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ALTERAÇÃO HIDROTERMAL E POTENCIAL METALOGENÉTICO DO VULCANO-PLUTONISMO PALEOPROTEROZOICO DA REGIÃO DE SÃO FÉLIX DO XINGU (PA), PROVÍNCIA MINERAL DE CARAJÁS

Dissertação apresentada por:

RAQUEL SOUZA DA CRUZ

Orientador: Prof. Dr. RAIMUNDO NETUNO NOBRE VILLAS (UFPA)

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DISSERTAÇÃO APRESENTADA POR

RAQUEL SOUZA DA CRUZ

Como requisito parcial à obtenção do Grau de Mestre em Ciências na Área de GEOLOGIA.

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Banca Examinadora:

Prof. Raimundo Netuno Nobre Villas
(Orientador- UFPA)

Prof. Régis Munhoz Krás Borges
(Membro - UFPA)

Prof. José Carlos Frantz
(Membro-UFRGS)

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Minha família, especialmente Emanuel e Lucas,
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“Há um tempo em que é preciso abandonar as roupas usadas,
que já tem a forma do nosso corpo, e
esquecer os nossos caminhos,
que nos levam sempre aos mesmos lugares.
É o tempo da travessia:
e, se não ousarmos fazê-la,
teremos ficado, para sempre,
à margem de nós mesmos.”
Fernando Pessoa

RESUMO

A região de São Félix do Xingu, centro-sul do Estado do Pará, expõe um sistema vulcano–plutônico excepcionalmente bem preservado e agrupado nas formações Sobreiro e Santa Rosa, nas quais foram reconhecidas alterações hidrotermais e mineralizações associadas. A Formação Sobreiro é constituída por fácies de fluxo de lava de composições andesítica, andesito basáltica e dacítica, conforme as proporções ou ausência de fenocristais de clinopiroxênio e/ou anfibólio. Fácies de rochas vulcanoclásticas ocorre geneticamente associada e é representada por tufos de cinza, cristais de tufo máfico, lapilli-tufo e brecha polimítica maciça. A Formação Santa Rosa é controlada por fissuras, formada por riolitos que compreendem fácies de fluxo de lava e fácies vulcanoclástica associada de tufos de cristais felsico, ignimbritos (tufo de cinza), lápilli-tufo, e brechas polimíticas maciças. Parte desse sistema é interpretado como *ash-flow caldera* parcialmente erodida e desenvolvida em vários estágios. Dados de petrografia, difração de raios X (DRX), microscopia eletrônica de varredura (MEV) e espectroscopia de infravermelho mostram as paragêneses de alterações hidrotermais que ocorrem nessas rochas. Em geral, os minerais de alteração desenvolvem cristais subeuédricos a anédricos e substituem minerais magmáticos. Os tipos de alterações hidrotermais identificados mostram-se incipientes a pervasivos, sendo distinguidas as alterações propilítica, sericítica, argílica e potássica, as quais se sobrepõem, além de fases fissurais de silicificação com hematita e carbonato associados. A alteração propilítica, predominante na Formação Sobreiro, apresenta ambos os estilos pervasivo e fissural. A paragênese resultante consiste de epidoto + clorita + carbonato + clinozoisita + sericita + quartzo ± albita ± hematita ± pirita, que é sobreposta por alteração potássica pervasiva ou controlado por fratura, representada principalmente por feldspato potássico + biotita ± hematita. Localmente, ocorre fratura com associação prehnita-pumpellyita precipitada que poderia estar relacionado com metamorfismo de baixo grau. A alteração sericítica é marcada pela ocorrência principalmente de sericita + quartzo + carbonato ± epidoto ± clorita ± muscovita. Manifesta-se principalmente nos tufos de cristais máficos. Entretanto, a sobreposição desses tipos de alteração fica evidenciada pelas relíquias de clorita da alteração propilítica e texturas das rochas, parcialmente obliteradas, em que restaram apenas pseudomorfos de plagioclásio sericitizado. Já na Formação Santa Rosa é pervasiva e caracterizada pela ocorrência de sericita + quartzo + carbonato. Apresenta-se também em estilo fissural, que é marcado pela presença de sericita + quartzo. É o principal tipo de alteração identificado nessa unidade, atribuindo às rochas coloração esbranquiçada. Dados de

MEV mostram que, associados à alteração sericítica, ocorrem fosfatos de chumbo e terras raras além de ouro, bem como rutilo e barita. A alteração potássica ocorre mais subordinadamente, em geral associada aos pórfiros graníticos e, localmente, aos riolitos. A paragênese característica é conferida por microclínio + biotita + clorita + carbonato + sericita ± albita ± magnetita. A alteração argílica intermediária foi reconhecida nos riolitos e possivelmente corresponde aos estágios finais da alteração hidrotermal. É caracterizada pela presença de montmorillonita + illita + caolinita + clorita ± sericita ± caolinita ± haloisita ± quartzo ± hematita, os quais foram identificados por DRX e espectroscopia de infravermelho. A argilização confere às rochas coloração esbranquiçada a rosa esbranquiçada. Os tipos de alteração foram controlados principalmente pela temperatura, composição do fluido e pela relação fluido/rocha. São compatíveis com anomalias térmicas relacionadas com o magma envolvendo uma diminuição da temperatura e neutralização devido à mistura com água meteórica, semelhante ao que foi descrito em mineralizações baixo e intermediário-sulfidação. A identificação de ouro e fases de acessórios compatíveis fornecem importantes subsídios para pesquisas prospectivas na região, sobretudo para potenciais depósitos epitermais *low-sulfidation* de metais preciosos (ouro e prata) em sistemas vulcano-plutônicos com *ash-flow calderas* associadas, assim como depósitos do tipo pórfiro de Cu, Au e Mo.

Palavras-chave: Alteração hidrotermal. Petrografia. SWIR. Vulcanismo. Cráton Amazônico

ABSTRACT

The region of Sao Felix do Xingu, south-central Pará, exposes a volcano-plutonic system exceptionally well preserved and grouped in the Sobreiro and Santa Rosa formations, in which hydrothermal alteration and mineralization associated were recognized. The Sobreiro Formation consists of lava facies flow of andesitic, basaltic andesite, and dacitic composition, according to the proportions or absence of clinopyroxene and/or amphibole phenocrysts. Volcaniclastic facies is genetically associated and is represented by mafic crystals tuff, lapilli-tuff, and massive polymictic breccia. Santa Rosa Formation is fissure-contolled and composed of lava flow facies and associated volcaniclastic facies of felsic crystal tuffs, ignimbrites, lapilli-tuff, and massive polymictic breccia. Part of this system is interpreted as ash-flow caldera partially eroded and developed in several stages. Conventional petrography, X-ray diffraction (XRD), scanning electron microscopy (SEM), and infrared spectroscopy show hydrothermal alteration paragenesis occurring in these rocks. In general, the alteration minerals develop subeuhedral anhedral crystals and replace magmatic minerals. The types of hydrothermal alteration identified are incipient the pervasive and are distinguished propylitic, sericitic, intermediate argillic, and potassic, which overlap, and fracture-controlled silicification associated with hematite and carbonate. Propylitic alteration, prevalent in Sobreiro Formation, presents both pervasive and fracture-controlled styles. The paragenesis consists of epidote + chlorite + carbonate + quartz + sericite + clinozoisite ± albite ± hematite ± pyrite, which is overlapped by pervasive potassic alteration or fracture-controlled, mainly represented by potassic feldspar + biotite ± hematite. Locally, fracture is filling with prehnite-pumpellyite association that suggests geothermal low-grade metamorphism conditions. The sericitic alteration is marked by the occurrence of mainly sericite + quartz + carbonate ± epidote ± chlorite ± muscovite. It is manifested mainly in mafic crystal tuff. However, the overlap of these types of changes is evidenced by relics of propylitic chlorite alteration and textures of rocks, partially obliterated, in which there were only pseudomorphs of sericitized plagioclase. In the Santa Rosa Formation the sericitic alteration is pervasive and characterized by the occurrence of sericite + quartz + carbonate. Also presents fracture-controlled, which is represented by sericite + quartz. It is the main type of change identified in this unit by assigning the whitish rocks. SEM data show that, associated with the sericitic alteration occur lead phosphate, gold, rutile, and barite. The potassic alteration is more subordinate, generally associated with granitic porphyry and locally to rhyolites. Paragenesis is given by microcline + biotite + chlorite + carbonate + sericite ± albite ± magnetite. The intermediate argillic alteration was recognized in rhyolites and possibly corresponds to the final stages of hydrothermal alteration. It is characterized by the presence of montmorillonite + illite + chlorite + sericite ± kaolinite ± halloysite ± quartz ± hematite, which were identified by infrared spectroscopy and XRD. It gives whitish to whitish pink to the rocks. The hydrothermal alteration types were mainly controlled by temperature, fluid composition, and fluid/rock ratios. They are compatible with thermal anomalies related to magma, and possible temperature decrease due to mixing and neutralization with meteoric water, similar to that described in low- and intermediate-sulfidation mineralization. Gold identification and compatible accessories phases provide important information for prospective studies in the region, especially for potential intermediate- and low-sulfidation epithermal deposits of precious metals (gold and silver) in volcano-plutonic systems with related ash flow calderas, as well the Au(Cu) and Mo porphyry-type deposits.

Keywords: Hydrothermal alteration. Petrography. SWIR. Volcanism. Amazonian Craton.

APRESENTAÇÃO

Esta dissertação foi elaborada no Programa de Pós-Graduação em Geologia e Geoquímica da Universidade Federal do Pará (PPGG), e foi organizada em capítulos, abaixo destacados. Os principais resultados alcançados neste trabalho compõem dois artigos científicos, que foram submetidos à publicação em periódicos especializados.

Do **Capítulo 1** constam a introdução, localização da área estudada, justificativa e objetivos. É também descrito o contexto geotectônico no qual as rochas de São Félix do Xingu estão inseridas. Por fim, são descritos os procedimentos metodológicos que foram aplicados para o desenvolvimento da dissertação.

O **Capítulo 2** é constituído pelo artigo intitulado "*A study of the hydrothermal alteration in Paleoproterozoic volcanic centers, São Félix do Xingu region, Amazonian Craton, Brazil, using short-wave infrared spectroscopy*" submetido para publicação no periódico *Journal of Volcanology and Geothermal Research*.

O **Capítulo 3** é constituído pelo artigo intitulado "*Metallogenetic significance of the hypogene alteration associated with the Paleoproterozoic volcanism of the Sao Felix do Xingu region, Amazonian Craton, Brazil*", o qual será submetido para Geologia USP – Série Científica.

No **Capítulo 4** são apresentadas as conclusões obtidas neste trabalho, o qual buscou contribuir para a evolução do conhecimento geológico da região de São Félix do Xingu e do Cráton Amazônico.

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CAPÍTULO I

1 INTRODUÇÃO

Na região do município de São Félix do Xingu, centro–sul do Estado do Pará, SE do Cráton Amazônico (Almeida *et al.* 1981), ocorrem extensos centros vulcano–plutônicos efusivos e explosivos paleoproterozoicos, representados pelas formações Sobreiro e Santa Rosa (Juliani & Fernandes 2010).

A Formação Sobreiro (~1,88 Ga) contém fácies de fluxo de lava de composições andesítica, andesito-basáltica e dacítica, bem como fácies vulcanoclástica geneticamente relacionada de tufos de cinza, vítreos e de cristais, as quais mostram assinatura geoquímica cálcio-alcalina de alto potássio e afinidade com granitoides de arco magmático. Por seu turno, a Formação Santa Rosa (~1,87 Ga) tem composição predominantemente riolítica (*lato sensu*), com domos de lava e vários tipos de rochas vulcanoclásticas associadas (Figura 1), e revela assinatura geoquímica de granitoides do tipo-A intraplaca extremamente evoluídos e silicosos, cuja evolução policíclica foi predominantemente controlada por grandes fissuras crustais orientadas segundo a direção NE–SW e, subordinadamente, NW–SE (Juliani & Fernandes 2010, Fernandes *et al*. 2011).

Trabalhos de campo sistemáticos desenvolvidos na região permitiram reconhecer halos de alteração hidrotermal nessas unidades vulcânicas, com evidência de ocorrência aurífera. Contudo, apesar da evolução do conhecimento a respeito da caracterização química, bem como da elaboração de modelos de erupção dos magmas que geraram esses litotipos, a alteração hidrotermal ainda não foi adequadamente descrita. Além disso, a alteração é considerada importante marcador para a identificação e hospedagem de depósitos epitermais de baixa e alta sulfidização de metais raros (ouro, prata, cobre, etc.) em sistemas vulcano–plutônicos, a exemplo da ocorrência descrita na Província Aurífera do Tapajós, a qual se encontra intimamente associada ao desenvolvimento de um conjunto de *ash-flow calderas* aninhadas (Juliani *et al.* 2005).

Este trabalho visou à realização de um estudo mais detalhado acerca dos tipos e estilos de alteração hidrotermal identificados nas formações Sobreiro e Santa Rosa, bem como à avaliação do potencial metalogenético dessas unidades, especialmente para depósitos epitermais.

2 **CONTEXTO GEOTECTÔNICO**

O Cráton Amazônico (Almeida *et al*. 1981) representa uma das maiores áreas pré-cambrianas do mundo. Está situado na região norte do Brasil e é constituído pelos escudos das Guianas e Brasil Central, separados pela cobertura sedimentar das Bacias do Amazonas e Solimões (Caputo *et al*. 1972).

A evolução do Cráton Amazônico foi associada por Amaral (1974) a uma plataforma arqueana retrabalhada por intenso plutonismo e vulcanismo anorogênico no Paleoproterozoico, conhecido como magmatismo Uatumã. Cordani (1979), com base em dados geocronológicos, a relacionou a arcos magmáticos insulares amalgamados ao redor de um núcleo arqueano. Estudos posteriores levaram à distinção de diversas províncias geocronológicas (Tassinari & Macambira 1999, 2004, Santos *et al*. 2000), apoiada em dados geocronológicos robustos e de geoquímica isotópica, que indicam fontes juvenis para as rochas dos terrenos paleoproterozoicos.

No arranjo proposto por Tassinari & Macambira (1999, 2004), o cráton é dividido em seis províncias geocronológicas, a saber: Amazônia Central (> 2.2 Ga), Maroni-Itacaiúnas (2.2–1.95 Ga), Ventuari-Tapajós (1.95–1.8 Ga), Rio Negro-Juruena (1.8–1.55 Ga), Rondoniana-San Ignácio (1.55–1.3 Ga) e Sunsás (1.3–1.0 Ga). Por seu turno, Santos *et al*. (2000) subdividem o Cráton Amazônico em sete províncias geocronológicas, com limites consideravelmente distintos da proposta anterior, anotando-se como principais diferenças a adição da Província Carajás, a designação de Província Transamazônica no lugar de Província Maroni-Itacaiúnas, a redefinição da Província Tapajós-Parima (Ventuari-Tapajós), a divisão da Província Rio Negro-Juruena nas províncias Rio Negro (englobando a região de Ventuari) e Rondônia-Juruena e, por fim, a ampliação da Província Sunsás.

A integração dos dados geológicos, geocronológicos, petrológicos (rochas ígneas félsicas e intermediárias), litoquímicos, geofísicos orbitais e aerotransportados, e metalogenéticos, até então somente disponíveis para a porção sul do Cráton Amazônico, indicou a existência de um zoneamento metalogenético, o qual se formou há aproximadamente 2,0–1,88 Ga na região compreendida entre o gráben da Serra do Cachimbo e São Félix do Xingu (Juliani *et al*. 2009, Fernandes *et al*. 2011). Além disso, Juliani *et al*. (2013) defendem que a geração e evolução tectono-magmática dos terrenos paleoproterozoicos na parte sul do Cráton Amazônico sendo esta formada por pelo menos dois arcos magmáticos continentais, denominados Arcos Tapajônicos, um mais antigo (2,13 –

1,95 Ga), predominantemente na parte sul, e outro mais novo (1,89 – 1,87 Ga) superposto, na parte norte, ambos orientados na direção E-W.

