data which demonstrate a large dispersion. This leads us to believe that during the volcanic environment, at shallows levels, the fluids were formed as from the action of surface-derived (meteoric) water as they have from the circulation of magmatic waters.

The assemblage carbonate-chlorite-epidote from the distal hydrothermal halo, and possibly the carbonate alteration observed at Valdetete, according to Hedenquist et al. (2000), forms as the result of the generation of CO₂-rich steam-heated water on the margin of the system. The incursion of this marginal water during the late-stage collapse of a system may account for the formation of calcite veins and Mn-rich carbonates that are commonly barren (Simmons et al., 2000), as depicted in the Valdetete ore body.

		Distal	Interm/proximal	Proximal			
	Magmatic	Carbonate-chlorite-epidote alteration	Sericite-pyrite alteration	Chlorite-hematite alteration	Veins type 1	Veins type 2	Veins type 3
Quartz							
K- feldspar		-----					
Plagioclase		-----					
Biotite							
Magnetite							
Ilmenite							
Hematite			-----	-----		-----	-----
Chlorite		-----	-----	-----			-----
Carbonate		-----			-----		-----
Epidote		-----					
Sericite			-----				-----
Adularia			-----				
Pyrite A			-----				
Pyrite B						-----	
Chalcopyrite			-----				-----
Sphalerite							-----
Galena						-----	-----
Gold/electrum							-----

Figure 4.19 – Stages of hydrothermal alteration, vein types, and paragenetic sequence of the mineralization in the Coringa deposit.

9.5. Deposit type

The Au-Ag mineralization at Coringa is composed of native gold and electrum, with local tellurides and selenides (Pista and Fofão targets, Correa-Lima and Klein, 2020), and minor base metals, present in relatively thin sulfide-rich veins. The sulfides are pyrite, galena, chalcopyrite, and iron-poor sphalerite (Appendix 2). Several lines of evidence indicate that this mineralization occurred in shallow depth. These include the hydrothermal mineral assemblage composed of Mn-carbonate, sericite, and adularia; presence of open-space filling textures, such as comb, and, especially, the close spatial and temporal (Feio, 2014) association with volcanic and shallow granite (Guimarães et al., 2019). The stable isotope results indicate mixing of a magmatic-hydrothermal fluid with cooler and diluted meteoric water as hydrothermal alteration progressed, with local evidence of boiling given by the presence of adularia. All these features are compatible with those of magmatic-hydrothermal deposits of the intermediate sulfidation precious metals type, which are commonly found in Phanerozoic volcano-plutonic settings (e.g., Wang et al., 2019). Nevertheless, some classic features of the Phanerozoic equivalents are lacking in the Orosirian Coringa deposit, including textures such as bladed calcite and colloform or cockade quartz, which could be ascribed to the subordinate role of boiling at Coringa, and the absence of sulfosalts.

9.6. Implications for the metallogensis of the Tapajós Mineral Province

As we have stated in the introductory section of this work, at least two issues regarding the metallogenic evolution of the TMP are long under debate: types of deposits or mineral systems, and existence of one or more gold mineralizing events.

Despite subordinate paleoplacer and debatable orogenic systems (Table 1), it is clear that most of the deposits studied in the TMP so far belong to some magmatic-hydrothermal system, either porphyry or non-porphyry (intrusion-related), with or without epithermal counterparts. Coringa belongs to this latter system.

Regarding the timing of mineralization, the lack of widespread robust dating hinders a categorical definition of this subject. Relative age estimates (i.e., maximum mineralization age based on the age of the host rock), and several ambiguous Pb-Pb dating of sulfides point out to two possible events, occurring at ca. 1980-1950 Ma and 1880-1870 Ma (Table 1 and references therein). In our opinion, only one event is well documented to date, which is represented by the epithermal V3-Botica deposit, with an Ar-Ar alunite age of 1876-1869 Ma (Juliani et al., 2005 – Table 1). However, and despite the equivocal Pb-Pb age of 1974 Ma

(Feio, 2014), the close relationship of the mineralization with the Orosirian post-collisional volcanic rocks and granite of 1989-1999 Ma, strongly suggest that Coringa represents an epithermal deposit formed at this time.

Therefore, our results indicate the operation of an early magmatic-hydrothermal mineral system of ca. 2.0-1.97 Ga associated with the post-collisional magmatism of this age, represented by the Vila Riozinho Formation, and the Creporizão Intrusive Suite and Serra Alkali Feldspar Granite. The youngest event corresponds to the already defined c. 1.87-1.86 Ga-old event, which is related to the extensional magmatism represented by the coeval Parauari and Maloquinha Intrusive Suites.

10. Conclusions

The results of this study allowed to conclude the following about the Coringa deposit:

- (1) Hosted in calc-alkaline volcanic rocks from Vila Riozinho Formation (magnetic pyroclastic facies), and in the shallow Serra Alkali Feldspar Granite, formed in post-collisional setting at ca. 1.99-1.90 Ga.
- (2) The mineralized shear-vein system is coincident with the north-northwest trend of the main regional structures, and with a magnetic discontinuity that may correspond to an important crustal discontinuity.
- (3) The hydrothermal alteration, and quartz-sulfide veining associations were grouped into: (a) early, intermediate to proximal sericite-pyrite alteration (400°C), (b) sulfide-rich Au-bearing veins (340°C), (c) sulfide-poor Au-bearing veins (243°C), (d) Chlorite-hematite alteration, and (e) late, distal carbonate-chlorite-epidote (propylitic) alteration (234°C).
- (4) The gold-silver mineralization occurs as native gold and electrum inclusions and filling fractures in pyrite.
- (5) Mineralization occurred in response to the mixing of magmatic-hydrothermal and meteoric fluids, with subordinate boiling.
- (6) All characteristics suggest an intermediate sulfidation epithermal deposit as the genetic model.
- (7) The mineralization is related to the operation of the first of two magmatic-epithermal mineral systems in the TMP (ca. 2.0-1.97 Ga, and 1.87-1.86).