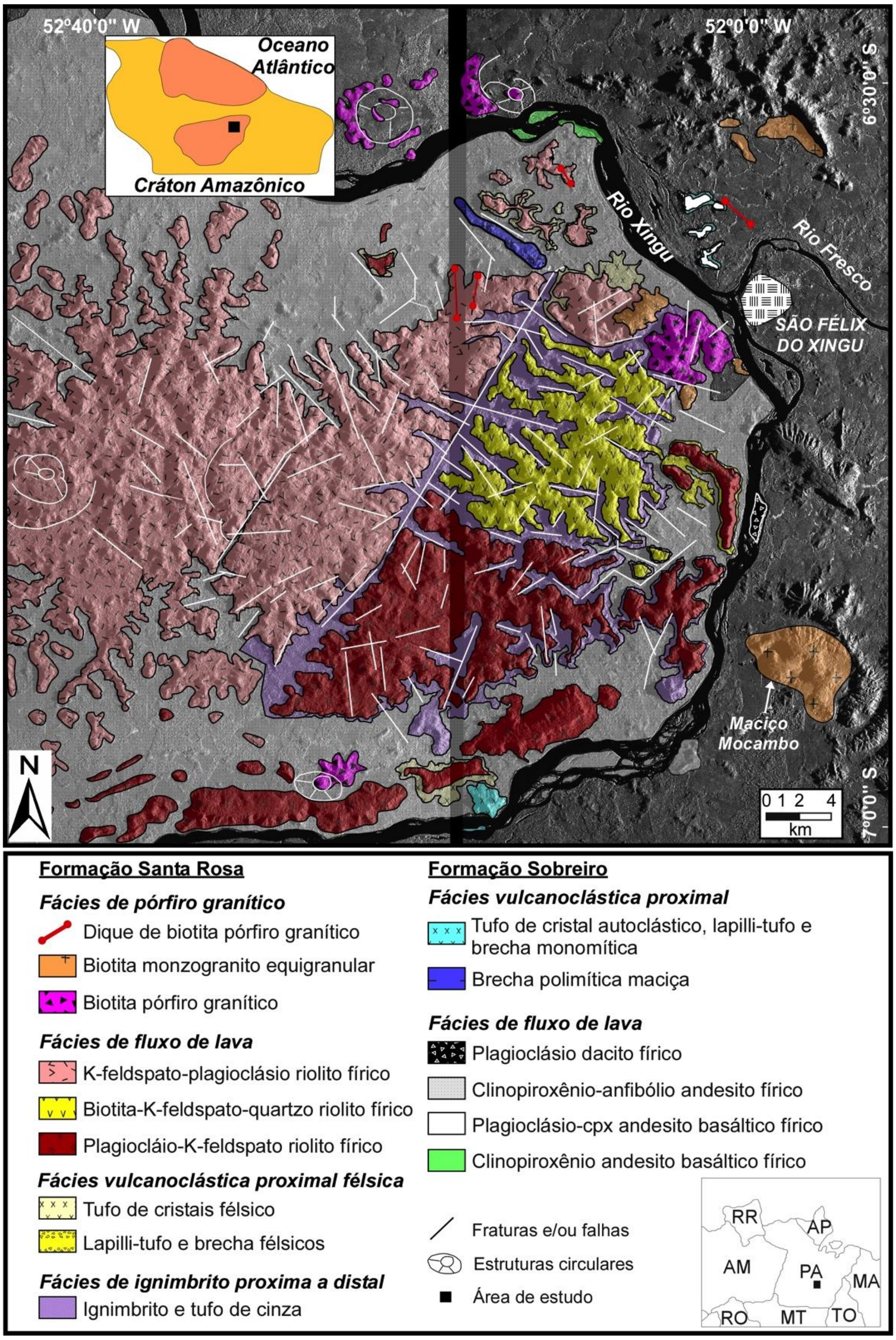

Figura 1 – Geologia da região de Santa Rosa (São Félix do Xingu) mostrando a distribuição das formações Sobreiro e Santa Rosa.
Fonte: (Juliani & Fernandes 2010).

3 **LOCALIZAÇÃO E ACESSO À ÁREA**

A região de São Félix do Xingu está localizada no centro–sul do Cráton Amazônico e o acesso terrestre é feito pela rodovia BR-155, partindo de Belém até o município de Xinguara, a partir de onde se segue pela PA-279 até São Félix do Xingu (Figura 2).

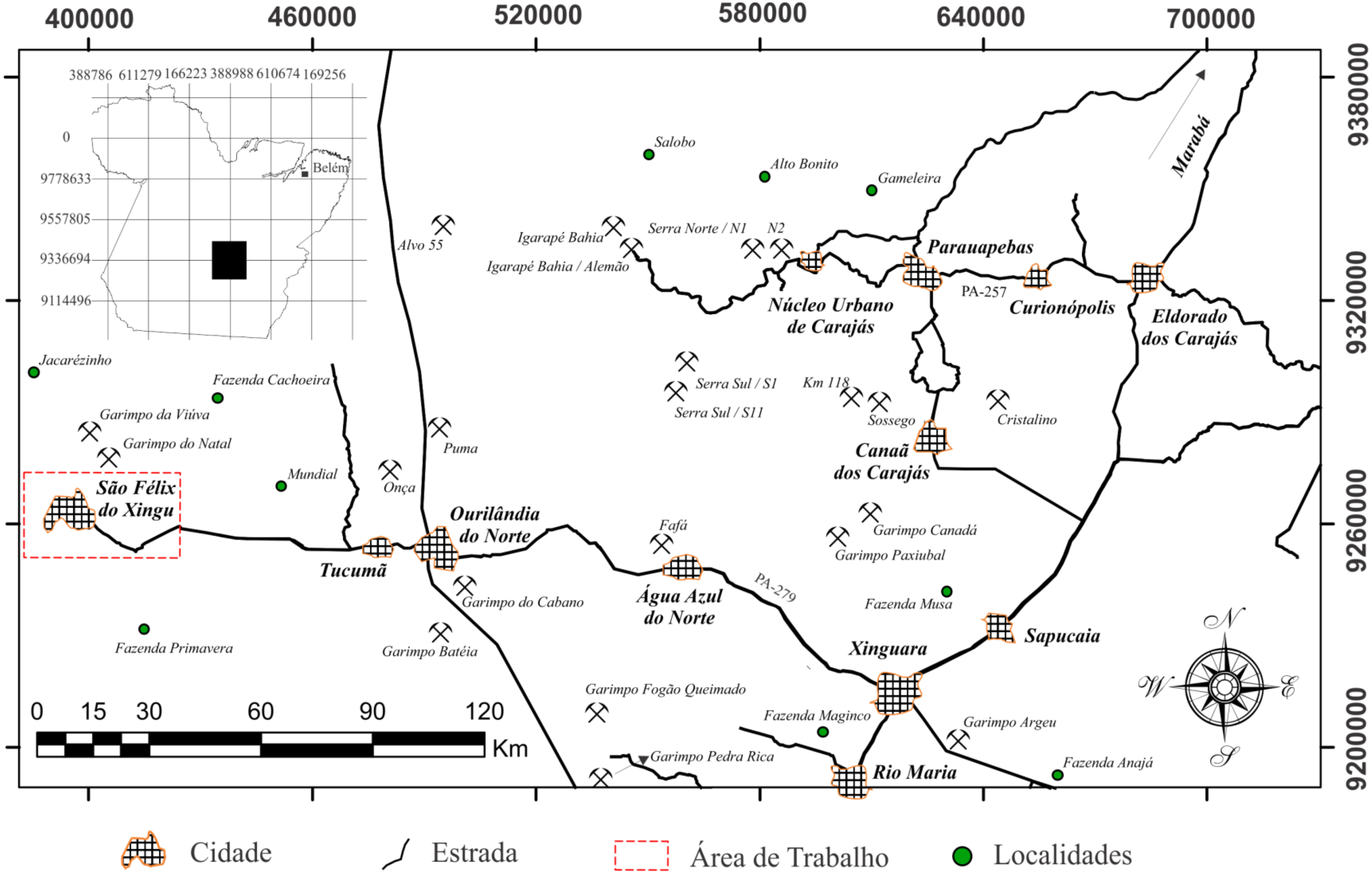

Figura 2 - Mapa de localização e acesso à região de São Félix do Xingu.
Fonte: Modificado de Vasquez *et al.* (2008).

4 TRABALHOS ANTERIORES

As associações vulcano–plutônicas paleoproterozoicas que ocorrem no Cráton Amazônico são agrupadas de maneira geral no magmatismo do tipo Uatumã. O magmatismo *sensu lato* Uatumã é caracterizado por manifestações vulcânicas efusivas e explosivas, de composição intermediária a ácida, representado por andesito basáltico, andesito, dacito, riodacito, riolito, quartzo latito, traquito tufos e ignimbritos de afinidade cálcio-alcalina e, subordinadamente, alcalina. Devido à grande extensão desse vulcanismo, são dadas denominações diferentes para as unidades geológicas de acordo com sua área de ocorrência (Figura 3). Na região próxima à São Félix do Xingu, as unidades vulcânicas pertencem ao Grupo Uatumã (Macambira & Vale 1997); na região do rio Tapajós, estas unidades pertencem ao Grupo Iriri (Pessoa *et al.* 1977); ao norte de Manaus, correspondem ao Grupo Iricoumé (Oliveira *et al.* 1975); e, por fim, no estado de Roraima, são enfeixadas no Grupo Surumu (Montalvão *et al.* 1975).

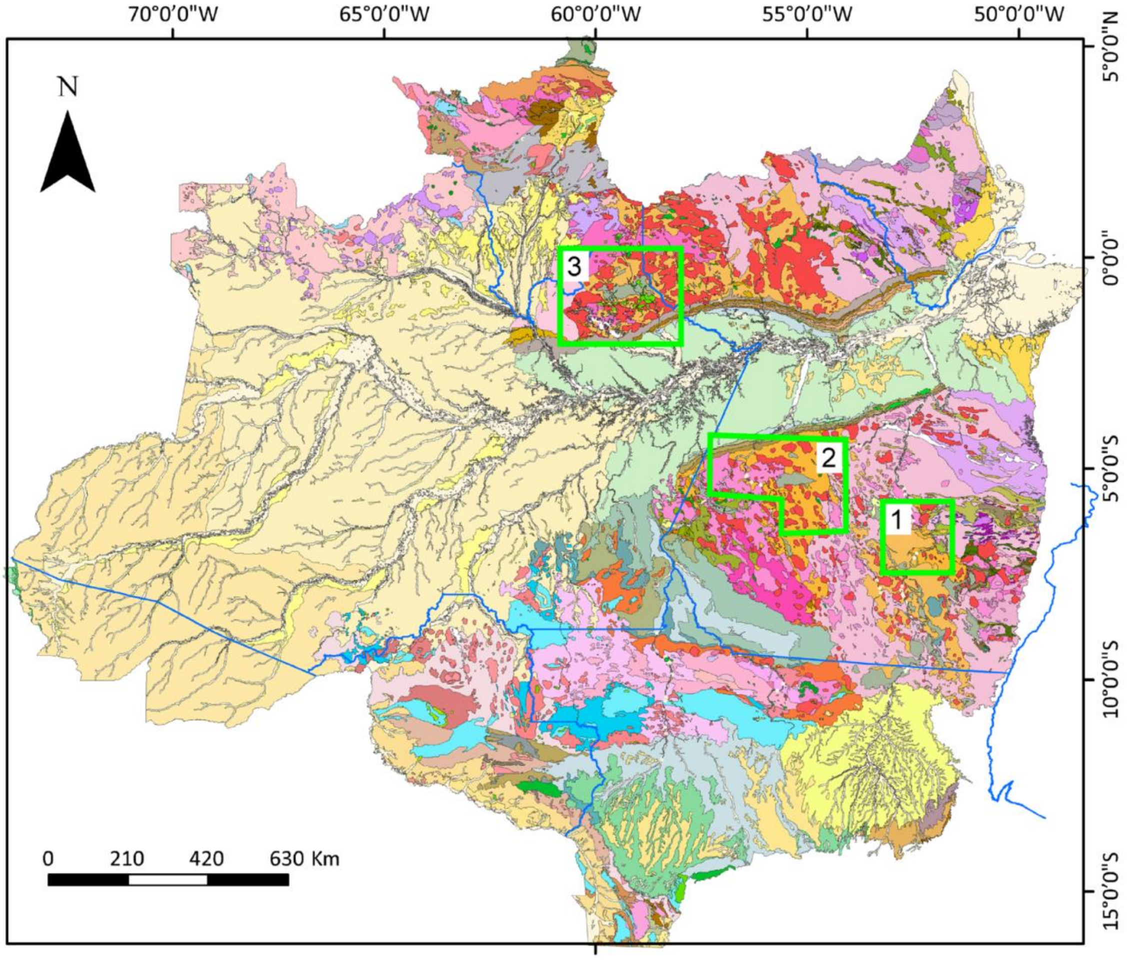

Figura 3 – Mapa geológico do Cráton Amazônico, com destaque para ocorrência de alguns correlatos do vulcanismo Uatumã (*lato sensu*). 1 – Grupo Uatumã em São Félix do Xingu; 2 – Grupo Iriri na Província Aurífera do Tapajós; e 3 – Grupo Iricoumé na Província Estanífera de Pitinga.
Fonte: (Bizzi *et al.* 2003)

Na região de São Félix do Xingu, Macambira & Vale (1997) diferenciaram uma associação formada por vulcanismo intermediário com predominância de diques e derrames de andesito, referentes à Formação Sobreiro, e um conjunto de rochas vulcânicas ácidas, com predominância de diques de riolito, agrupados na Formação Iriri, ambas constituindo o Grupo Uatumã.

Teixeira *et al.* (1998) obtiveram em andesitos e riolitos do Grupo Uatumã idade de referência Pb-Pb em rocha total de 1875 ± 79 Ma. Teixeira *et al.* (2002) caracterizaram a Formação Sobreiro como cálcio-alcalina, metaluminosa e com peculiaridades anorogênicas, originadas em paleoambiente cratônico continental. Para a Formação Iriri, estes autores atribuem natureza cálcio-alcalina de alto potássio, e de ambiência continental e intraplaca. Teixeira *et al.* (2003) sugeriram a existência de um domo ou de uma caldeira vulcânica durante a origem das formações Sobreiro e Iriri.

Fernandes *et al.* (2006) diferenciaram um vulcanismo bimodal, proveniente de fontes vulcânicas distintas na região, ocorrido entre o final de um evento orogênico e o início de uma fase de *rift* intracontinental. A Formação Sobreiro foi caracterizada como cálcio-alcalina de alto potássio, metaluminosa e com afinidade geoquímica de geração em arco vulcânico, enquanto que a Formação Iriri foi classificada como subalcalina a alcalina, metaluminosa a peraluminosa e com afinidade geoquímica com rochas formadas em ambiente intraplaca.

Pinho *et al.* (2006) realizaram datações Pb-Pb em zircão de maciços granitoides relacionados à Suíte Intrusiva Velho Guilherme e vulcanitos da Formação Sobreiro. Os maciços Serra da Queimada, Santa Rosa e Porfirítico de Vila Santa Rosa revelaram idades de 1882 ± 12 Ma, 1888 ± 3 Ma e 1881 ± 3 Ma, respectivamente. Fernandes *et al.* (2008) denominaram de Formação Santa Rosa as rochas vulcânicas e vulcanoclásticas originalmente definidas como Formação Iriri, pois esta era muitas vezes correlacionada ao Grupo Iriri na Província Aurífera do Tapajós, de características geoquímicas distintas. Além das rochas vulcânicas e vulcanoclásticas descritas anteriormente, foi reconhecida ainda uma fácies subvulcânica representada por pórfiros petrográfica e quimicamente semelhantes à Formação Santa Rosa.

Lagler *et al.* (2009) identificaram, na região de Vila Tancredo Neves, NE de São Félix do Xingu, nas rochas da Formação Sobreiro, diferentes graus de alteração hidrotermal, com propilitização e sericitização incipientes. Na Formação Santa Rosa, variados estilos de alteração hidrotermal sericítica do tipo QSP (quartzo + sericita + pirita) são comuns, além de zonas de metassomatismo potássico ao redor de intrusões de pórfiros graníticos.

Juliani & Fernandes (2010) enfatizaram a relação entre o vulcano–plutonismo Uatumã e o episódio distensivo paleoproterozoico que se estende até o Mesoproterozoico, com vulcanismo bimodal, enxames de diques e bacias tafrogênicas associadas (Brito Neves 1999). Para a Formação Sobreiro, aqueles autores destacaram que o ambiente tectônico ainda não é bem conhecido, pois, embora a assinatura geoquímica cálcio-alcalina de alto potássio a shoshonítica sugira um magmatismo de arco vulcânico maturo a pós-orogênico, nenhuma evidência de subducção foi encontrada nas proximidades de São Félix do Xingu. Já para a Formação Santa Rosa, Juliani & Fernandes (2010) sugeriram um modelo geológico de erupções alimentadas por fissuras crustais profundas, com 1) geração de batólitos em câmaras magmáticas profundas, 2) faturamento das rochas encaixantes permitindo a ascensão do magma para níveis crustais mais rasos, 3) intensa atividade explosiva, com geração de produtos vulcanoclásticos e posteriormente vulcanismo representado por domos de lava e 4) colocação de *stocks* e diques de pórfiros graníticos e maciços granitoides tardios, com atividade hidrotermal significativa.