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References

- Aguja-Bocanegra, M.A., 2013. Mineralizações epitermal low-sulfidation e do tipo pórfiro superpostas associadas ao magmatismo félsico de 1,88 Ga na parte norte da Província Mineral do Tapajós (PA). Dissertação de Mestrado, Instituto de Geociências, Universidade de São Paulo, 235p.
- Assunção, R.F. S, Klein, E.L., 2014. The Moreira Gomes deposit of the Cuiú-Cuiú goldfield: Fluid inclusions and stable isotope constraints and implications for the genesis of granite-hosted gold mineralization in the Tapajós Gold Province, Brazil. *Journal of South American Earth Sciences* 49, 85-105.
- Biondi, J. C., Borgo, A., Chauvet, A., Monié, P., Bruguier, O., Ocampo, R. 2018. Structural, mineralogical, geochemical, and geochronological constraints on ore genesis of the gold only Tocantinzinho deposit (Para State, Brazil). *Ore Geology Reviews*, v. 102, p. 154-194.
- Biondi, J. C. 2019 Formation of the Tocantinzinho 1.89Ga gold-only deposit (Pará State, northern Brazil), based on sulfur, oxygen, hydrogen, and carbon isotope data. *Journal of South American Earth Sciences*.
- Bodnar, R.J. 1993. Revised equation and table for determining the freezing point depression of H₂O-NaCl solutions. *Geochimica et Cosmochimica Acta* 57, pp. 683-684.
- Borges R.M.K., Dall'agnol R., Lamarão C.N., Figueiredo M.A.B.M., Leite A.A.S., Barros C.E.M., Costi H.T. 2009. Petrografia, química mineral e processos hidrotermais associados ao depósito de ouro São Jorge, Província Aurífera do Tapajós, Cráton Amazônico. *Revista Brasileira de Geociências*, 39(2), 375-393.
- Borgo A., Biondi J.C., Chauvet A., Bruguier O., Monié P., Baker T., Ocampo R., Friedman R., Mortensen J. 2017. Geochronological, geochemical and petrographic constraints on Paleoproterozoic Tocantinzinho deposit (Tapajos Gold Province, Brazil): implications for

- timing, regional evolution, and deformation style of its host rocks. *Journal of South American Earth Sciences* 75 (2017) 92-115.
- Canet, C., Franco, S.I., Prol-Ledesma, R.M., Gonzáles-Partida, E., Villanueva-Estrada, R.E. 2011. A model of boiling for fluid inclusion studies: Application to the Bolaños Ag–Au–Pb–Zn epithermal deposit, Western Mexico. *Journal of Geochemical Exploration*, 110, 118-125.
- Cathelineau M. and Nieva D. 1985. A chlorite solid solution geothermometer. The Los azules (Mexico) geothermal system. *Contrib. Mineral. Petrology* 91: 235-244.
- Cassini L.V, Juliani C., Gutierrez D.F.G. 2017. O Sistema Hidrotermal do Patrocínio, Província Mineral do Tapajós (PA): Petrografia, Geoquímica e Idades U-Pb. In: Lima A.M.M., Gorayeb P.S.S. (Orgs). *Contribuições à Geologia da Amazônia*. Belém, SBG. 10, 109-125.
- Chmielewski, A.G.; Wierchnicki, R.; Derda, M.; Mikolajczuk, A. 2002. Sulfur isotope composition of selected polish cols. *NUKLEONIKA* 2002;47(Supplement 1): S67–S68
- Clayton R.N., Mayeda, T.K., 1963. The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates from isotopic analyses. *Geochim. Cosmochim. Acta* 27, 43– 52.
- Collins, P.L.F. 1979. Gas hydrates in CO₂ -bearing fluid inclusions and the use of freezing data for estimation of salinity. *Economic Geology* (1979) 74 (6): 1435–1444. <https://doi.org/10.2113/gsecongeo.74.6.1435>
- Cooke, D.R., Wilson, A.J., Lickfold, V., Crawford, A.J. 2002. The alkaline Au-Cu porphyry province of NSW. *AusIMM 2002 Annual Conference*, Auckland, New Zealand, pages 197-202.
- Corrêa-Lima R.G. and Klein E.L. 2020. Hydrothermal alteration, mineralization, and fluid inclusions in the Pista and Fofão prospects: implications for the genetic model of the Coringa polymetallic deposit, SE Tapajós Mineral Province, Amazonian Craton, Brazil. *Journal of Geological Survey of Brazil*, 3, 33-59. <https://doi.org/10.29396/jgsb>
- Coutinho M.G.N. 2008. *Província Mineral do Tapajós: geologia, metalogenia e mapa preliminar para ouro em SIG*. Rio de Janeiro: CPRM, 420 p.
- De Hoog, J.C.M., Taylor, B.E., van Bergen, M.J. 2009. Hydrogen-isotope systematics in degassing basaltic magma and application to Indonesian arc basalts. *Chemical Geology*, 266, 256-266.

- Dreher A.M., Vlach S.R.F., Martini S.L. 1998. Adularia associated with epithermal gold veins in the Tapajós Mineral Province, Pará State, Northern Brazil. *Revista Brasileira de Geociências*, 28, 397-404.
- Dzick W.A. 2015. Coringa mineral resource NI 43-101 technical report: project n. V1491. Vancouver: Snowden, Available online at <https://anfieldgold.com/projects/technical-reports/> (accessed on 08 March 2016).
- Echeverri-Misas C.M., 2010. Geologia e gênese do depósito de Au-(Cu) do Palito, Província Aurífera do Tapajós. Dissertação de Mestrado, IG/USP.
- Ellis, R., de Wet, B., Macleod, I. M. 2012. Inversion of magnetic data from remanent and induced sources: Presented at the 22nd ASEG International Geophysical Conference. Australia Society of Exploration Geophysicists.
- Feio J.V.B. 2014. Petrografia das rochas hospedeiras e do minério aurífero e estudo de isótopos de chumbo no alvo Mato Velho, SE da Província Aurífera do Tapajós, Pará. Graduation Work. Instituto de Geociências, Universidade Federal do Pará, Belém.
- Fekete, S., Weis, P., Driesner, T., Bouvier, A.S., Baumgartner, L., Heinrich, C.A. 2016. Contrasting hydrological processes of meteoric water incursion during magmatic-hydrothermal ore deposition: Na oxygen isotope study by ion microprobe. *Earth and Planetary Science Letters* 451 (2016) 263–271.
- Field, C. W., Fife, R. H. 1985. Light stable isotope systematics in epithermal systems: review in *Geology* 2, 99–128.
- Fraga, L.M., Vasquez, M.L., Dreher, A.M., 2017. A influência da Orogenia Eo-orosiana na formação da SLIP Uatumã, parte central do Cráton Amazônico. *Anais do 15º Simpósio de Geologia da Amazônia*, Belém. 405-408 p.
- Fraga, L.M.B., Cordani, U., 2019. Early Orosirian tectonic evolution of the Central Guiana Shield: insights from new U-Pb SHRIMP data. In: 11th Inter Guiana Geological Conference: Tectonics and Metallogeny of NE South America. *Proceedings*, pp. 59-62.
- Friedman, I. and O'Neil, J.R. 1977. Compilation of stable isotope fractionation factors of geochemical interest. In: *Data of Geochemistry* 6th, Geol. Surv. Prof. Paper 440–KK, p. 61.
- Goldstein R.H., Reynolds T.J. 1994. Systematics of fluid inclusions in diagenetic minerals. *SEPM Short Course* 31, 199.
- Guimarães, S. B., Klein, E. L., Chaves, C. L., Souza, S. M., Castro, J. M. R., Queiroz, J. D. S., Feio, J. V. B., Lima, R. G. C., 2015. Metalogenia das Províncias Minerais do Brasil:

- Área sudeste do Tapajós, Estado do Pará. 1. ed. Brasília: CPRM - Serviço Geológico do Brasil, 2016. v. 1. 61p.
- Guimarães, S. B., Klein, E. L., Correa, R.T., 2019. Reassessment of the geology of the southeastern Tapajós Gold Province, Amazonian Craton, Brazil, based on field, petrographic, and airborne geophysical data. *Journal of the Geological Survey of Brazil* vol 2, no 1, 1-16.
- Guimarães, S. B. & Klein, E. L., 2020. Geochemical and isotopic constraints on the host rocks of the magmatic-hydrothermal Coringa gold-silver (Cu-Pb-Zn) of the Tapajós Mineral Province, Amazonian Craton, Brazil. *Journal of South America Earth Sciences*, 103, 102726. DOI: 10.1016/j.jsames.2020.102726
- Harris, C., Vogeli, J., 2010. Oxygen isotope composition of garnet in the Peninsula Granite, Cape Granite Suite, South Africa: constraints on melting and emplacement mechanisms. *South African Journal of Geology*, 113, 401–412.
- Hedenquist, J.W., Arribas, A., Gonzalez-Urien, E., 2000. Exploration for epithermal gold deposits. *Rev. Econ. Geol.* 13, 245–277.
- Heinrich, C.A. 1995. Geochemical evolution and hydrothermal mineral deposition in Sn (-W-base metal) and other granite-related ore systems: some conclusions from Australian examples, in Thompson, J.F.H., ed., *Magma, fluids, and ore deposits: Mineralogical Association of Canada (MAC) Short Course*, v. 23, p. 203–220.
- Hey, M. H. 1954. A new review of chlorites. *The mineralogy magazine*, 30: 277-292.
- Jacobi P. 1999. The discovery of epithermal Au-Cu-Mo proterozoic deposits in the Tapajós Province, Brazil. *Revista Brasileira de Geociências*, 29, 277-279.
- Johnson, A., Aisengart, T. 2014. Interpretation of magnetic data at low magnetic latitudes using magnetization vector inversion. *Journal of Geophysics*, 35(3), 91-96.
- Juliani, C., Carneiro, C.C., Carreiro-Araújo, S. A., Fernandes, C. M. D., Monteiro, L. V. S., Crósta, A. P., 2013. Estruturação dos arcos magmáticos paleoproterozoicos na porção sul do Cráton Amazônico: implicações geotectônicas e metalogenéticas. *Anais do 13º Simpósio de Geologia da Amazônia*. Belém, p.157-160.
- Juliani C., Correa-Silva R.H., Monteiro L.V.S., Bettencourt J.S., Nunes C.M.D. 2002. The Batalha Au-Granite system e Tapajós Province, Amazonian Craton, Brazil: hydrothermal alteration and regional implication. *Precambrian Research*, 119(1-4), 225-256.
- Juliani C., Rye R.O., Nunes C.M.D., Snee L.W., Silva R.H.C., Monteiro L.V.S., Bettencourt J.S., Neumann R., Alcover Neto A. 2005. Paleoproterozoic high-sulfidation

- mineralization in the Tapajós gold province, Amazonian Craton, Brazil: geology, mineralogy, alunite argon age, and stable isotope constraints. *Chemical Geology*, 215, 95-125.
- Juliani, C., Monteiro, L. V. S., Echeverri-Misas, C. M., Lagler, B., Fernandes, C.M.D., 2012. Gold and base metal porphyry and epithermal mineralization in Paleoproterozoic magmatic arcs in the Amazonian Craton, Brazil. In: *International Geology Congress*, 12. IUGS[CD-ROM].
- Kerrick, R. 1987. The stable isotope geochemistry of Au-Ag vein deposits in metamorphic rocks, in Kyser, T.K., ed., *Stable isotope geochemistry of low-temperature fluids: Mineralogical Association of Canada, Short Course Handbook*, v. 13, p. 287–336.
- Klein, E.L., Almeida, M.E., Rosa-Costa, L.T. 2012. The 1.89-1.87 Ga Uatumã Silicic Large Igneous Province, northern South America. In: *International Association of Volcanology and Chemistry of the Earth's Interior, Large Igneous Province Commission*, November 2012 LIP of the month.
- Klein, E. L., Almeida, M.E., Vasquez, M.L., Bahia, R.B.C., Quadros, M.L.E.S., Ferreira, A.L., 2001. *Geologia e recursos minerais da Província Mineral do Tapajós, Estados do Pará e Amazonas: folhas SB.21-V-D, SB.21-Y-B, SB.21-X-C, SB.21-Z-A e SB.21-Z-C. Escala 1:500.000. Brasília: CPRM, 1 CD-ROM. Programa Levantamentos Geológicos Básicos do Brasil. Projeto Especial Província Mineral do Tapajós (Promin - Tapajós).*
- Klein, E.L., Guimarães, S.B., Rodrigues, J.B., Chaves, C.L., Souza-Gaia, S.M., Lopes, E.C.S., Castro, J.M.R., 2018. The Novo Progresso Formation, Tapajós Gold Province, Amazonian Craton: zircon U-Pb and Lu-Hf constraints on the maximum depositional age, reconnaissance provenance study, and tectonic implications. *Journal of the Geological Survey of Brazil (JGSB)* 2018, 1 (1) 31-42.
- Klein, E.L., Rodrigues, J.B., Queiroz, J.D.S., Oliveira, R.G., Guimarães, S.B., Chaves, C.L., 2017. Deposition and tectonic setting of the Palaeoproterozoic Castelo dos Sonhos metasedimentary formation, Tapajós Gold Province, Amazonian Craton, Brazil: age and isotopic constraints, *International Geology Review*, 59:7, 864-883.
- Klein, E.L., Rosa-Costa, L.T., Carvalho, J.M.A., 2004. Estudo de inclusões fluidas em veio de quartzo aurífero do prospecto Patinhas, Província Aurífera do Tapajós, Cráton Amazônico. *Rev. Brasil. Geociên.* 34, 59 e 66.
- Klein, E. L., Vasquez, M.L., Rosa-Costa, L.T., Carvalho, J. M.A., 2002. Geology of Paleoproterozoic gneiss- and granitoid-hosted gold mineralization in southern Tapajós