Fernandes *et al.* (2011) concluíram que a Formação Sobreiro e a Formação Santa Rosa não são comagmáticas, embora com idades próximas, devido à: 1) abundância espacial e estilos distintos de erupção; 2) processos de diferenciação diferentes, dados pelas mudanças sistemáticas nas assembleias de fenocristais; 3) presença comum de fenocristais zonados nas rochas da Formação Sobreiro e de fenocristais não zonados na Formação Santa Rosa; 4) lacuna composicional de SiO_2 entre as duas unidades; 5) *trends* de diferenciação observados em diagramas de variação de elementos traços incompatíveis *versus* compatíveis; e 6) clara correlação negativa de Ni *versus* Rb para as rochas da Formação Sobreiro. Propuseram para a Formação Sobreiro um modelo de *flat-subduction*, em contrapartida a um magmatismo cálcio-alcalino intracontinental sem relação com subducção. Esse modelo estaria relacionado a uma zona de subducção de orientação geral E–W com início na região do Tapajós, onde mudanças no ângulo de subducção da placa fizeram com que esta se locomovesse quase que horizontalmente por centenas de quilômetros sob a crosta continental, causando a migração do arco magmático para regiões mais distais, no caso a região de São Félix do Xingu.

Por fim, Cruz *et al.* (2014) propuseram, com base em dados mineralógicos, características químicas e geotermobarometria dos fenocristais de clinopiroxênio, anfibólio e feldspatos de rochas das diferentes fácies da Formação Sobreiro, que elas indicam uma evolução magmática polibárica relacionada a arco magmático continental em condições altamente oxidantes e oscilantes, as quais permaneceram até a total solidificação da lava em superfície. Por sua vez, os dados químicos dos feldspatos da Formação Santa Rosa confirmam fontes dominantemente crustais para os seus litotipos e seu caráter extremamente evoluído, corroborando com sua assinatura geoquímica intraplaca e sua correlação com o magmatismo anorogênico que está bem registrado em praticamente todo o Cráton Amazônico.

5 **JUSTIFICATIVA**

A Província Mineral de Carajás tem uma função estratégica para o estado do Pará e para o Brasil, pois abriga em seu subsolo importantes depósitos minerais de ferro, cobre, zinco, níquel, alumínio, ouro, manganês, estanho, platinoides, entre outros. A Província Aurífera do Tapajós é outro exemplo de importância econômica no Cráton Amazônico, onde se explotaram oficialmente mais de 200 toneladas de ouro até 1997 (Faraco *et al*. 1997), tanto aluvionar como coluvionar. Com o avanço das pesquisas sistemáticas na região, foram identificadas mineralizações epitermais (baixa e alta sulfidização) paleoproterozoicas em vulcânicas félsicas cálcio-alcalinas do Grupo Iriri (Nunes *et al.* 2001, Juliani *et al*. 2005), até hoje as mais antigas do mundo, assim como, mais recentemente, pórfiros auro-cupríferos (Misas 2010), abrindo dessa forma novos horizontes para a exploração mineral nesta parte do Cráton.

Entretanto, diversas áreas desta megaunidade tectônica ainda são pouco conhecidas e não mereceram trabalhos mais detalhados e consistentes focados em alteração hidrotermal, visando à formulação de modelos metalogenéticos que possam ser testados pela indústria mineral. Em razão disso, é necessário nessa região:

- ✓ Continuidade de mapeamento geológico; estudos petrográficos e mineralógicos de zonas hidrotermalizadas associadas às formações Sobreiro e Santa Rosa, já que as mesmas são indicadoras da existência de possíveis depósitos minerais;
- ✓ A relação dessas zonas de alterações hidrotermais com o modelo de evolução geológica das unidades vulcânicas. A identificação de caldeiras na Província Aurífera do Tapajós indica que não deve haver continuidade lito e cronoestratigráfica entre as unidades vulcânicas das diferentes regiões do Cráton Amazônico, ou até mesmo em uma única província geológica. Isso se deve ao processo de formação e evolução de um complexo de caldeiras continental (Lipman 1984).
- ✓ A formação de recursos humanos capacitados para a caracterização estratigráfica, petrogenética e metalogenética de sequências vulcânicas félsicas, em especial as que ocorrem no Cráton Amazônico.

6 **OBJETIVOS**

Com base no que foi exposto acima, pretendeu-se com este trabalho aprofundar o conhecimento sobre os vários litotipos vulcano–plutônicos hidrotermalmente alterados que ocorrem na região de São Félix do Xingu, com vista a avaliar seu potencial metalogenético, em especial para depósitos epitermais baixa e alta sulfidização de metais preciosos (ouro e prata) ou de base (cobre), a exemplo da ocorrência descrita na Província Aurífera do Tapajós, a qual se encontra intimamente associada ao desenvolvimento de um conjunto de *ash flow calderas* (cf. Lipman 1984). Em razão disso, os objetivos específicos desta pesquisa foram:

- ✓ Caracterização dos diversos tipos vulcânicos hidrotermalizados associados às formações Sobreiro e Santa Rosa, bem como das fases acessórias muito finas e óxidos de Fe e Ti;
- ✓ Identificação e caracterização detalhada das zonas ou halos de alteração hidrotermal, que servem como indicadores de potenciais depósitos minerais;

7 **PROCEDIMENTOS METODOLÓGICOS**

7.1 PESQUISA BIBLIOGRÁFICA

Realizaram-se levantamentos bibliográficos sobre a geologia da área proposta para os estudos, bem como em relação aos diversos temas abordados durante o desenvolvimento do trabalho, por meio de consultas ao Portal de periódicos da CAPES e consulta ao acervo da biblioteca da UFPA.

7.2 AMOSTRAGEM

Neste trabalho foram utilizadas amostras coletadas para os projetos desenvolvidos na região de São Félix do Xingu pelo co-orientador Carlos Marcello Dias Fernandes. Contudo, no período de 05 a 16 de junho de 2011 foi realizada outra etapa de campo, na qual foram coletados dados e amostras utilizadas tanto para o trabalho de conclusão de curso da autora deste trabalho, quanto para o desenvolvimento desta dissertação.

7.3 PETROGRAFIA

A partir de estudos petrográficos mesoscópicos, selecionaram-se amostras representativas das rochas vulcânicas para petrografia microscópica. O estudo de lâminas delgadas envolveu descrições mineralógicas detalhadas e análises texturais de 200 lâminas, conforme recomendações de Williams *et al.* (1962), Fisher & Schmincke (1984), McPhie *et al.* (1993), Gifkins *et al.* (2005), com vista (a) ao reconhecimento das fases minerais, suas relações de contato, formas e dimensões, presença de inclusões, intercrescimentos (exsolução e substituição) e (b) à caracterização de paragêneses (magmáticas e hidrotermais).

7.4 DIFRAÇÃO DE RAIOS X

As análises qualitativas de difração de raios X (DRX) foram empregadas como forma complementar à identificação petrográfica de alguns minerais muito finos e argilo–minerais, comuns em algumas fácies da alteração hidrotermal.

Essas análises foram executadas em difratômetro modelo *X´Pert Pro MPD* (PW 3040/60) PANalytical, com goniômetro PW3050/60 (teta/teta), e com tubo de raios X cerâmico de ânodo de Cu ($K\alpha1$ = 1,540598Å) modelo PW3373/00, foco fino longo, filtro $K\beta$ de Ni, detector X’Celerator RTMS (*Real Time Multiple Scanning*) no modo *scanning* e com *active length* 2,122º. Consistiram nas seguintes condições instrumentais: varredura 5° a 75° em 2θ, 40 kV, 40 mA, passo 0,02° em 2θ e tempo/passo 5s, fenda divergente 1/2º e anti-espalhamento 1º, máscara 10 mm, movimento da amostra *spinning*, com 1 rps.

A aquisição de dados foi feita com o *software X'Pert Data Collector*, versão 2.1a, e o tratamento dos dados com o *software X´Pert HighScore* versão 2.1b. A identificação das fases minerais baseou-se em comparações com as fichas do banco de dados do *International Center for Diffraction Data - Powder Diffraction File* (ICDD-PDF). A referida fase do trabalho foi realizada no Laboratório de Caracterização Mineral do Instituto de Geociências da UFPA, coordenado pelo professor Rômulo Simões Angélica.

7.5 ESPECTROSCOPIA DE INFRAVERMELHO

As assinaturas espectrais foram obtidas de um conjunto de 55 rochas alteradas hidrotermalmente usando um espectro radiômetro portátil ASD *FieldSpec* 4. Este é um tipo de sensor capaz de medir o comportamento da luz analisando os comprimentos de onda do espectro visível, e a faixa do infravermelho até 2500 nm. O espectro radiômetro portátil ASD *FieldSpec* 4 é constituído por cabos de fibra óptica protegida e flexível, o que ajuda na captura de mais espectros, além de auxiliar no controle do instrumento. Possui uma sonda de contato de alta intensidade de iluminação com *spot size* de 10 mm a qual é recomendada para caracterização de minerais de exploração. Ademais, é constituído de painéis de referência para calibração branco e cinza, de tamanhos variados, tendo sido utilizado neste trabalho o painel de 6 x 6 cm. As análises foram efetuadas no Instituto de Geociências da Universidade de São Paulo (USP), sob a supervisão dos professores Teodoro Isnard Ribeiro de Almeida e Caetano Juliani.

O processamento dos dados foi realizado a partir dos *softwares ViewSpecPro* 6.0 e *ENVI* 4.7. A livraria espectral mineral do *United State Geological Survey* (*USGS*) foi usada para análise comparativa e classificação espectral, identificando-se assim as fases minerais presentes nas rochas estudadas.

7.6 MICROSCOPIA ELETRÔNICA DE VARREDURA

A caracterização das fases minerais acessórias foi complementada por estudos em microscópio eletrônico de varredura (MEV) com EDS (Energy Dispersive Spectroscopy) acoplado. Esta etapa foi realizada no Laboratório de Microscopia Eletrônica de Varredura (LABMEV) do Instituto de Geociências da UFPA, coordenado pelo professor Claudio Nery Lamarão, utilizando-se microscópio eletrônico LEO-ZEISS, modelo 1430. Contudo, análises também foram realizadas no laboratório da CPRM sob supervisão do pesquisador Marcelo Vasquez.

CAPÍTULO II

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ELSEVIER

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Raquel Souza da Cruz [a], Carlos Marcello Dias Fernandes [a,*], Raimundo Netuno Nobre Villas [a], Caetano Juliani [b], Lena Virgínia Soares Monteiro [b], Teodoro Isnard Ribeiro de Almeida [b], Bruno Lagler [b], Cleyton de Carvalho Carneiro [c], Carlos Mario Echeverri Misas [b]

[a] Geoscience Institute, Federal University of Pará, Brasil
[b] Geoscience Institute, São Paulo University, Brasil
[c] Polytechnic School, São Paulo University, Brasil

A study of the hydrothermal alteration in Paleoproterozoic volcanic centers, São Félix do Xingu region, Amazonian Craton, Brazil, using short-wave infrared spectroscopy

Raquel Souza da Cruz[1], Carlos Marcello Dias Fernandes[1,*], Raimundo Netuno Nobre Villas[1], Caetano Juliani[2], Lena Virgínia Soares Monteiro[2], Teodoro Isnard Ribeiro de Almeida[2], Bruno Lagler[2], Cleyton de Carvalho Carneiro[3], Carlos Mario Echeverri Misas[2]

[1]Geoscience Institute, Federal University of Pará, [2]Geoscience Institute, São Paulo University, [3]Polytechnic School, São Paulo University

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*Corresponding author:
Carlos Marcello Dias Fernandes
Faculdade de Geologia, Instituto de Geociências, Universidade Federal do Pará
Rua Augusto Corrêa 1, CEP 66075-110, Belém–PA, Brasil
Telephone: +55 (91)3201-7107
Fax: +55 (11)3201-7609
E-mail: cmdf@ufpa.br

Abstract

Hypogene hydrothermal minerals have been identified by short-wave infrared spectroscopy in hydrothermally altered rocks from the Sobreiro and Santa Rosa formations, which belong to a Paleoproterozoic volcano–plutonic system in Amazonian craton. Three clay minerals are spectrally recognized: montmorillonite, kaolinite, and illite. The integration of these data with those available in the literature, including gold occurrences, suggests that those rocks are hydrothermal products of both volcanic thermal sources and later crustal intrusions, as evidenced by variable styles of propylitic, sericitic, potassic, and intermediate argillic alteration. The influence of meteoric fluids is emphasized. This low cost exploratory technique, which can be applied to hand samples, seems to be promising in the separation of hydrothermally altered volcano–plutonic centers in regions submitted to severe weathering conditions, in addition to aid elaborating models for prospecting mineral deposits.

Keywords: Infrared spectroscopy; Hydrothermal alteration; Gold; Clay minerals; Volcanism; Amazonian craton

1 **INTRODUCTION**

The Amazonian craton (Almeida *et al*. 1981) experienced an extensive intermediate to acid magmatism related to a Paleo- to Mesoproterozoic volcano–plutonic event. This event has been historically known as Uatumã (Juliani & Fernandes 2010, Pessoa *et al*. 1977) and resulted in the formation of magmatic units outcropping in an area of over 1,500,000 km^2, constituting a Large Igneous Province (Klein *et al*. 2013), according to the concept of Coffin and Eldholm (1994). Both volcanic and plutonic rocks display exceptionally well-preserved textures and structures showing that they were not affected by the tectono-metamorphic Trans-Amazonian cycle (Hurley *et al*. 1967) and other later orogenic events related to Paleoproterozoic evolution of the southern portion (Fig. 1) of the Amazonian craton (Fernandes *et al*. 2011, Juliani *et al*. 2014).

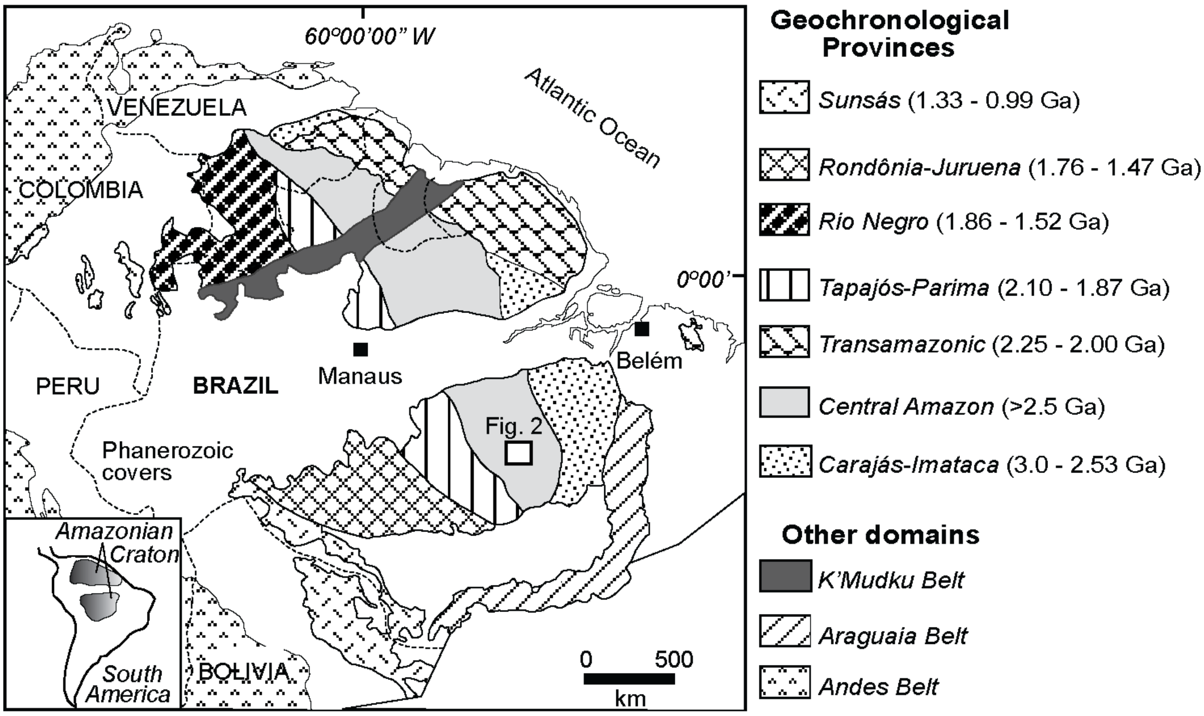

Figure 1 – Main geochronological provinces of the Amazonian craton, according to Santos *et al*. (2000). The square marks the location of the São Félix do Xingu region whose geological map is shown in Fig. 2.