- Gold Province, Amazonian Craton, Brazil. *International Geology Review*, v. 44, p. 544-558.
- Kranidiotis, P., MacLean, W.H. 1987. Systematics of chlorite alteration at the Phelps Dodge massive sulfide deposit, Matagami, Quebec. *Economic Geology* 82 (7): 1898–1911. <https://doi.org/10.2113/gsecongeo.82.7.1898>
- Lamarão, C.N., Dall'Agnol, R., Lafon, J.M., Lima, E.F., 2002. Geology, geochemistry, and Pb–Pb zircon geochronology of the Paleoproterozoic magmatism of Vila Riozinho, Tapajós Gold Province Amazonian Craton, Brazil. *Precambrian Research*, 119: 189-23.
- Lamarão, C.N., Dall'Agnol, R., Pimentel, M.M., 2005. Nd isotopic composition of Paleoproterozoic volcanic and granitoid rocks of Vila Riozinho: implications for the crustal evolution of the Tapajós gold province, Amazon cráton. *Journal of South American Earth Sciences* 18 (2005) 277–292.
- Lambert, I.B., Phillips, G.N., Groves, D.I., 1984. Sulfur isotope compositions and genesis of Archaean gold mineralization, Australia, and Zimbabwe. In: Foster, R.P. (Ed.), *Gold'82: The Geology, Geochemistry, and Genesis of Gold Deposits 1*. Geological Society of Zimbabwe Special Publication, pp. 373–387.
- Lopes, A.A.C. and Moura, M. M., 2019. The Tocantinzinho Paleoproterozoic Porphyry-Style Gold Deposit, Tapajós Mineral Province (Brazil): Geology, Petrology, and Fluid Inclusion Evidence for Ore-Forming Processes. *Minerals*, 9, 29; doi:10.3390/min9010029
- Monier P., Robert J.L. 1986. Muscovite solid-solutions in the system K_2O - MgO - FeO - Al_2O_3 - SiO_2 - H_2O : an experimental study at 2 kbar pH_2O and comparison with natural Li-free white micas. *Mineralogical Magazine*, 50, 257-266.
- Ohmoto, H., Rye, R.O. 1979. Isotopes of sulfur and carbon. In: Barnes, H.L. (Ed.), *Geochemistry of Hydrothermal Ore Deposits*, 2nd ed. Wiley, New York, pp. 509 – 567.
- O'Neil, J. R., Taylor, H. P. 1969. Oxygen isotope equilibrium between muscovite and water. *J. Geophys. Res.*, 74, 6012–6022.
- Prenn, N., Peralta, E., Breckenridge, L., Sim, R., Davis, B.M., Smith, M., Michel, R., King, N., Fisher, B., 2017. Coringa Gold Project, Brazil. Feasibility Study NI 43-101 Technical Report. Available at <https://www.serabigold.com/wp-content/uploads/2018/02/Coringa-FS-43-101.pdf>, access on March 23, 2019.
- Queiroz, J.D.S. & Klein, E.L., 2018. The Paleoproterozoic metaconglomerate-hosted Castelo de Sonhos gold deposit, Tapajós Gold Province, Amazonian Craton: a modified

- paleoplacer origin. *Journal of the Geological Survey of Brazil*, 1 (2), 81-99.
<https://doi.org/10.29396/jgsb.2018.v1.n2.3>
- Queiroz, J.D.S., Klein, E.L., Rodrigues, J.B., 2015. Rochas intrusivas na bacia paleoproterozoica Castelo dos Sonhos, Cráton Amazônico: geocronologia, aspectos geoquímicos e implicações para litoestratigrafia, limite entre os domínios Tapajós e Iririxingu e idade da mineralização no depósito aurífero Castelo de Sonhos. *Boletim Paraense Emílio Goeldi. Ciências Naturais*.
- Roedder, E., 1984. Fluid inclusions. *Reviews in Mineralogy* 12, 644 pp.
- Santiago E.S.B., Villas R.N.N., Ocampo R.C. 2013. The Tocantinzinho gold deposit, Tapajós Province, State of Pará: host granite, hydrothermal alteration, and mineral chemistry. *Brazilian Journal of Geology*, 43(1), 185-208.
- Santos, J.O.S., Groves, D.I., Hartmann, L.A., Moura, M.A., McNaughton, N.J., 2001. Gold deposits of the Tapajós and Alta Floresta Domains, Tapajós – Parima orogenic belt, Amazon Craton, Brazil. *Mineralium Deposita*, 6: 279-299.
- Santos, J.O.S., Van Breemen, O.B, Groves, D., Hartmann, L.A, Almeida, A M.E, McNaughton, N.J., Fletcher, I.R., 2004. Timing and evolution of multiple Paleoproterozoic magmatic arcs in the Tapajós Domain, Amazon Craton: constraints from SHRIMP and TIMS zircon, baddeleyite and titanite U-Pb geochronology. *Precambrian Research*, 131: 73-109.
- Santos M.D., Aquino L.B.M., Serra V.F.H., Lima M.V.G.R., Galarza M.A., Lafon J.M. 2013. Geocronologia das rochas hospedeiras e do minério com implicações na gênese do depósito aurífero palito, Província Tapajós, sudoeste do Pará. In: *Simpósio de Geologia da Amazônia*, 13, 702-704.
- Schimmelmann, A., DeNiro, M.J., 1993. Preparation of organic and water hydrogen for stable isotope analysis: effects due to reaction vessels and zinc, *Analytical Chemistry*, 65, 789–792.
- Shanks, W.C. P. 2001. Stable isotopes in seafloor hydrothermal systems: Vent fluids, hydrothermal deposits, hydrothermal alteration, and microbial processes. In: Valley, J. W. and Cole D. R. (eds.) *Stable Isotope Geochemistry. Reviews in Mineralogy and Geochemistry*, vol. 43, pp. 469 – 526. Washington, D .C: Mineralogical Society of America.
- Shepherd, T.J., Rankin, A.H., Alderton, D.H., 1985. A practical guide for fluid inclusion studies. Blackie & Son, Glasgow, 239 pp.

- Sheppard, S.M.F. 1986. Characterization and isotopic variations in natural waters. In *Stable Isotopes in High-Temperature Geological Processes* (J.W. Valley, H.P. Taylor Jr. & J.R.O'Neil, eds.). *Rev. Mineral.* 16, 165-183.
- Silva Júnior, C. A., and Klein, E. L. 2015. Geologia e características do fluido minealizador dos alvos auríferos Jerimum de Cima e Babi, campo mineralizado do Cuiú-cuiú, Província Aurífera do Tapajós, Cráton Amazônico, com base em estudo de inclusões fluidas e de isótopos estáveis. *Bol. Mus. Para. Emílio Goeldi. Cienc. Nat.*, Belém. v.10, n.2, p. 199-230.
- Simmons, S.F., White, N.C., John, D.A., 2005. Geological characteristics of epithermal precious and base metal deposits. *Econ. Geol.* 485–522 100th Anniversary Volume.
- Suzuoki, T. and Epstein, S. 1976. Hydrogen isotope fractionation between OH-bearing minerals and water. *Geochimica et Cosmochimica Acta*, Volume 40, Issue 10, p. 1229-1240. DOI:10.1016/0016-7037(76)90158-7
- Tokashiki, C. C., Juliani, C., Monteiro, L. V. S., Echeverri-Missas, C. M., Aguja, M. A., Arrais, L. B., 2015. Eventos vulcânicos de 1,97 Ga com mineralizações de ouro epitermais low- e intermediate sulfidation na porção sul da Província Mineral Tapajós (PA). *Contribuições à Geologia da Amazônia*. Vol.9
- Vasquez, M. L., Chaves, C. L., Moura, E. M., Oliveira, J. K. M., 2017. Geologia e Recursos Minerais das Folhas São Domingos - SB.21-Z-A-II e Jardim do Ouro - SB.21-Z-A-III, Estado do Pará, Escala 1:100.000. Belém: CPRM - Serviço Geológico do Brasil, 2017. 305 p.
- Vasquez, M.L., Klein, E.L., Ricci, P.S.F., 2002. Granitoides pós-colisionais da porção leste da Província Tapajós. In: E.L. Klein, M.L.Vasquez, L.T. Rosa-Costa. (eds.). *Contribuições à Geologia da Amazônia*, Belém v.3, p. 67-84.
- Vasquez, M.L., Rosa-Costa, L.T., Silva, C.M.G., Klein, E.L., 2008. Compartimentação Tectônica. In: M.L. Vasquez; L.T. Rosa-Costa (orgs.). 2008. *Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará*. Escala 1:1.000.000. Belém: CPRM. p. 39-112.
- Vasquez, M.L., Rosa-Costa, L.T. (orgs.), 2008. *Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará*. Escala 1:1.000.000. Belém: CPRM. p. 39-112.

- Vasquez, M.L., Cordani, U. G., Sato, K., Barbosa, J.P.O., Faraco, M.T.L., Maurer, V.C. 2019. U-Pb SHRIMP dating of basement rocks of the Iriri-Xingu domain, Central Amazonian province, Amazonian craton, Brazil. *Brazilian Journal of Geology*, vol.49, n.3.<https://doi.org/10.1590/2317-4889201920190067>
- Veloso, A.S.R., Santos, M.D., 2013. Geologia, petrografia e geocronologia das rochas do depósito aurífero Ouro Roxo, Província Tapajós, Jacareacanga (PA), Brasil. *Braz. J.Geol.* 43(1), 22 e 36.
- Vennemann, T.W., O'Neil, J.R., 1993. A simple and inexpensive method of hydrogen isotope and water analyses of minerals and rocks based on zinc reagent. *Chemical Geology (Isotope Geosciences Section)*, 103, 227–234.
- Villas, R.N.N.; Santiago, E.S.B.; Castilho, M.P. 2013. Contexto geológico, estudos isotópicos (C, O e Pb) e associação metálica do depósito aurífero Tocantinzinho, domínio Tapajós, Província Tapajós-Parima. *Geologia USP Série Científica*, 13, 119-138.
- Wagner, T., Williams-Jones, A.E., and Boyce, A.J., 2005, Stable isotope-based modeling of the origin and genesis of an unusual Au-Ag-Sn-W epithermal system at Cirotan, Indonesia: *Chemical Geology*, v. 219, p. 237–260.
- Wang, L.; Qin, K. Z.; Song, G; Li, G.M. 2019. A review of intermediate sulfidation epithermal deposits and subclassification. *Ore Geology Reviews* 107 (2019) 434–456. <https://doi.org/10.1016/j.oregeorev.2019.02.023>
- Zang, W. and Fyfe, W.S. 1995. Chloritization of the hydrothermally altered bedrock at the Igarapé Bahia gold deposit, Carajás, Brazil. *Mineralium Deposita*, vol. 30, pp 30-38.
- Zheng, Y. F., Hoefs, J. 1993. Carbon and oxygen isotopic covariations in hydrothermal calcites: theoretical modeling on mixing processes and application to Pb–Zn deposits in the Harz mountains, Germany. *Mineralium Deposita* 28(2), 79-89.

5. CONCLUSÕES

A combinação dos dados de trabalho de campo, petrografia e geofísica aérea de alta resolução (magnetometria e espectrometria gama) permitiu a consolidação de um novo mapa geológico para a porção Sudeste da Província Mineral Tapajós (PMT) na escala de 1:100.000, melhorando a definição das unidades litoestratigráficas, e de áreas de ocorrência de outras unidades (**Fig. 4.2**).

As rochas vulcânicas e piroclásticas formam uma associação abundante na área de estudo, não mapeadas anteriormente, e neste trabalho são correlacionadas à Formação Vila Riozinho (FVR), aumentando assim, a área de ocorrência dessa formação.

Uma parte da Formação Vila Riozinho no sudeste da PMT apresenta um padrão magnético anômalo que compreende um grupo de rochas com o mais alto conteúdo magnético da área de estudo, e assim foi definido um fácies específico. Este fácies magnético consiste em sequências de ignimbritos de composição riolítica (com poucas ocorrências de brechas).

As rochas vulcânicas e piroclásticas da FVR (1996-2033 Ma) são de alto K, álcali-cálcicas e magnesianas, enquanto as rochas do fácies magnético são principalmente ferro alcalinas, ou seja, mostra condições de cristalização relativamente reduzidas.

Apesar da diferença química, o fácies magnético foi datado de 2024 a 1968 Ma, idade semelhante atribuída a FVR. Os isótopos Nd-Hf revelam idades modelo entre 2,38 e 2,42 Ga e valores de épsilon variando de -2,1 a -3,2, que são muito semelhantes aos da FVR "normal" (Sm-Nd TDM = 2,49-2,25 Ga, ENd = -3,71 a -1,03).