In the São Félix do Xingu region, located in the Carajás Mineral Province, SE of the Pará state (Fig. 2), this volcano–plutonic event is represented by preserved effusive and explosive Paleoproterozoic volcanic, sub-volcanic, and plutonic rocks grouped in the 1880 Ma lower Sobreiro Formation and in the 1879 Ma upper Santa Rosa Formation. The Sobreiro Formation comprises high-K calc-alkaline andesites, dacites, monomitic breccias, volcanic agglomerate, lapilli-tuff, and mafic crystal tuffs, whereas the latter includes A-type rhyolites, granitic porphyries, equigranular granitoids, and several volcaniclastic rocks. These units are geological, geochronological, and petrologically distinct (Fernandes *et al*. 2011, Juliani & Fernandes 2010).

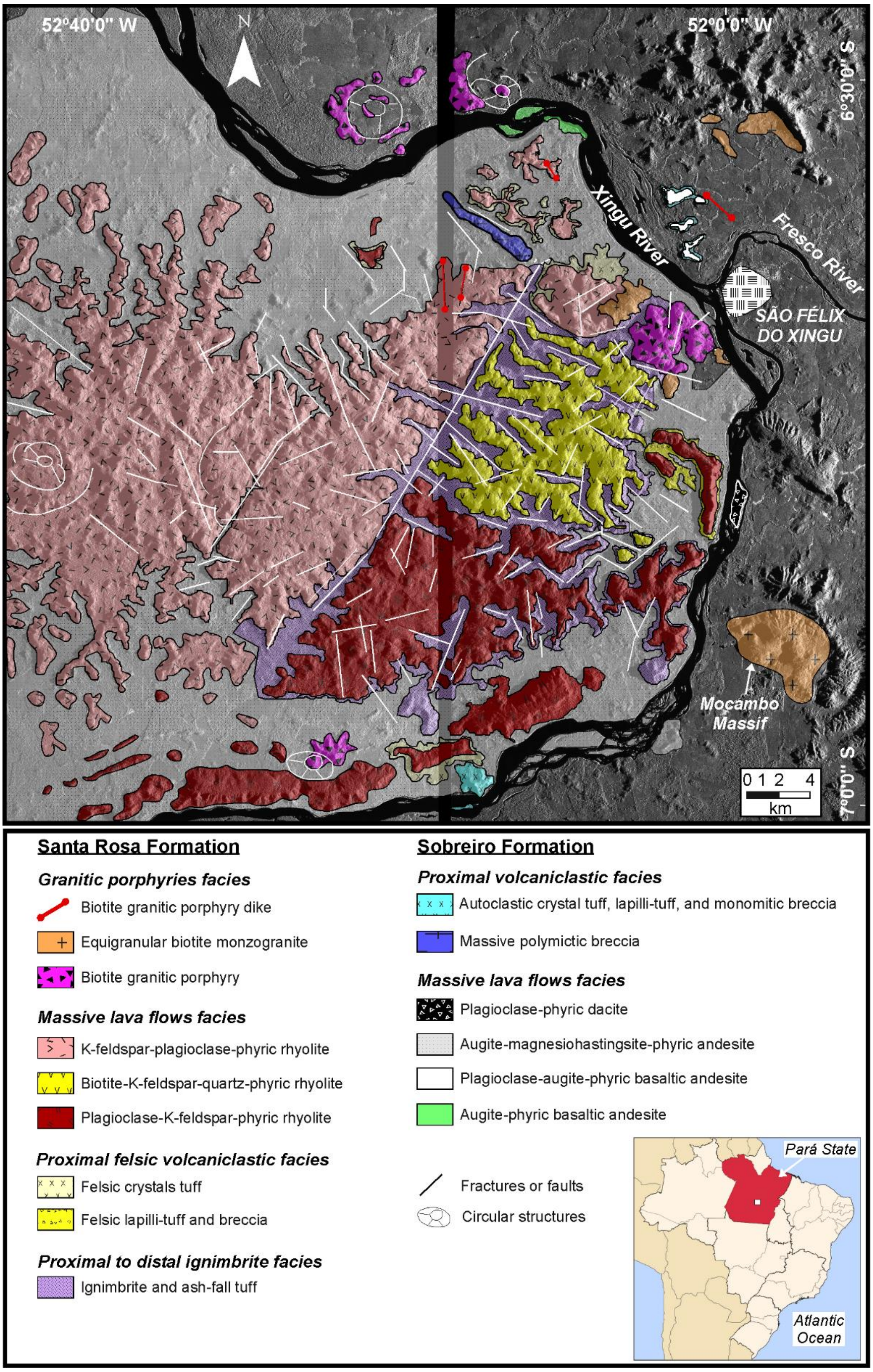

Figure 2 – Geological map of the São Felix do Xingu region (Pará State).
Modified from Juliani & Fernandes 2010.

In recent years, most of the research work in the São Félix do Xingu volcanic sequences has been focused primarily on their geological evolution and petrogenesis (Cruz *et al*. 2014a, Fernandes *et al*. 2011, Juliani & Fernandes 2010, Lagler 2011). Lately, much attention has also been directed to the hydrothermally altered volcanic rocks, which are potential hosts for mineralization**.** Based on extensive fieldwork and detailed petrographic studies, Cruz (2015) has shown the existence of at least twelve hypogene hydrothermal centers with propylitic, potassic, sericitic, and intermediate argillic alteration, as well as evidence for gold mineralization, , spatially and temporally associated with the volcanism.

Short-wave infrared (SWIR) and near infrared (NIR) spectrometry seems promising for mapping hydrothermally altered zones in areas where fresh samples are hard to be collected and non-continuous outcrops are scarce. The application of the SWIR technique in the São Félix do Xingu region provided not only valuable data for prospecting high value mineral deposits, such as gold, but also could give insight of the hydrothermal processes associated with the volcano–plutonism of the rocks under investigation. Similar studies could be done in other areas with intense hydrothermal alteration and well-known economically important mineral deposits; for instance, the southwestern Cordillera of the United States or the Sierra Madre Occidental of Mexico (Camprubí & Albinson 2007, Valencia-Moreno *et al*. 2007).

These spectrometric tools are becoming increasingly common nowadays, since they allow rapid analyses to be performed directly on samples, due to the high sensitivity of the infrared radiation to vibrations of the Al–OH, Mg–OH, Fe–OH, Si–OH, CO_3, NH_4, and SO_4 bonds, which are present in the structure of various hydrothermal minerals (Clark *et al*. 1990, Hunt 1977). The several absorption band positions and shapes can be correlated to mineral composition and crystallinity variations (Duke 1994, Gaffey 1986, Guatame Garcia 2013).

The aim of this paper is to describe the acquired infrared spectral data of hydrothermally altered rock samples to use them in conjunction with the available information on the geology and petrography of the Sobreiro and Santa Rosa formations to better understand the hydrothermal processes and the potential of the infrared spectroscopy technique for other regions of the Amazonian craton.

2 **TECTONIC SETTING**

The São Félix do Xingu region is located in the southern part of the Amazonian craton, which represents one of the largest Precambrian terrains of the world. The craton lies in northern Brazil and consists of the Guyanas and Central Brazil shields, separated by the Phanerozoic Amazon and Solimões sedimentary basins (Caputo 1991).

The tectonic evolution of the Amazonian craton is controversial. Based on structural and geophysical data, it was initially considered a large reworked Archean platform (Almeida *et al*. 1981, Costa & Hasui 1997) that was reactivated during the Trans-Amazonian cycle. Other models emerged as more geochronological and isotopic data became available, supporting the craton division into provinces (Fig. 1), genetically related to continental accretion events around the Archean Carajás nucleus (Cordani & Brito Neves 1982, Santos *et al*. 2000, Tassinari & Macambira 1999).

Recently, integration of geological, geochronological, and metallogenetic data obtained for multiple occurrences of calc-alkaline volcanic rocks in the Central Brazil shield suggests the existence of a possible metallogenetic zoning formed between ca. 2000 and 1880 Ma in this tectonic unit (Juliani *et al*. 2009). This model assumes an ocean–continent orogeny generated by a continuous, approximately E-W-trending subduction zone with arc migration towards North, which resulted in at least two major continental magmatic arcs named “Arcos Tapajônicos”. In this context, the occurrence of younger volcanic associations (1880 Ma) can be explained by the unusual change in the angle of the subducted slab known as flat subduction (Fernandes *et al*. 2011, Ferrari *et al*. 2012, Gutscher *et al*. 2000, Kay *et al*. 2005, Sacks 1983).

A very well-preserved 1860 Ma high-sulfidation gold mineralization was identified in the Tapajós Mineral Province (Juliani *et al*. 2005), west of São Félix do Xingu region. It is hosted by hydrothermal breccias in the uppermost part of a ring-structure volcanic cone in a rhyolitic volcanic ring complex with granitoids stocks in large nested calderas. The hydrothermal breccias are cone-shaped, flare upward, and contain vuggy silica. They are covered by a brecciated cap of massive silica in the uppermost part of a ring-structure volcanic cone. Recently, the genetically related Palito gold–(copper) porphyry-type deposit was also characterized in the Tapajós Mineral Province and suggests polymetallic specialization for this province (Juliani *et al*. 2012, Juliani *et al*. 2014).

3 **GEOLOGY OF THE SÃO FÉLIX DO XINGU REGION**

In the São Félix do Xingu region, the Archean Rio Maria Granite–Greenstone Terrain and metavolcano-sedimentary units of the Itacaiúnas Supergroup (Araújo *et al*. 1988) are recognized. The Uatumã volcano-plutonic event is represented by the Sobreiro and Santa Rosa formations, which are crosscut by A-type tin-bearing granitoids of the Velho Guilherme Suite (ca. 1860 Ma; of the (Teixeira *et al*. 2002). Mesozoic mafic dikes, as well as Cenozoic lateritic covers and sedimentary deposits, represent younger units in the region.

Available geochronological data yielded ca. 1880 ±6 Ma (TIMS Pb–Pb in zircon) for the Sobreiro Formation, and ca. 1879 ±2 Ma (TIMS Pb–Pb in zircon) for the Santa Rosa Formation (Fernandes *et al*. 2011, Pinho *et al*. 2006). Although the assumed crystallization ages for these units are very close, their geochemical compositions, geological features, and eruption styles points to their non-cogeneticity. The main geological features of the Sobreiro and Santa Rosa formations are summarized below.

3.1 SOBREIRO FORMATION

The Sobreiro Formation is represented by massive and layered, usually amygdaloidal, lava flow facies mainly composed of andesites, basaltic andesites, and dacites. An association of basic to intermediate proximal sub-aerial volcaniclastic facies, including monomictic breccias, volcanic agglomerates, lapilli-tuffs, laminated tuffs, and crystal tuffs, mineralogically similar to the lava flow facies, also occurs in this formation (Juliani & Fernandes 2010). Conspicuous horizontal to sub-horizontal flow foliation structures are observed in these rocks, which reveal a geochemical signature compatible with Andean-type continental magmatic arc environment and transitional metaluminous high-K calc-alkaline to shoshonitic affinity (Cruz *et al*. 2014a, Fernandes *et al*. 2011).

3.2 SANTA ROSA FORMATION

The Santa Rosa Formation comprises at least four volcanic rock facies: 1) massive, layered, and foliated rhyolitic lava flows, and thick dikes of banded rhyolite and ignimbrite; 2) highly rheomorphic felsic ignimbrites associated with a thin unwelded ash-fall tuffs; 3) felsic crystal tuffs, lapilli-tuffs, and co-ignimbritic breccias; and 4) stocks and dikes of granitic porphyry and subordinate equigranular granitic intrusions. Vertical flow banding is a common characteristic. The felsic lava flow facies is the most abundant, and is topographically characterized by symmetrical steep hills that make up a system of coalescent lava domes. A fissure-controlled polycyclic eruption system has been proposed to explain this association (Juliani & Fernandes 2010). The Santa Rosa rocks exhibit A-type intraplate geochemical signature, peraluminous character, and transitional sub-alkaline to alkaline composition (Fernandes *et al*. 2011).

4 METHODS AND ANALYTICAL PROCEDURES

Over two hundred thin sections were prepared from both altered and non-altered rock samples from the Sobreiro and Santa Rosa formations. They were examined petrographically, a few with scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectrometry (EDS) at the Geosciences Institute of the Federal University of Pará (IG-UFPA).

Additionally, fifty-five hydrothermally altered rock samples were analyzed at the Geoscience Institute of the São Paulo University (USP). Ten to fifteen infrared spectroscopic measurements were made on each sample, resulting in 546 spectra. The spectral elements were acquired in nanometers and then converted to micrometers in order to have them interpreted accurately.

The measurements were made at various portions of the samples using a portable ASD FieldSpec 4 spectroradiometer with ranges of 0.4–2.5 μm for wavelength and 350–2500 nm for resolution. The equipment has a high illumination contact probe with a 10 mm spot size, which is recommended for mineral exploration work. The results are recorded in reflectance values proportional to a maximum reflectance of a 6 x 6 cm white fluoropolymer panel (pattern). Data processing was carried out with the ViewSpecPro 6.0 and ENVI 4.7 softwares. The mineral spectral library of the United States Geological Survey (Clark *et al*. 2007) was used for comparison and identification of mineral phases present in the rocks.

This study focuses on clay minerals, since they are common in the hydrothermally altered rocks from those units and the molecular vibrations of their fundamental cation–O–H bonds are particularly active in the SWIR and NIR regions. The detailed description and explanation of the vibrational processes in minerals and their signatures can be found in Hunt (1977), Hunt & Salisbury (1970), and Hunt & Ashley (1979).

5 **PETROGRAPHY**

5.1 SOBREIRO FORMATION

The lava flow facies is composed predominantly of black to gray massive basaltic andesite and andesite (Fig. 3A) with minor dark purple dacite and rhyodacite. The andesites are mainly holocrystalline and porphyritic, and contain euhedral phenocrysts of magnesiohastingsite, augite, and oligoclase–andesine (Figs. 3B, 3C). The groundmass is usually flow-oriented, with plagioclase microlites and fine anhedral potassic feldspar crystals. Fine amphibole and clinopyroxene crystals occur scattered in the groundmass. Rhyodacite and dacite are composed of plagioclase phenocrysts immersed in a cryptocrystalline matrix consisting of feldspars. Amygdales filled by chlorite, epidote, and quartz are common. Magnetite and very subordinate zircon occur as the main primary accessory minerals in the rhyodacitic rocks. Volcaniclastic rocks are black, dark grey, and dark purple. They are poorly sorted and exhibit fragmental textures with abundant angular fragments of magnesiohastingsite, augite, and oligoclase–andesine, besides intermediate to basic lithic fragments supported by a vitrophyric groundmass (Fig. 3D). Subordinate monomitic breccias show intermediate to mafic centimeter-sized angular fragments supported by a dark purple groundmass.

Propylitization is the most important alteration process recognized in this unit, in both pervasive and fracture-controlled styles. The resulting paragenesis consists of epidote + chlorite + albite + clinozoisite ± sericite ± carbonate ± quartz ± pyrite, which was overprinted by pervasive or fracture-controlled potassic alteration represented by potassic feldspar + biotite (Fig. 3E). Sericitic alteration is more restricted and represented by the assemblage sericite + quartz ± carbonate ± epidote ± chlorite that occurs mainly in the volcaniclastic rocks and mafic crystal tuffs. Its styles range from incipient to pervasive, being locally fracture-controlled, as it is the prehnite-pumpellyite association that could be related to overprinting of low-grade geothermal metamorphism (Fig. 3F).

5.2 SANTA ROSA FORMATION

The lava flow rocks are predominantly light pink, massive porphyritic rhyolites and subordinate dark purple rhyodacites. These rocks display mainly glomeroporphyritic holocrystalline to hypocrystalline textures with euhedral plagioclase and potassic feldspar phenocrysts immersed in a felsitic microgranular groundmass, where spherulites and granophyric intergrowths, and lithophysae are usual features (Fig. 4A). Quartz phenocrysts are commonly reabsorbed and rounded. Varietal biotite is rare. Fluorite, zircon, Fe–Ti oxides, and apatite are the main primary accessory minerals.

The ignimbrite shows welded flow-like eutaxitic or parataxitic texture of alternating cryptocrystalline and fine-grained layers with felsitic, locally spherulitic, groundmass (Fig. 4B). The ash-fall tuffs are dark to light red and present thin-laminated parallel structures, dispersed angular-shaped fine-grained quartz and feldspar crystals, and felsic lithic fragments. Unwelded, slightly compacted ash-fall tuffs were also identified and show conspicuously glassy shards. The crystal tuffs and lapilli-tuffs comprise purple and light pink felsic rocks with abundant angular shaped ash- to lapilli-sized feldspar and quartz crystal fragments, and minor rhyolite fragments set in a fine- to medium-grained volcaniclastic matrix. Zircon, Fe–Ti oxides, and apatite were identified in these rocks.