A Suíte Intrusiva Creporizão (SIC) (1956-2002 Ma) teve seus limites modificados, e apresenta grande extensão na área de estudo, no sudeste da PMT compõe-se por biotita sienogranitos a monzogranitos equigranulares a porfirítico de cor cinza. Apresentam alto K, são cálcio-alcalinos a álcali-cálcicos, metaluminosos e magnesianos. A Suíte Intrusiva Maloquinha (SIM), intrusiva nas unidades mais antigas, mostra assinatura álcali-cálcica a alcalina, e ferrosa, e a distribuição de elementos traço típica de granitos alcalinos saturados de sílica e datada de 1883 ± 17 Ma.

O feldspato alcalino granito Serra (1968-2020 Ma) representa uma nova unidade identificada. Representada por dois pequenos corpos de rochas cálcio-alcalinas, equigranulares rosadas de fino a médio, e com textura granofírica (**Fig. 4.2**). A mineralização ouro-prata do depósito Coringa está parcialmente hospedada no contato entre a Formação Vila Riozinho e o granito da Serra. Os valores de ENd, para o Granito Serra, são moderados a fortemente negativos (-8,0 a + 0,1) e idades modelo de 2,27 a 3,15 Ga, o mesmo intervalo

daqueles apresentados pelas rochas da SIC, portanto o Granito Serra foi interpretado como uma variedade diferenciada da SIC.

Por outro lado, a similaridade nas assinaturas geoquímica e isotópica da SIC e da FVR indicam que eles pertencem ao mesmo evento magmático durante o período Orosiriano. E, considerando as relações cronológicas com eventos magmáticos precedentes na PMT, atribuídos à configuração do arco, interpretamos esse evento como pós-colisional, com as assembléias de colisão ocorrendo fora do TMP, no Escudo das Guianas, como parte de um grande cinturão orogênico de Orosirian. A SIM está associado ao SLIP de Uatumã (~ 1,89-1,86 Ga), que foi estabelecido em um evento extensional em todo o craton que se seguiu à orogenia Orosiriana.

Diante deste cenário, hospedado em rochas vulcânicas félsicas e granitos, que foram datados e atribuídos às unidades da Formação Vila Riozinho (1996 ± 21 Ma) e ao Granito Serra (1999 ± 25 Ma), ocorre o depósito Coringa.

O depósito Au-Ag (Cu-Pb-Zn) do Coringa representa um sistema mineral composto por dezenas de corpos mineralizados (**Fig. 4.2**). O sistema de veios mineralizados é coincidente com o trend regional de direção norte-noroeste. As venulações modificaram em intensidades variáveis o conjunto primário e as texturas das rochas hospedeiras, gerando halos de alteração hidrotermal, são elas: (a) Alteração carbonato-clorita-epidoto (distal), (b) Alteração sericita-pirita (intermediária / proximal), (c) Alteração clorita-hematita (proximal), e (d) Zona de minério: caracterizada por muitos veios de quartzo.

A mineralização está quase exclusivamente associada aos veios de quartzo- sulfeto. Além da prata e ouro, a associação mineralógica consiste em pirita, galena, esfalerita, calcopirita e hematita. Ocasionalmente, sericita, hematita, clorita e Mn-calcita são observados. Os sulfetos também ocorrem como disseminações em ignimbritos, granito e brecha. Os grãos de ouro ocorrem como inclusões na pirita, em forma livre ou fraturas.

Foram descritos dois grupos de inclusões fluidas: a) fluidos aquoso-carbônicos de provável origem magmática, possivelmente relacionadas ao posicionamento do magma em níveis mais rasos da crosta, e o principal aprisionamento ocorreu a 320-345°C (temperatura total de homogeneização do FI tipo 3); b) fluidos aquosos de origem meteórica, cuja entrada foi favorecida por fraturamento, apresentou baixas salinidades e temperaturas de captura, 160 a 330 ° C (temperatura de homogeneização FI tipo 2). A clorita (de distal) foi formada principalmente neste estágio (224 a 241°C), consistente com a temperatura das inclusões de fluidos do tipo 2 e com dados petrográficos que demonstram uma grande dispersão. Isso nos

leva a crer que durante o ambiente vulcânico, em níveis rasos, ocorreu mistura dos fluidos formados a partir da ação das águas de superfície (meteóricas), com fluidos da circulação das águas magmáticas.

A assembleia mineral hidrotérmica, com a presença de Mn-calcita, mica branca (sericita), clorita, adulária, a estreita relação com rochas vulcânicas riolíticas alcalinas e alcalinas e com evidências de mistura de fluidos (meteóricos – magmáticos) de baixa salinidade, são características que convergem para classificar o depósito Coringa como um depósito epitermal de intermediária sulfetação.

REFERÊNCIAS

- Almeida M.E., Brito M.F.L., Ferreira A.L., Monteiro M.A.S. 2000. *Projeto Especial Província Mineral do Tapajós. Geologia e recursos minerais da Folha Vila Mamãe Anã (SB.21-V-D). Estados do Pará e Amazonas*. CPRM, Brasília. [CD-ROM].
- Buhn B., Pimentel M.M., Matteini M., Dantas E.L. 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-IC-MS). *Anais da Academia Brasileira de Ciências*, **81**(1):99-114.
- Cawood P.A., Kroner A., Collins W.J., Kusky T.M., Mooney W.D., Windley B.F. 2009. Accretionary orogens through earth history. *Geol. Soc. London Spec. Publ.*, **318**: 1–36.
- Cawood P.A., Kroner A., Pisarevsky S. 2006. Precambrian plate tectonics: criteria and evidence. *GSA Today*, **16**: 4–11.
- Chauvel C & Blichert-Toft J.E. 2001. A hafnium isotope and trace element perspective on melting of the depleted mantle. *Earth and Planetary Science Letters*, **190**, 137-151.
- Chu N. C., Taylor R. N., Chavagnac V., Nesbitt R.W., Boella R. M., Milton J. A., German C. R., Bayon G., Burton K. 2002. Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: an evaluation of isobaric interference corrections. *Journal of Analytical Atomic Spectrometry* **17**, 1567-1574.
- Coney P.J., Jones D.L., Monger J.W.H. 1980. Cordilleran suspect terranes. *Nature*, vol. **288**: 329-333.
- Corrêa-Lima R.G. & Klein E.L. 2020. Hydrothermal alteration, mineralization and fluid inclusions in the Pista and Fofão prospects: implications for the genetic model of the Coringa polymetallic deposit, SE Tapajós Mineral Province, Amazonian Craton, Brazil. *Journal of Geological Survey of Brazil*, **3** (1): 33-59.
- Clayton R.N. & Mayeda T.K. 1963. The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates from isotopic analyses. *Geochim. Cosmochim. Acta* **27**: 43–52.
- Fernandes C.M.D., Juliani C., Monteiro L.V.S., Lagler B., Echeverri Missas C.M. 2011. High-K calc-alkaline to A-type fissure-controlled volcano-plutonism of the São Félix do Xingu region, Amazonian craton, Brazil: exclusively crustal sources or only mixed Nd model ages? *Journal of South American Earth Sciences*, **30**:1-18.
- Fraga L.M., Vasquez M.L., Dreher A.M. 2017. A influência da Orogenia Eo-orosiana na formação da SLIP Uatumã, parte central do Cráton Amazônico. *Anais do 15º Simpósio de Geologia da Amazônica, Belém*. 405-408 p.
- Guimarães S. B., Klein E. L., Chaves C. L., Souza S. M., Castro J. M. R., Queiroz J. D. S., Feio J. V. B., Lima R. G. C. 2015. *Metalogenia das Províncias Minerais do Brasil: Área sudeste do Tapajós, Estado do Pará*. 1. ed. Brasília, DF: CPRM - Serviço Geológico do Brasil, 2016. v. 1. 61p.