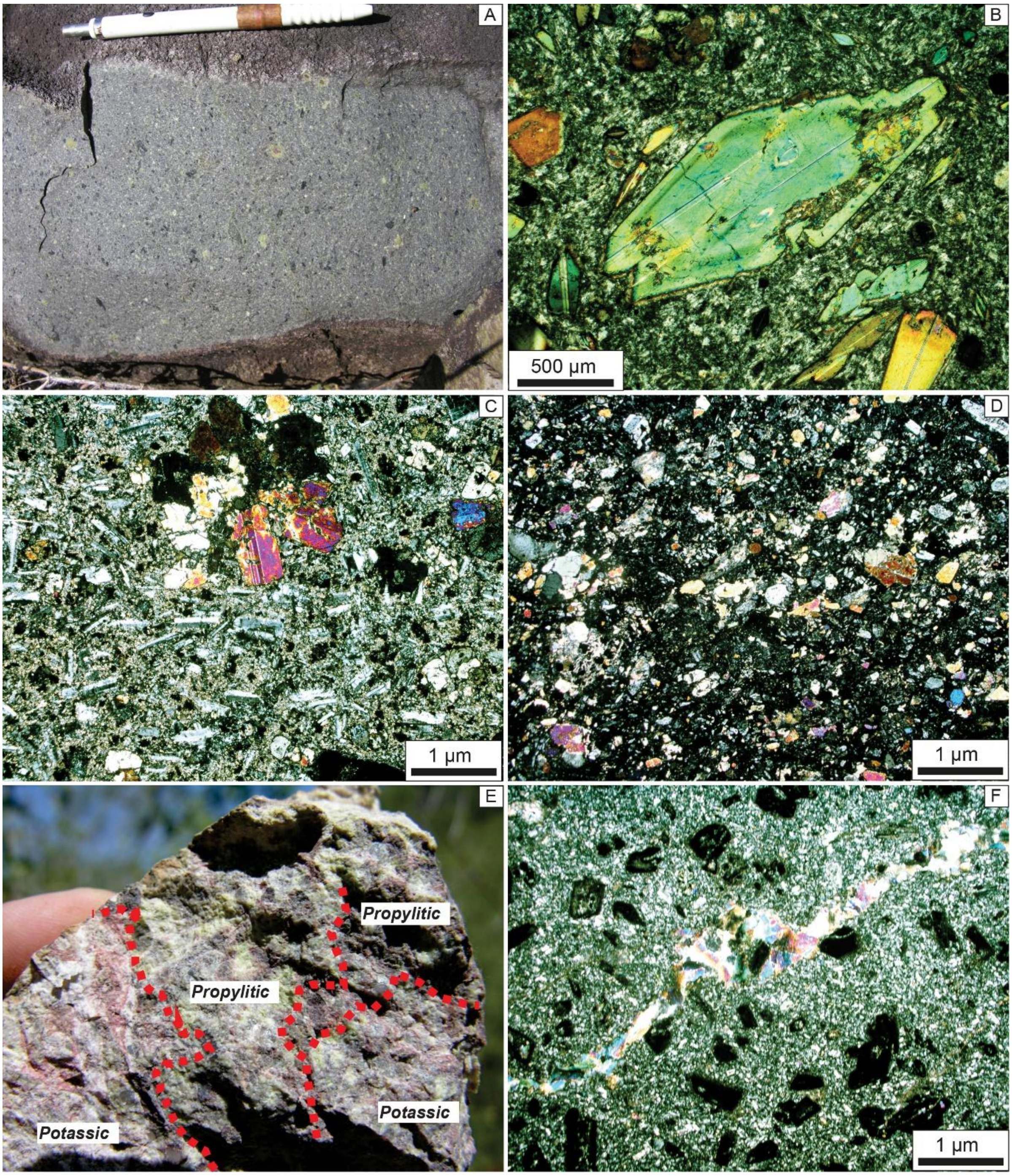

Figure 3 – Representative field and microscopic features of rocks from the Sobreiro Formation. Photomicrographs with crossed nicols (B, C, D and F). A) Outcrop of an amigdaloydal amphibole-phyric andesite; B) Euhedral phenocryst of magnesiohastingsite immersed in fine-grained groundmass of an andesite; C) Aggregate of augite phenocrysts amid plagioclase microlites that dominate the cryptocristalline groundmass of a basaltic andesite; D) Poorly sorted mafic crystal tuff with amphibole and clinopyroxene clasts; E) Hand sample of andesite (?) showing a propylitic assemblage overprinted by potassic alteration; and F) Fracture-controlled filling of prehnite-pumpellyite association in andesite.

Granitic porphyries are massive, light pink to reddish rose, and have coarse potassic feldspar and plagioclase phenocrysts and quartz megacrysts in a dark pink, reddish rose or black quartz–feldspar microgranitic groundmass (Fig. 4C), in which anhedral quartz and potassic feldspar crystals and granophyric intergrowths are noticeable. Biotite, zircon, fluorite, titanite, apatite, and minor magnetite and ilmenite are the main accessory minerals.

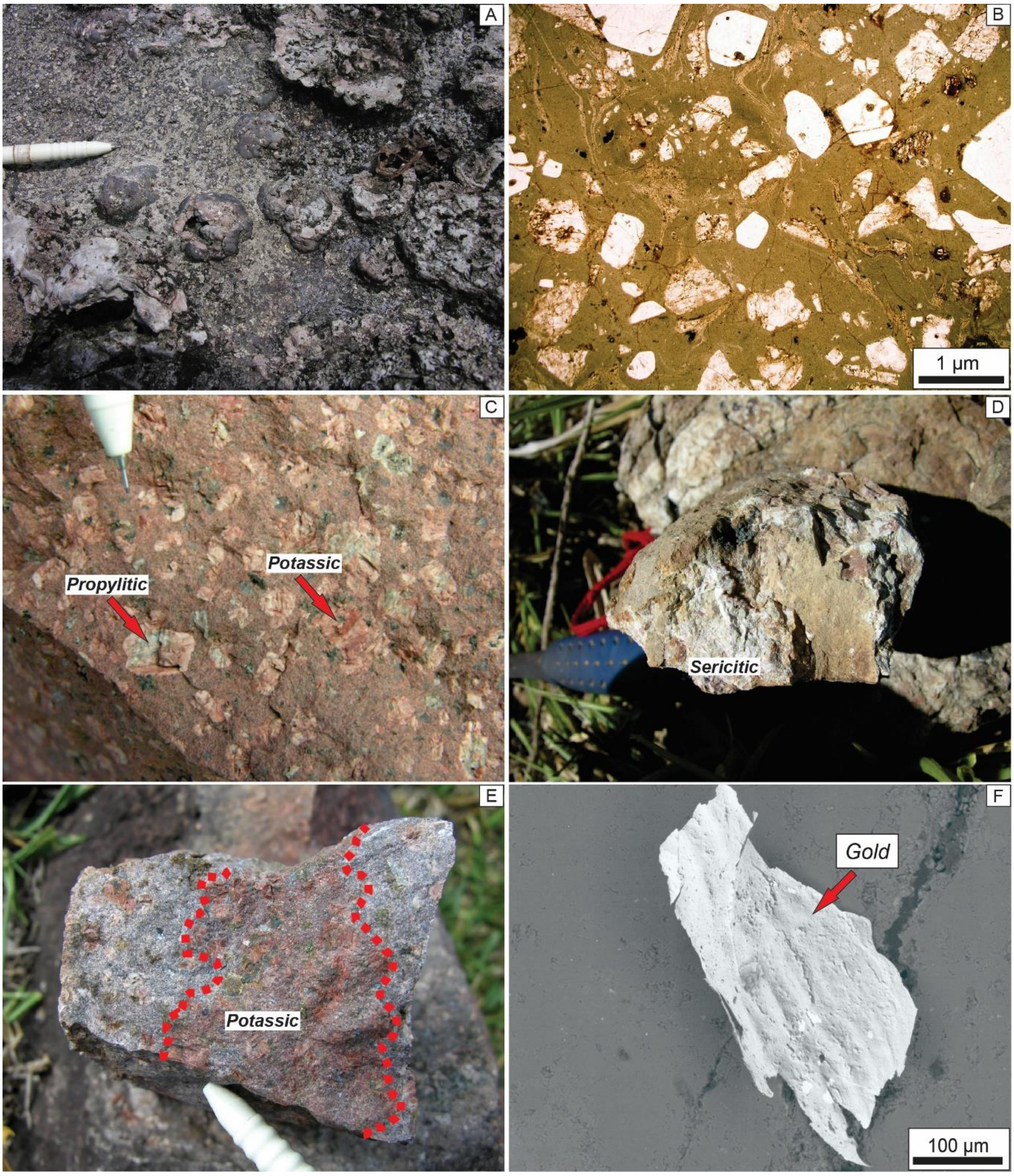

Figure 4 – Representative field and microscopic features of rocks from the Santa Rosa Formation. A) Outcrop of a lithophysae-rich aphyric rhyolite; B) Photomicrograph (uncrossed nicols) of parataxitic texture in a welded ignimbrite; C) Outcrop of a granitic porphyry with propylitic and potassic alterations (reddish plagioclase); D) Hand sample of a rhyolite (?) presenting pervasive seriticic alteration; E) Fracture-controlled potassic alteration in a block of granitic porphyry; and F) Backscattered electron – SEM micrograph of a gold particle in sericitic alteration zone of a rhyolite (?).

The most common hydrothermal alteration type in the Santa Rosa Formation is sericitic (Fig. 4D), resulting in mineral paragenesis represented by sericite + quartz and latter carbonate. Subordinate potassic alteration (Fig. 4E) has microcline + biotite ± magnetite. Both alterations are pervasive and fracture-controlled, the latter developing commonly a stockwork pattern. Chlorite, sericite, and albite also occur and are probably related to overprinting of propylitic or chloritic alterations. Gold, generally very fine-grained (Fig. 4F), occurs in the sericitic zone (Fig. 5A, 5B) and was identified by SEM technique, although in a few hand samples its particles are sufficiently coarse to be seen with the naked eye. A pervasive intermediate argillic alteration was also recognized, but the clay minerals are very difficult to be properly identified with conventional petrographic techniques (Fig. 5C, 5D, 5E). There are also texturally diverse quartz veins, the comb type being a common feature, especially in samples from outcrops with stockwork structures (Fig. 5F).

6 **SWIR RESULTS**

Propylitic, sericitic, intermediate argillic, and potassic alteration types have been identified in rocks of the Sobreiro and Santa Rosa formations, with incipient to pervasive or locally fracture-controlled (stockwork) styles. The overprinting process of the alterations is common, making it difficult to associate some pervasively altered samples to either the Sobreiro or Santa Rosa formations due to the unclear contact relationships between them. The distribution and alteration types of the analyzed samples in São Félix do Xingu region are shown in Figure 6.

The characterization of the hydrothermal system was initially based on conventional techniques such as mesoscopic and microscopic petrography, scanning electron microscopy, and X-ray diffractometry, as well as field observations (Cruz *et al*. 2014b). SWIR spectroscopy was used here to discriminate minerals that were not recognized in previous studies, thus providing a better assessment of the hydrothermal history of the Sobreiro and Santa Rosa formations during the eruptive events.

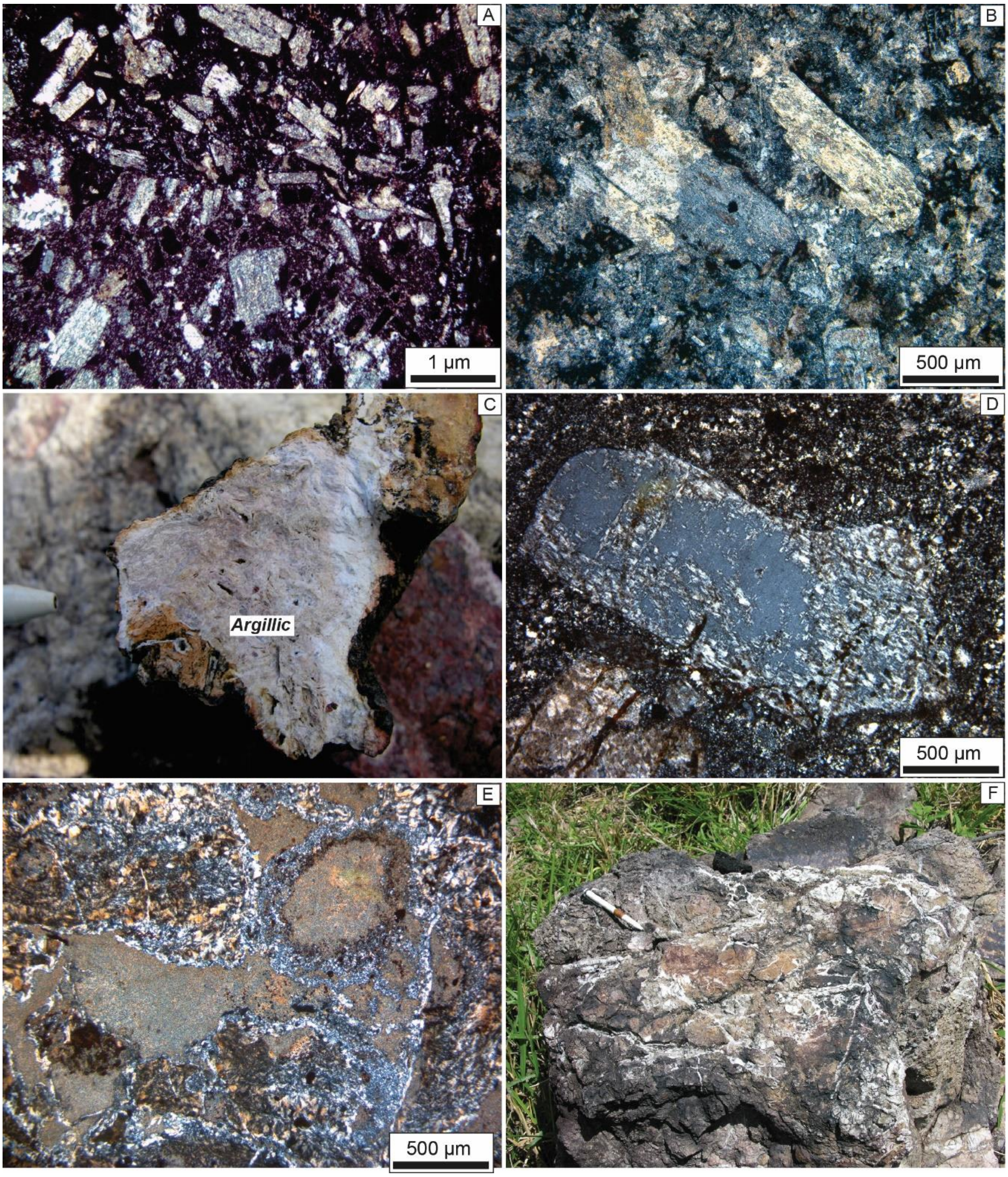

Figure 5 – Representative field and microscopic features of hydrothermalized rocks from the Santa Rosa Formation. A and B) Photomicrographs (crossed nicols) showing pervasive sericitic alteration in a rhyolite; C) Hand sample of a rhyolite (?) strongly modified by argillic alteration; D and E) Photomicrographs (crossed nicols) of a rhyodacite presenting, respectively, selective and pervasive intermediate argillic alteration; and F) Stockwork with quartz filling in a rhyolite.

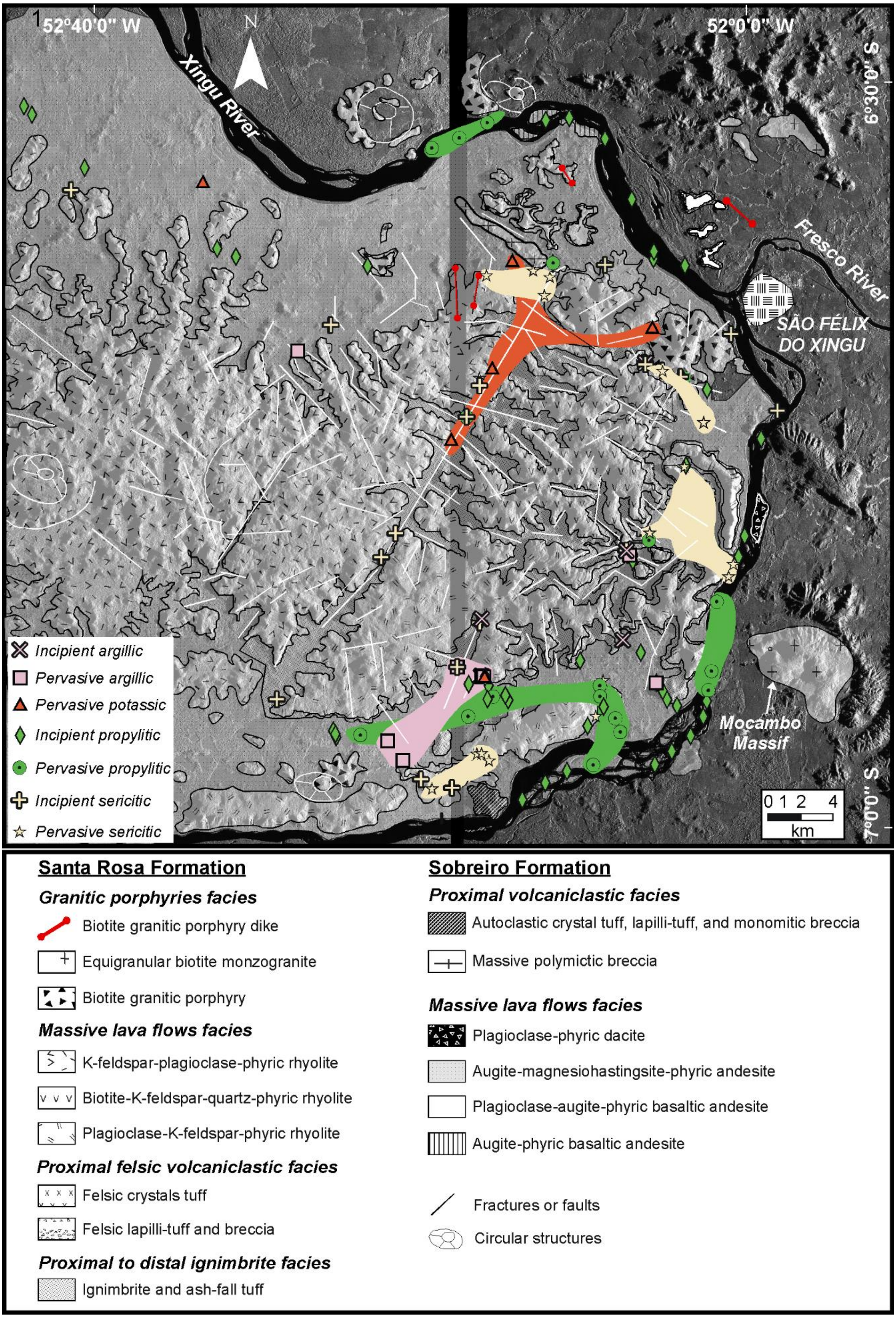

Figure 6 – Preliminary hydrothermal alteration map for the Sobreiro and Santa Rosa formations with location and types of hydrothermal alteration.
Fonte: (Juliani & Fernandes 2010)

6.1 MONTMORILLONITE

Montmorillonite is a common mineral in the studied rocks, especially in those from the Santa Rosa Formation, and is characterized by a strong absorption of water at 1.4 and 1.9 μm wavelengths (Fig. 7). These diagnostic intervals also indicate that inseparable water molecules may exist in some way in the structure of the montmorillonite (Hunt & Salisbury 1970). In general, the spectra show a good crystallinity for this phase. The presence of the hydroxyl group (OH^-) at the longer 2.21 μm wavelength indicates a low Al content in its structure (Post & Noble 1993).

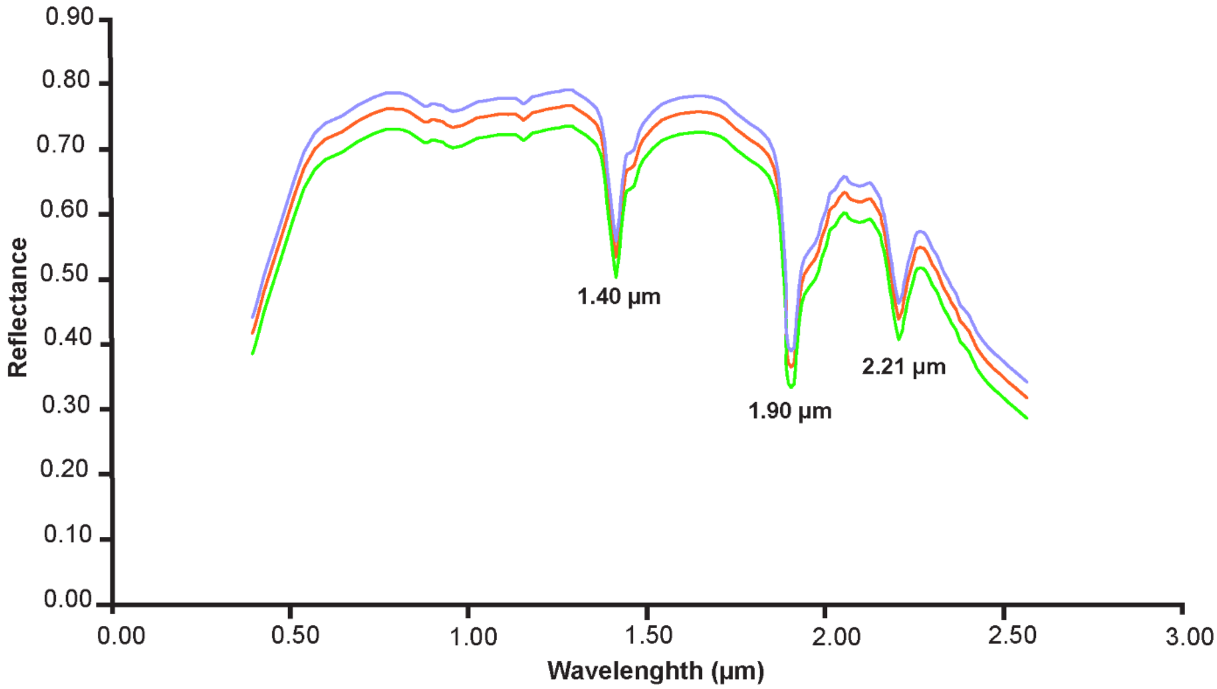

Figure 7 – Representative reflectance spectra of three montmorillonite-rich samples from the Santa Rosa Formation.

Some samples reveal spectra with a mixture of minerals. The depth of the absorption feature at 1.4 and 1.9 μm is indicative of water content and its location in the mineral structure, representing a distinctive feature for montmorillonite and illite/muscovite (Post & Noble 1993). Montmorillonite has higher water contents and shows deeper and broader water feature than illite or muscovite. The associated mineral phase is illite, which has narrower (1.4 and 1.9 μm) features when compared to montmorillonite (Fig. 8). Thus, it was possible to define the zone of alteration of montmorillonite with subordinate illite.

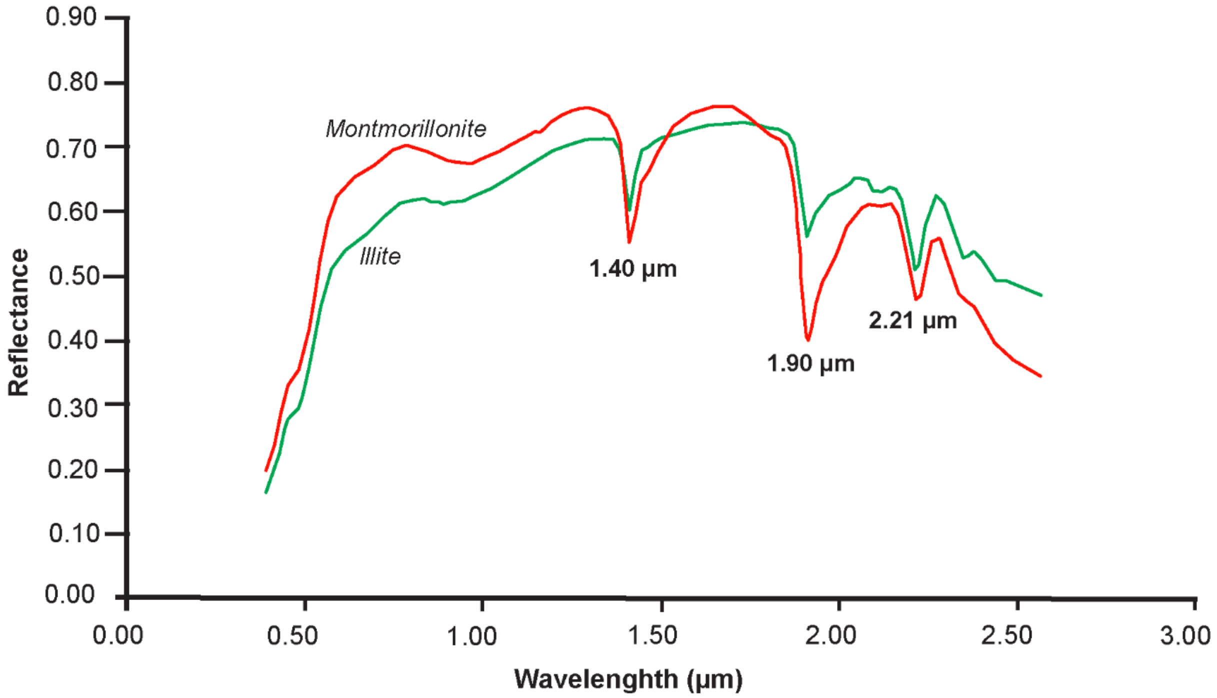

Figure 8 — Reflectance spectra for samples from the Santa Rosa Formation containing both montmorillonite and illite.

6.2 KAOLINITE/HALLOYSITE

Minerals of the kaolinite group commonly replace the feldspars present in the rocks of the Santa Rosa Formation and reveal the diagnostic spectral bands of the OH^- radicals, controlled by absorption at 1.4 and 2.2 µm wavelengths, and typical Al–OH doublets (double absorption features) in some spectra (Fig. 9). The location of the hydroxyl in the mineral structure produces changes in its vibration energy, revealing weak doublets in poorly crystalline halloysite, and well defined ones in kaolinite and dickite (Brindley *et al*. 1986), the most important minerals of the kaolinite group. The distinct absorption at 1.9 µm wavelength in all samples is related to the presence of molecular water and reflects poorly crystalline kaolinite or halloysite, suggesting that both phases may be present in the samples. On the other hand, the distinct Al–OH doublets suggest the presence of subordinate kaolinite with a well-ordered lattice. Although speculative, the development of a doublet near 2.16 µm could be interpreted as dickite, which is more ordered and crystalline.

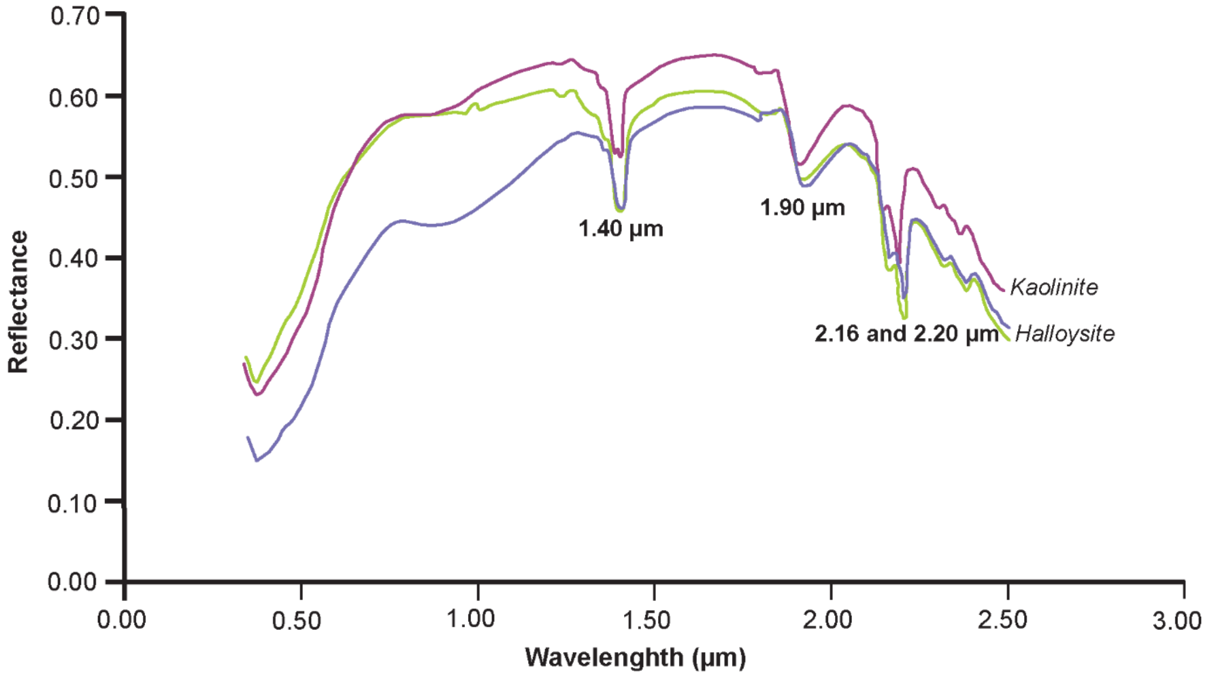

Figure 9 – Representative reflectance spectra of kaolinite and halloysite in samples from the Sobreiro and Santa Rosa formations.

6.3 ILLITE

In the studied samples, illite was identified by the presence of an important spectral Al–OH band near 2.21 µm, despite the overlap with montmorillonite. Although illite also contains water, the presence of this constituent is much more evident in the montmorillonite spectra. The analyzed spectra show a single absorption at 1.41 µm, followed by water absorption at 1.91 µm. Depending on its composition, absorption may occur at the 2.18–2.22 µm wavelength range, and characterizes K-rich illite (Fig. 10). In contrast with the montmorillonite spectra, illite exhibits a spectral feature at the 2.35–2.46 µm wavelength range, which is related to Fe and Mg Tschermak cation exchange that modifies the Al–OH band (Clark *et al*. 1990, Duke 1994). These results suggest the development of the alteration zone of illite with subordinate montmorillonite.

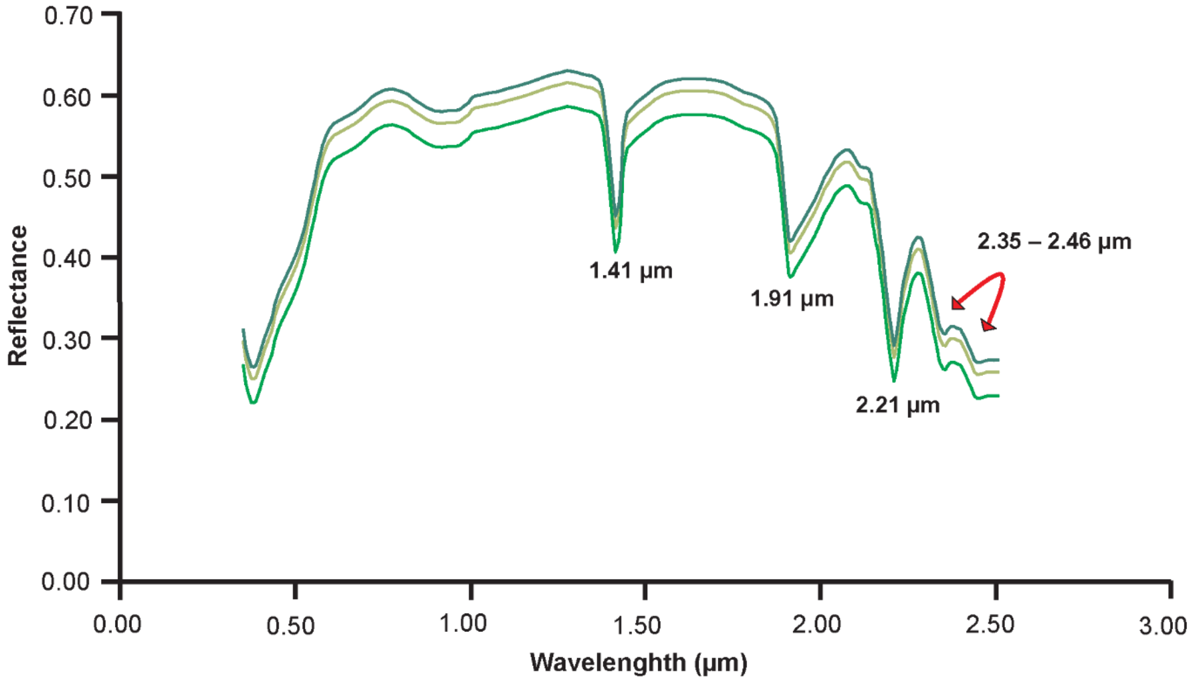

Figure 10 – Representative reflectance spectra of the illite-rich samples from the Santa Rosa Formation.

7 **DISCUSSION**

The infrared spectra reveal characteristic absorptions due to the hydroxyl radical, indicating the presence of clay minerals. Such minerals are products of hypogene hydrothermal alteration processes related to physical and chemical changes induced by the contact of hydrothermal solutions with the rock through which they circulated (Pirajno 2009). These fluids attack chemically the pre-existing minerals, forming a stable mineralogical assemblage in response to the new physico–chemical conditions. This process is characterized by mass transfer between the fluids and the mineral environment, whose intensity depends upon the composition, textures, and structures of the rock, as well as temperature and nature of these fluids (Gifkins *et al*. 2005). Clay minerals can also be generated by superficial weathering. However, as the clay mineral occurrences here described are restricted to the hydrothermally altered centers, where alteration overprinting is a distinct feature, a hypogene origin seems to be a more consistent hypothesis.