Guimarães S. B., Klein E. L., Correa R.T. 2019. Reassessment of the geology of the southeastern Tapajós Gold Province, Amazonian Craton, Brazil, based on field, petrographic, and airborne geophysical data. *Journal of the Geological Survey of Brazil* **2** (1): 1-16,

Harris C. & Vogeli J. 2010. Oxygen isotope composition of garnet in the Peninsula Granite, Cape Granite Suite, South Africa: constraints on melting and emplacement mechanisms. *South African Journal of Geology*, **113**: 401–412.

Hedenquist J.W., Arribas A., Gonzalez-Urien E. 2000. Exploration for epithermal gold deposits. *Economic Geology*, **13**: 245–277.

Juliani C., Carneiro C.C., Carreiro-Araújo S. A., Fernandes C. M. D., Monteiro L. V. S., Crósta A. P. 2013. Estruturação dos arcos magmáticos paleoproterozoicos na porção sul do Cráton Amazônico: implicações geotectônicas e metalogenéticas. In: SBG, 13º Simpósio de Geologia da Amazônia. Belém, *Anais.*, p.157-160.

Juliani C., Fernandes C.M.D., Monteiro L.V.S., Lagler B., Echeverri-Misas C.M. 2011. Very low-grade metamorphism and very well preserved epithermal mineralization in the Paleoproterozoic Uatumã LIP, southern Amazonian craton, Brazil. *Geophysical Research Abstracts*, **13**, p.115-118

Klein E.L., Almeida M.E., Rosa-Costa L.T. 2012. The 1.89-1.87 Ga Uatumã Silicic Large Igneous Province, northern South America. In: International Association of Volcanology and Chemistry of the Earth's Interior, Large Igneous Province Commission, November 2012 LIP of the month [*Proceeding...*]

Klein E. L., Almeida M.E., Vasquez M.L., Bahia R.B.C., Quadros M.L.E.S., Ferreira A.L., 2001. *Geologia e recursos minerais da Província Mineral do Tapajós, Estados do Pará e Amazonas: folhas SB.21-V-D, SB.21-Y-B, SB.21-X-C, SB.21-Z-A e SB.21-Z-C. Escala 1:500.000*. Brasília: CPRM, 1 CD-ROM. Programa Levantamentos Geológicos Básicos do Brasil. Projeto Especial Província Mineral do Tapajós (Promin - Tapajós).

Klein E.L., Guimarães S.B., Rodrigues J.B., Chaves C.L., Souza-Gaia S.M., Lopes E.C.S., Castro J.M.R. 2018. The Novo Progresso Formation, Tapajós Gold Province, Amazonian Craton: zircon U-Pb and Lu-Hf constraints on the maximum depositional age, reconnaissance provenance study, and tectonic implications. *Journal of the Geological Survey of Brazil (JGSB)* 2018, **1** (1) 31-42.

Klein E.L., Rodrigues J.B., Queiroz J.D.S., Oliveira R.G., Guimarães S.B., Chaves C.L., 2017. Deposition and tectonic setting of the Palaeoproterozoic Castelo dos Sonhos metasedimentary formation, Tapajós Gold Province, Amazonian Craton, Brazil: age and isotopic constraints, *International Geology Review*, **59**:7, 864-883.

Kroonenberg S.B., Roever E.W.F., Fraga L.M, Reis N.J., Faraco T., Lafon J.-M., Cordani U., Wong T.E. 2016. Paleoproterozoic evolution of the Guiana Shield in Suriname: A revised model. *Netherlands Journal of Geosciences* **95**, p.491–522. doi:10.1017/njg.2016.10.

Lamarão C.N., Dall'Agnol R., Lafon J.M., Lima E.F. 2002. Geology, geochemistry, and Pb–Pb zircon geochronology of the Paleoproterozoic magmatism of Vila Riozinho, Tapajós Gold Province Amazonian Craton, Brazil. *Precambrian Research*, **119**: 189-23.

Lindgren W. 1922. A suggestion for the terminology of certain mineral deposits. *Economic Geology* **17**, 292–294.

Lindgren W. 1933. *Mineral Deposits*. McGraw-Hill, New York, pp. 930.

Matteini M., Dantas E.L., Pimentel M.M., Buhn B. 2010. Combined U-Pb and Lu-Hf isotope analyses by laser ablation MC-ICP-MS: methodology and applications. *Anais da Academia Brasileira de Ciências* **82**(2):479-491.

Milhomem Neto J.M., Lafon J.M., Galarza M.A. 2017. Lu-Hf em zircão por LA-MC-ICP-MS no laboratório Pará-Iso (UFPA): metodologia e primeiro exemplo de aplicação na porção sudeste do Escudo das Guianas. In: Lima A.M. & Gorayeb P. (eds.) *Contribuições à Geologia da Amazônia* v.10, p.195-208.

Prazeres W.V. 1979. *Projeto Estanho dos Granitos Maloquinha*: relatório anual. Manaus, DNPM/CPRM, v. 1-A, 301, p.

Queiroz J.D.S., Klein E.L., Rodrigues J.B. 2015. Rochas intrusivas na bacia paleoproterozoica Castelo dos Sonhos, Cráton Amazônico: geocronologia, aspectos geoquímicos e implicações para litoestratigrafia, limite entre os domínios Tapajós e Iriri-Xingu e idade da mineralização no depósito aurífero Castelo de Sonhos. *Boletim Paraense Emílio Goeldi. Ciências Naturais*, **10**: 341-380p.