The 1.9 µm wavelength for montmorillonite is related to water absorption and is very strong in this phase due to its expansibility. Our data indicate the occurrence of at least two distinct groups of montmorillonite: one with sharp and well-defined wavelengths, and another with a very broad pattern. The accentuated wavelengths may indicate that water molecules are located in well-defined positions, whereas the broad wavelengths show disorganization or water molecules occupying more than one position in the mineral structure. In epithermal systems, this gradual variations in the arrangement of the crystal structure and composition are related to increasing pressure and temperature that result in a succession from montmorillonite to montmorillonite-illite, to illite-montmorillonite, to illite, and finally to muscovite-sericite (Guatame Garcia 2013, Velde 1977). The change from montmorillonite to illite and from illite to muscovite-sericite takes place at approximately 100 – 130 ºC and 210 – 230 ºC, respectively (Pirajno 2009, Steiner 1968). Indeed, in the studied area the pervasive sericitic alteration type occurs at the outermost portion of the Santa Rosa Formation, whereas the intermediate argillic alteration type occurs at the center, suggesting a preliminary lateral zonation of the hydrothermal system (Fig. 6).

Poorly crystalline kaolinite and halloysite may be products of the tropical weathering that prevails in the Amazonian region. However, at temperature above 200 ºC, high-crystallinity dickite is formed. As the temperature falls to 120 ºC, dickite becomes disordered and changes to ordered kaolinite.

At the final stage, under surface conditions, cool meteoric or acid groundwater moves downward favoring the formation of less ordered halloysite (Brathwaite *et al*. 2014, Guatame Garcia 2013, Yuan *et al*. 2014). Although the genesis of halloysite is controversial, it has been also interpreted as a product of the reaction between sulphate-bearing solutions and kaolinite. This reaction leads to the formation of a gel phase, from which halloysite and associated alunite crystallize (Ece & Schroeder 2007, Ece *et al*. 2008, Rattigan 1967). The presence of dickite is not ruled out given the doublet pattern that appears in some spectra. More investigation is needed to confirm or not its occurrence.

The hypogene clay minerals recognized in altered rocks of the Sobreiro and Santa Rosa formations characterize an intermediate argillic hydrothermal alteration, most likely produced by acid leaching at 100 – 300 °C (Gifkins *et al*. 2005, Pirajno 2009). Potassium, calcium, magnesium, and sodium were partially leached from the altered volcanic rocks. Because of the polyphasic construction of volcano–plutonic systems related to ash flow calderas or fissure-controlled eruptions, as shown by the São Félix do Xingu volcanic units, the thermal flow and fluid availability vary greatly according to the magma type, crustal level, and host rocks (Juliani & Fernandes 2010, Lipman 1984). In the São Félix do Xingu volcanic centers, temperature and fluid–rock ratios might have played an important role not only in the formation and distribution of the clay minerals, but also in the metal deposition.

Since no systematic prospective work has been carried out in these São Félix do Xingu volcanic units, infrared spectral data could be very useful to identify and map different hydrothermal alteration types. These data could provide important information to guide the exploration for epithermal and genetically related porphyry-type deposits of rare and base metals (gold, silver, copper, molybdenum, etc.) in volcano–plutonic systems (Arribas Jr. *et al*. 1995, Hedenquist *et al*. 2000, Sillitoe 2010), similar to others already described in the Tapajós Mineral Province (Juliani *et al*. 2002, Juliani *et al*. 2012, Juliani *et al*. 2005). Gold mineralization associated with sericitic alteration in pervasive or, locally, stockwork styles observed in rocks of the Santa Rosa Formation, in addition to the occurrence of granitic porphyry intrusions, point to a metallogenetic potential for intrusion-related gold systems (Hart 2007) or low- to intermediate-sulfidation epithermal mineralizations (Einaudi *et al*. 2003, Sillitoe & Hedenquist 2003).

The tectono-magmatic environment that has been envisaged for the Sobreiro and Santa Rosa formations supports the aforementioned interpretations and serves to steer a preliminary reconstruction of the hydrothermal systems related to these units (Fernandes *et al*. 2011). Petrogenetic modeling and Nd model ages (3000 – 2490 Ma) for the Sobreiro Formation strongly suggest its generation by mixing of calc-alkaline mantle-derived magmas and anatectic melts of Archean sources beneath the volcanic sequences in the São Félix do Xingu region. The Santa Rosa Formation could have been formed by A-type magmas originated from anatexis of several Archean crustal sources (with T_{DM} 3120 – 2560 Ma). The magmas would have been cyclically fed through deep fissures (Juliani & Fernandes 2010) that were opened during an intense Paleo- to Mesoproterozoic extensional event of the Amazonian craton (Brito Neves 1999), similar to that proposed for the Sierra Madre Occidental ignimbrites (Aguirre-Díaz & Labarthe-Hernandez 2003). These data support considering a transition from an Andean-type subduction to a dominantly extensional tectonic setting for the volcanic and plutonic rocks of the São Félix do Xingu region. In this scenario, later pulses of granitic porphyries most likely sealed the Santa Rosa Formation, allowing the onset of the hydrothermal systems powered by the magmatic heat anomalies that caused the circulation of aqueous solutions, mostly of meteoric derivation. This favors acid leaching of the volcanic rocks and formation of montmorillonite, kaolinite, and illite in intermediate argillic hydrothermal alteration zones.

8 **CONCLUSIONS**

1. The integration of the available data with those obtained with infrared spectroscopy for the Sobreiro and Santa Rosa formations upholds the existence of a hypogene hydrothermal system materialized by several types and styles of hydrothermal alterations directly related to the Paleoproterozoic volcano–plutonic framework.

2. The earliest alteration stage in rocks of the lower Sobreiro Formation is represented by propylitic alteration (epidote + chlorite + clinozoisite + quartz + carbonate + albite) that was overprinted by potassic alteration (potassic feldspar + biotite). This overprinting could be related to hydrothermal fluids sourced from later A-type intrusions or to the recharge of petrologically more evolved magmas that generated that formation. Subordinate sericitic alteration (sericite + quartz ± epidote ± chlorite) is identified also. In turn, the upper Santa Rosa Formation exhibits mainly sericitic (sericite + quartz ± gold), potassic (biotite + microcline + sericite ± albite ± magnetite), and intermediate argillic (montmorillonite + kaolinite-halloysite + illite) alterations. These alteration types are compatible with magma-related thermal anomalies, and magmatic-sourced fluids, involving a temperature decrease and neutralization due to mixing with meteoric water, similar to what has been described in low- and intermediate-sulfidation epithermal mineralizations.

3. Infrared spectroscopy proved to be a very useful tool for the identification of hydroxyl-bearing minerals and the characterization of the different hydrothermal alteration types recognized in the rocks of the Sobreiro and Santa Rosa formations. This technique is much more incisive especially when it is complemented by other analytical techniques such as petrography, X-ray diffractometry, and scanning electron microscopy. In areas subjected to severe chemical weathering, as in the Amazonian craton, this low cost, high-quality technique can readily identify hydrothermal mineral phases and be valuable in preparing hydrothermal alteration maps for mineral exploration projects, no matter how dense the rainforest cover is.

4. The identification of hydrothermal minerals should also involve satellite-based multispectral remote sensing. The application of image processing techniques specifically designed for mineral mapping to the ASTER SWIR will enable an advance in mineral prospecting in the Amazonian craton.

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CAPÍTULO III

Metallogenetic significance of the hypogene alteration associated with the Paleoproterozoic volcanism of the Sao Felix do Xingu region, Amazonian Craton, Brazil

Raquel Souza da Cruz[1], Carlos Marcello Dias Fernandes[1,*], Raimundo Netuno Nobre Villas[1], Caetano Juliani[2], Lena Virgínia Soares Monteiro[2], Bruno Lagler[2], Carlos Mario Echeverri Misas[2]

[1]Geoscience Institute, Pará Federal University (UFPA), [2]Geoscience Institute, São Paulo University

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* Corresponding author:
Carlos Marcello Dias Fernandes
Faculdade de Geologia, Instituto de Geociências, Universidade Federal do Pará
Rua Augusto Corrêa 1, CEP 66075-110, Belém–PA, Brazil
Telephone: +55 (91)3201-7107
Fax: +55 (11)3201-7609
E-mail: cmdf@ufpa.br

Abstract

Geological, petrographic, scanning electron microscopy, and X-ray diffraction studies revealed hydrothermalized lithotypes evidenced by overprinted zones of potassic, propylitic, sericitic, and intermediate argillic alterations types, with pervasive and fracture-controlled styles, in Paleoproterozoic volcano–plutonic units of the São Félix do Xingu region, Amazonian craton, northern Brazil. The Sobreiro Formation presents propylitic (epidote + chlorite + carbonate + clinozoisite + sericite + quartz ± albite ± hematite ± pyrite), sericitic (sericite + quartz + carbonate ± epidote ± chlorite ± muscovite), and potassic alterations. Low-grade metamorphic association (prehnite-pumpellyite), common in geothermal fields, is also identified in this unit. The Santa Rosa Formation shows mainly potassic (biotite + microcline + carbonate + sericite ± albite ± magnetite), intermediate argillic (montmorillonite + kaolinite/halloysite + illite), and sericitic (sericite + quartz + carbonate ± gold) alterations. These findings in arc-related volcanic rocks strongly suggest the involvement of magma-sourced fluids and draw attention to the metallogenetic potential of these volcanic units for Paleoproterozoic epithermal and rare and base metal porphyry-type mineralizations, as already identified in others portions of the Amazonian craton.

Keywords: Hydrothermal alteration, Fracture-controlled, Epithermal, Carajás Mineral Province

1 **INTRODUCTION**

The Carajás Mineral Province (CMP) and neighboring regions, SE of Pará state (Fig. 1), host voluminous deposits of iron, manganese, gold, nickel, copper, and other base metals (Bettencourt & Dall'Agnol 1987, DOCEGEO 1988, Teixeira *et al*. 2002, Juliani *et al*. 2005, Monteiro *et al*. 2008) formed during Archean and Proterozoic times within the Amazonian craton (Almeida *et al*. 1981). This fact has attracted researchers from all over the world interested in developing studies that could elucidate the mineralizing processes and their relationship with magmatic events, as well as the crustal evolution of the province as a whole.

In the São Félix do Xingu region, located in the CMP, volcanic and associated plutonic rocks are widespread and related to an extensive intermediate to acid Paleo- to Mesoproterozoic volcano–plutonic event that occurred in the Amazonian craton (Juliani & Fernandes 2010). Those rocks cover an area of over 1,500,000 km^2 and represent a Large Igneous Province (Coffin & Eldholm 1994). Their textures and structures are remarkably well-preserved, showing that they were not disturbed by the tectono-metamorphic Trans-Amazonian cycle (Hurley *et al*. 1967). The volcanic rocks are included in the lower 1.88 Ga Sobreiro Formation (high-K calc-alkaline andesites, dacites, and mafic crystal tuffs) and in the upper 1.87 Ga Santa Rosa Formation (A-type rhyolites, porphyries, granites, and volcaniclastic rocks).

Extensive fieldwork and detailed petrographic study revealed at least twelve centers of hydrothermalized rocks and associated gold mineralization in the São Félix do Xingu region (Fig. 1B). Despite the advances in the knowledge of the stratigraphy, petrography, petrogenesis, and geological evolution of the Sobreiro and Santa Rosa formations in the last years (Juliani & Fernandes 2010, Fernandes *et al*. 2011, Cruz *et al*. 2014), the metallogenetic potential of their hydrothermalized rocks is still poorly assessed.

This paper aims to characterize petrographically and mineralogically the hydrothermalized rocks of those formations in order to define the types and styles of hydrothermal alteration, as well as to contribute to unravel their relationship with the gold mineralization and volcanic evolution.

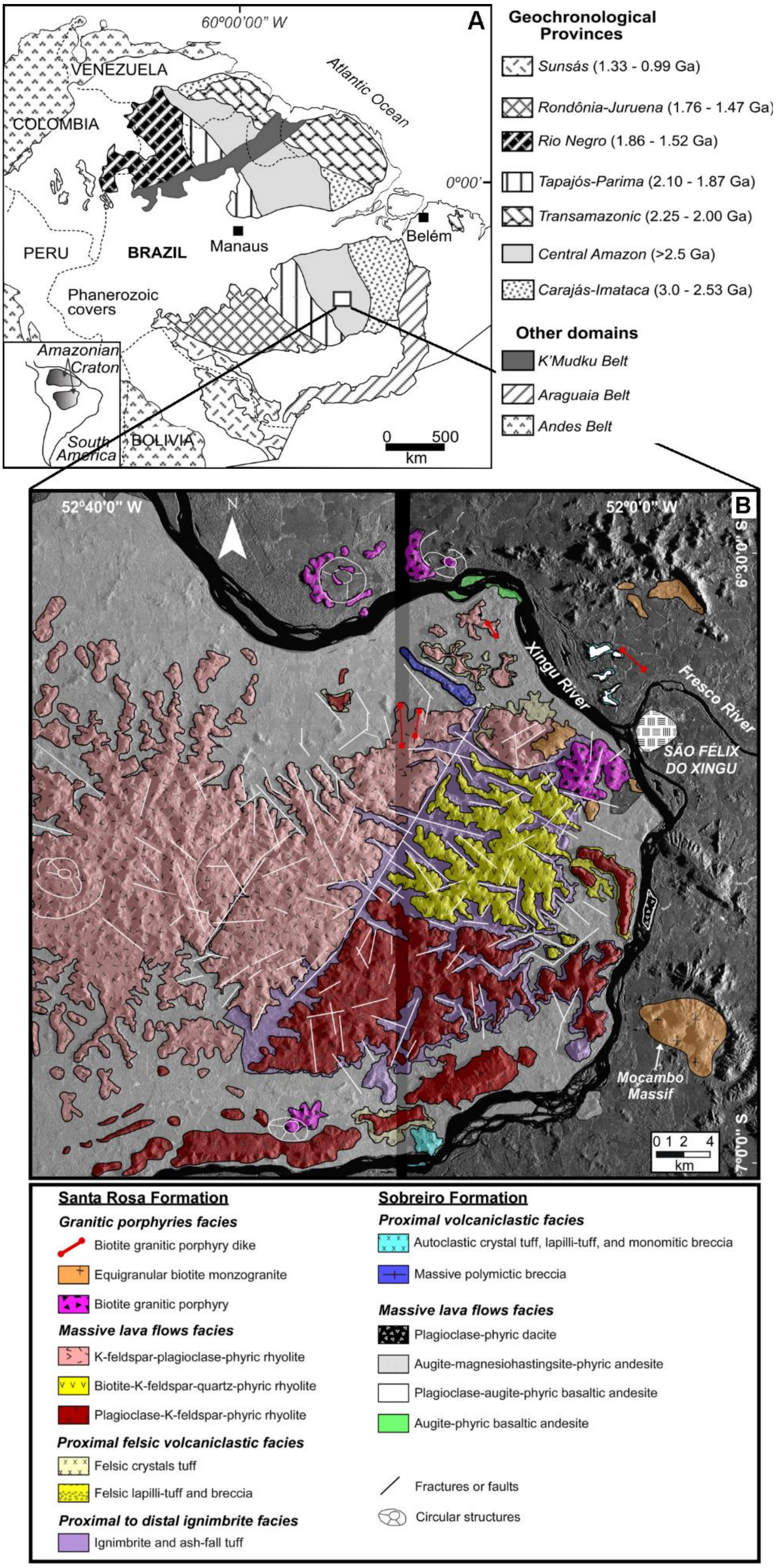


Figure 1 – A) Geochronological provinces of the Amazonian craton (Santos *et al*. 2000); B) Geological map of the Sobreiro and Santa Rosa formations.
Font: (Juliani & Fernandes 2010).

2 TECTONIC EVOLUTION OF THE AMAZONIAN CRATON

The understanding of the Paleoproterozoic evolution of the Amazonian craton is still incomplete and presents challenging problems. Historically, based on structural and geophysical data, it had been considered a large Archean platform reworked and reactivated during the 2.1 Ga Trans-Amazonian event (Amaral 1974, Almeida *et al*. 1981). Available Sm-Nd, U–Pb, and Pb–Pb (TIMS) isotopic data have allowed other researchers to interpret the Amazonian craton as a product of successive continental accretion events related to island arc environments. The craton was then divided into six (Tassinari & Macambira 1999) or seven (Santos *et al*. 2000) geochronological provinces (Fig. 1A). Given that the limits of these provinces are not well defined, the matter has stimulated a heated debate among geologists who investigate that region.