Santos J.O.S. 2003. Geotectônica do Escudo das Guianas e Brasil-Central. In: Bizzi L.A. et al. (Ed.). *Geologia, tectônica e recursos minerais do Brasil*: texto, mapas e SIG. Brasília,DF, CPRM – Serviço Geológico do Brasil. p. 169-226, il.

Santos J.O.S., Groves D.I., Hartmann L.A., Moura M.A., McNaughton N.J. 2001. Gold deposits of the Tapajós and Alta Floresta Domains, Tapajós – Parima orogenic belt, Amazon Craton, Brazil. *Mineralium Deposita*, **6**: 279-299.

Santos J.O.S., Van Breemen O.B, Groves D., Hartmann L.A, Almeida A. M.E., McNaughton N.J., Fletcher I.R. 2004. Timing and evolution of multiple paleoproterozoic magmatic arcs in the Tapajós Domain, Amazon Craton: constraints from SHRIMP and TIMS zircon, baddeleyite and titanite U-Pb geochronology. *Precambrian Research*, **131** (1): 73-109.

Santos J.O.S., Hartmann L.A., Gaudette H.E., Groves D.I., McNaughton N.J., Fletcher I.R. 2000. New understanding of the Amazon Craton provinces, based on fieldwork and radiogenic isotope data. *Gondwana Research*, **3**: 453-488.

Sato K. & Tassinari C.C.G. 1997. Principais eventos de acreção continental no Cráton Amazônico, baseados em idade modelo Sm-Nd, calculada em evoluções de estágio único e estágio duplo. In: M.L. Costa & R.S. Angélica (coord.). *Contribuições à Geologia da Amazônia*, v.1, p.91-142.

Schimmelmann A. & DeNiro M.J. 1993. Preparation of organic and water hydrogen for stable isotope analysis: effects due to reaction vessels and zinc. *Analytical Chemistry*, **65**: 789–792.

Simmons S.F., White N.C., John D.A. 2005. Geological characteristics of epithermal precious and base metal deposits. *Economic Geology 100th Anniversary Volume*, p. 485–522.

Tassinari C.C.G. 1996. *O mapa geocronológico do Cráton Amazônico no Brasil: revisão dos dados isotópicos*. Tese de Livre Docência, IG/USP, 139 p.

Tassinari C.C.G. & Macambira M.J.B. 1999. Geochronological Provinces of the Amazonian Craton. *Episodes*, **22** (3):174-18.

Taylor S.R. & McLennan S.M. 1985. *The Continental Crust: its composition and evolution*. Blackwell, Oxford. 312 pp.

Teixeira W., Tassinari C.C.G., Cordani U.G., Kawashita K. 1989. A review of the geochronology of the Amazonian Craton: Tectonic implications. *Precambrian Research*, **42**:213-227.

Tokashiki C. C., Juliani C., Monteiro L. V. S., Echeveerri-Missas C. M., Aguja M. A., Arrais L. B. 2015. Eventos vulcânicos de 1,97 Ga com mineralizações de ouro epitermais low- e intermediate sulfidation na porção sul da Província Mineral Tapajós (PA). In: Gorayeb P & Lima A.M. (eds.). 2015. *Contribuições à Geologia da Amazônia*, v.9, p. 119-138.

Vasquez M. L., Chaves C. L., Moura E. M., Oliveira J. K. M. 2017. *Geologia e Recursos Minerais das Folhas São Domingos - SB.21-Z-A-II e Jardim do Ouro SB.21-Z-A-III, Estado do Pará, Escala 1:100.000*. Belém: CPRM - Serviço Geológico do Brasil, 305 p.

Vasquez M.L., Rosa-Costa L.T., Silva C.M.G., Klein E.L. 2008. Compartimentação Tectônica. In: Vasquez M.L. & Rosa-Costa L.T. (orgs.). 2008. *Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto explicativo dos mapas geológico e tectônico e de recursos minerais do Estado do Pará. Escala 1:1.000.000*. Belém: CPRM. p. 39-112.

Vasquez M.L. & Dreher A.M. 2011. Uma avaliação da estratigrafia dos eventos magmáticos de 1900-1860 Ma do Cráton Amazônico. In: 12º *Simpósio Geologia da Amazônia, Anais...*Boa Vista-Roraima, p. 210-214.

Vennemann T.W. & O'Neil J.R. 1993. A simple and inexpensive method of hydrogen isotope and water analyses of minerals and rocks based on zinc reagent. *Chemical Geology* (Isotope Geosciences Section), **103**, 227–234.

Wang L., Qin K. Z., Song G., Li G.M. 2019. A review of intermediate sulfidation epithermal deposits and subclassification. *Ore Geology Reviews*, **107**: 434–456.

Wedepohl K.H. 1995. The compositions of the continental crust. *Geochimica et Cosmochimica Acta*, **59** (7):1217-1232.



UNIVERSIDADE FEDERAL DO PARÁ
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA E GEOQUÍMICA

PARECER

Sobre a Defesa Pública da Tese de Doutorado de STELLA BIJOS GUIMARÃES

A banca examinadora da Tese de Doutorado de **STELLA BIJOS GUIMARÃES** orientanda do Prof. Dr. **Evandro Luiz Klein (CPRM)**, composta pelos professores doutores **Roberto Perez Xavier (Membro-UNICAMP)**, **Valmir da Silva Souza (Membro-UnB)**, **Jean Michel Lafon (Membro-UFPA)**, e **Marco Antonio Galarza (Membro-UFPA)**, após apresentação da sua tese intitulada "**GEOLOGIA E METALOGÊNESE DO DEPÓSITO Au-Ag (Pb-Zn) DO CORINGA, SUDESTE PROVINCIA MINERAL TAPAJÓS, PARÁ**", emite o seguinte parecer:

A candidata realizou sua apresentação de forma clara, bem organizada e segura no tempo estipulado. Na arguição mostrou domínio da temática abordada e respondeu às perguntas formuladas pela banca. O trabalho escrito foi apresentado na forma de três artigos, sendo dois já publicados e o terceiro em estágio avançado de revisão em periódico de impacto internacional. Dessa forma, o manuscrito atende às exigências para uma tese de doutorado.

Finalmente, a banca examinadora decidiu por unanimidade aprovar a tese de doutorado.

Belém, 16 de setembro de 2020.

Prof. Dr. Evandro Luiz Klein (Orientador – CPRM-PPGG)

Prof. Dr. Roberto Perez Xavier (Membro-UNICAMP)

Prof. Dr. Valmir da Silva Souza (Membro-UnB)

Prof. Dr. Jean Michel Lafon (Membro-UFPA)

Prof. Dr. Marco Antonio Galarza (Membro-UFPA)