Amid these uncertainties, alternative models have emerged as the one proposed for the southern portion of this tectonic unit based on the available geological, geochronological, and metallogenetic data (Fernandes *et al*. 2011). According to these authors, a possible zoning of Au–Cu–(Mo) porphyry-type, Au–Ag–base metal epithermal, and A-type granitoid-related base metal mineralizations formed between 2.0 and 1.88 Ga could be related to the approximately E-W-trending Andean-type subduction zone**.** The spatial distribution of these mineralizations would have been greatly controlled by the subduction angle, which flattened as the arc migrated toward North (Sacks 1983) similarly to what has been described in the Mexican Volcanic Belt (Ferrari *et al*. 1999) and the Andean Belt (Kay *et al*. 2005).

Geophysical studies corroborate this interpretation for the Tapajós Mineral Province (Carneiro *et al*. 2013, Juliani *et al*. 2014). The NW-SE regional trend in this province is related to major faults and strike-slip shear zones that controlled the emplacement of post-tectonic felsic volcano–plutonic associations, whereas E-W-trending structures are meaningful at the northern portion. These structures show aeromagnetometric features that suggest more crustal penetrability. The deeper character of the E-W-trending structures, inferred from residual magnetic field, reveals the most likely direction of the mobile belt and older magmatic arcs generated in the southern portion of the Amazonian craton.

3 GEOLOGY OF THE SÃO FÉLIX DO XINGU VOLCANIC AND RELATED ROCKS

Well-preserved Paleoproterozoic volcano–plutonic centers occur in the São Félix do Xingu region and are comparable to those described in much younger volcanic provinces worldwide. Their rocks have been grouped in the Sobreiro (ca. 1.88 Ga) and Santa Rosa (ca. 1.87 Ga) formations, which are unmetamorphosed and little modified by weathering processes. On the other hand, they have been affected to a lesser or greater extent by several types and styles of hypogene hydrothermal alterations, recognized in at least twelve centers. Some altered rocks host gold mineralization that preferably occurs in the sericitic zones developed in the Santa Rosa Formation.

A brief overview of the Sobreiro and Santa Rosa formations is given below. A more detailed description of their geological features can be found in Fernandes *et al*. (2011) and Juliani & Fernandes (2010).

3.1 SOBREIRO FORMATION

This unit is made up of massive and layered, usually amygdaloidal, volcanic rocks, which can be separated into two distinct facies. The lava flow facies is mainly composed of andesite, basaltic andesite, rhyodacite, and dacite, whereas the proximal subaerial volcaniclastic facies consists of basic to intermediate rocks that include monomictic breccias, volcanic agglomerates, lapilli-tuffs, laminated tuffs, and crystal tuffs. Both facies reveal essentially the same mineralogical association.

The lava flow facies is volumetrically more expressive and crops out usually as isolated blocks in areas of flat topography, mainly along the Xingu River. Its rocks show horizontal to sub-horizontal flow foliation and high-K calc-alkaline signature, in addition to a dominant metaluminous character and geochemical affinity with Andean-type subduction-related granitoids.

The andesites are mainly holocrystalline and porphyritic. They display variable proportions of euhedral phenocrysts of plagioclase, magnesiohastingsite, and augite. The plagioclase phenocrysts exhibit conspicuous oscillatory zoning with composition that varies from oligoclase to andesine. Fine anhedral potassic feldspar crystals and plagioclase microlites are immersed in a generally flow-oriented groundmass together with fine grains of amphibole and clinopyroxene. The rhyodacites and dacites are also porphyritic, but the phenocrysts are only represented by plagioclase set in a cryptocrystalline groundmass consisting of feldspars. The associated volcaniclastic rocks are variably colored (black, gray, and dark purple), exhibiting fragmental textures with abundant poorly sorted angular fragments of magnesiohastingsite, augite, and andesine crystals, as well as intermediate to basic lithic fragments supported by a vitrophyric groundmass. Subordinate breccia bodies show intermediate to mafic angular blocks (up to 1 m in diameter) supported by a dark purple groundmass.

3.2 SANTA ROSA FORMATION

The polyphasic evolution of the Santa Rosa Formation gave rise to at least four distinct volcanic rock facies: 1) rhyolitic lava flows and thick dikes of banded rhyolite and ignimbrite; 2) highly rheomorphic felsic ignimbrite associated with unwelded ash-fall tuff; 3) felsic crystal tuff, lapilli-tuff, and co-ignimbritic breccias; and 4) stocks and dikes of granitic porphyry, and subordinate equigranular granitic intrusions. The felsic lava flow facies is dominant and represented by massive, bedded and foliated rocks that constitute a system of lava domes. The eruption of rhyolites and ignimbrites, some of them channeled along valleys, was controlled by two major NE-SW lineaments that might have resulted from reactivation of older faults of the Archean basement. Those structures host thick rhyolite and ignimbrite composite dikes that display vertical flow banding and have been emplaced in several intrusive episodes. Stocks and dikes of granitic porphyries, mineralogically and geochemically similar to the rhyolitic flows and ignimbrites, are intrusive into the volcanic and older rocks. The rocks of the Santa Rosa Formation evolved in an extensional tectonic environment and show A-type geochemical signature and peraluminous character.

The rhyolite has generally glomeroporphyritic holocrystalline to hypocrystalline textures with euhedral plagioclase and potassic feldspar phenocrysts surrounded by a felsitic fine-grained groundmass, in which spherulites and granophyric intergrowths are common. Quartz phenocrysts are rounded, reflecting the high degree of magma reabsorption they have undergone. Biotite is rare, whereas fluorite, zircon, Fe-Ti oxides, and apatite make up the suite of primary accessory minerals.

The ignimbrite exhibits welded flow-like eutaxitic texture defined by cryptocrystalline and fine-grained beds that alternate with felsitic, locally spherulitic, groundmass. Dark to light red ash-fall tuffs present thin-laminated parallel structures; dispersed angular-shaped fine quartz and feldspar crystals; and felsic lithic fragments. Unwelded, slightly compacted ash-fall tuffs show characteristically Y- and cuspate-shaped glassy shards. The crystal tuffs and lapilli-tuffs associated with ignimbrites comprise purple and light pink felsic rocks with abundant angular shaped ash- to lapilli-sized feldspar and quartz crystal fragments, and minor rhyolite fragments set in a fine- to medium-grained volcaniclastic groundmass. Zircon, Fe-Ti oxides, and apatite are accessories.

Granitic porphyries are massive, light pink to reddish pink, and consist of coarse potassic feldspar, and plagioclase phenocrysts (up to 5 cm long), and quartz megacrysts immersed in a dark pink, reddish pink or black microgranitic groundmass, which reveals anhedral quartz and potassic feldspar grains and granophyric intergrowths. Biotite is also rare, while zircon, fluorite, titanite, apatite, and minor magnetite and ilmenite are accessories.

4 **METHODS**

All rock samples from the Sobreiro and Santa Rosa formations were collected in outcrops. Two hundred thin sections were prepared from selected samples for petrographic work, which was refined with scanning electron microscopy (SEM) and X-ray powder diffraction (XRD). The SEM analyses of 16 samples were performed in a Leo-Zeiss 1430 model microscope coupled with a Gatan Mono-CL and Sirius-SD dry EDS (Energy-dispersive X-ray Spectroscopy) housed at the Electron Microscopy laboratories of the Geoscience Institute (Pará Federal University) and Brazilian Geological Survey (CPRM). For the operational conditions were used an electron current = 90 μA, a constant acceleration voltage = 20 kV, and a work distance = 15 mm. The XRD spectra for 17 samples were obtained with X'Pert PRO diffractometer (PANalytical PW3040/60), equipped with a PW3050/60 goniometer (Theta/Theta) and a ceramic X-ray tube with Cu anode (CuKa1 = 1.540598 Å). The operating conditions were: a 40 mA current, a 40 kV voltage, a 0.02º (2θ) step size, a count time of 5 s, and a 5−75º (2θ) angular range. The mineral phases were indexed using the PDF-ICDD database (Powder Diffraction File – International Center for Diffraction Data).

5 HYDROTHERMAL ALTERATION

Rocks of the Sobreiro and Santa Rosa formations show incipient, pervasive, and fracture-controlled (stockwork pattern) hydrothermal alteration styles. Four main types of hydrothermal alteration have been recognized in the studied samples: propylitic, sericitic, intermediate argillic, and potassic (Fig. 2). Overprinting is common in several samples. Subordinate fracture-controlled silicification also occurs, forming an assemblage of quartz + hematite + carbonate. A description of these types of hydrothermal alteration is presented below.

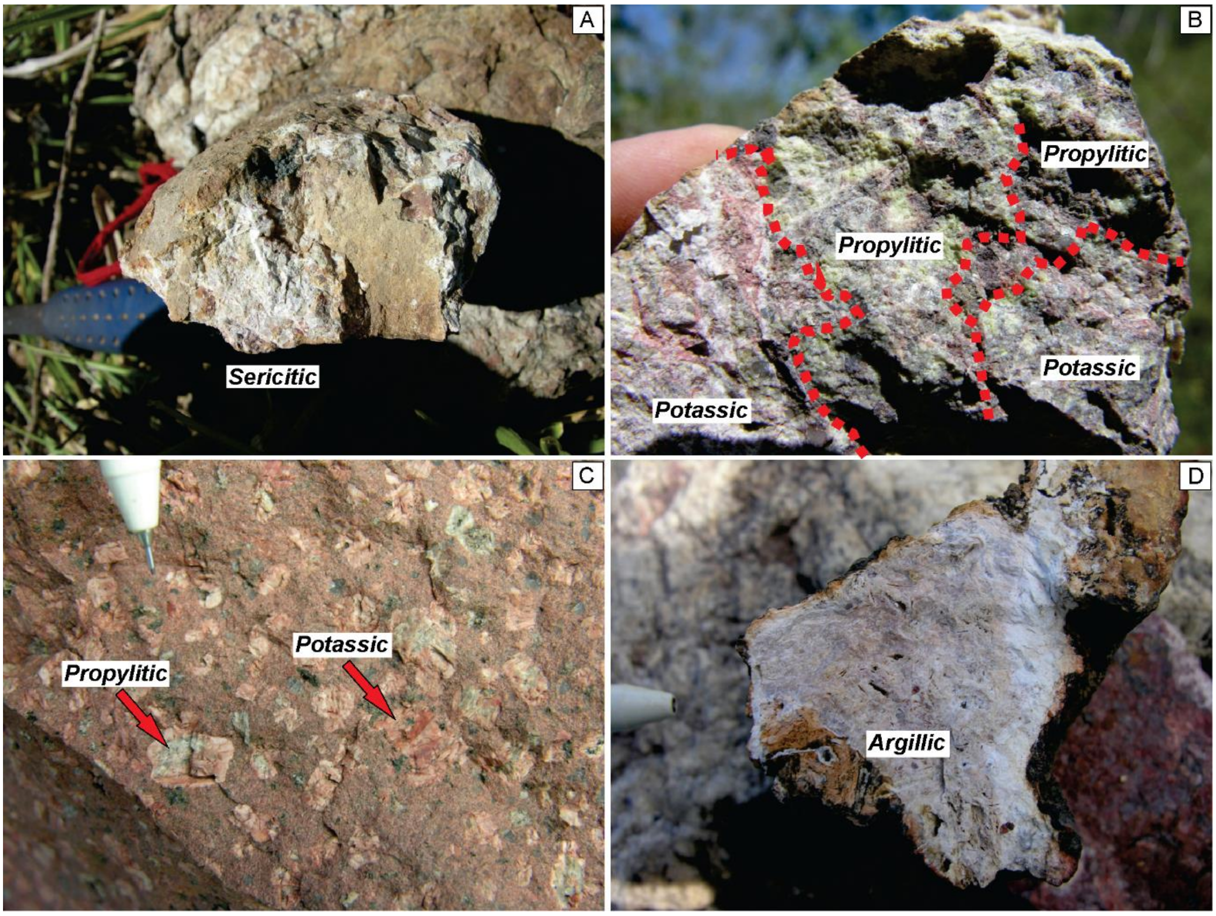


Figure 2 – Representative samples of the distinct hydrothermal alteration types. A) Sericitic alteration developed in rhyolite of the Santa Rosa Formation; B) Propylitic alteration overprinted by potassic alteration in sample of the Sobreiro Formation; C) Granitic porphyry of the Santa Rosa Formation affected by with propylitic and potassic alterations (reddish plagioclase); and D) Intermediate argillic alteration present in rocks of the Santa Rosa Formation.

5.1 SOBREIRO FORMATION

5.1.1 **Propylitic alteration**

The propylitic alteration affected incipiently to pervasively the rocks of this unit. Locally, phenocrysts of plagioclase, clinopyroxene or amphibole were completely destroyed and pseudomorphically replaced by propylitic selvages. Fracture-controlled style occurs where the rocks were subjected to brittle mechanical regime and is marked by an array of veins and veinlets. Propylitization lends a characteristic green color to the rocks (Figs. 3A, B) and is represented by assemblages consisting of epidote + chlorite + carbonate + clinozoisite + sericite + quartz ± albite ± hematite ± pyrite. Prehnite and pumpellyite are locally found as fracture-filling minerals.

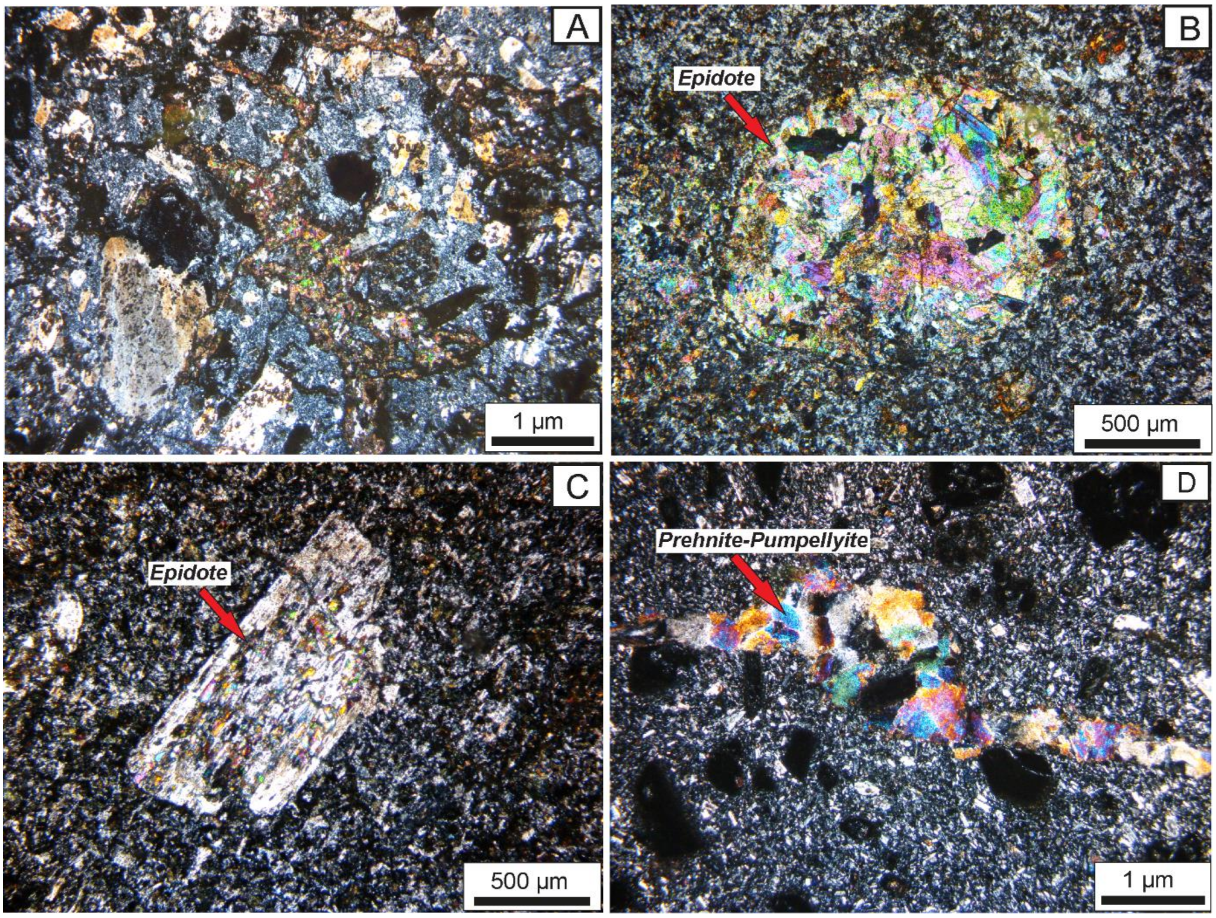
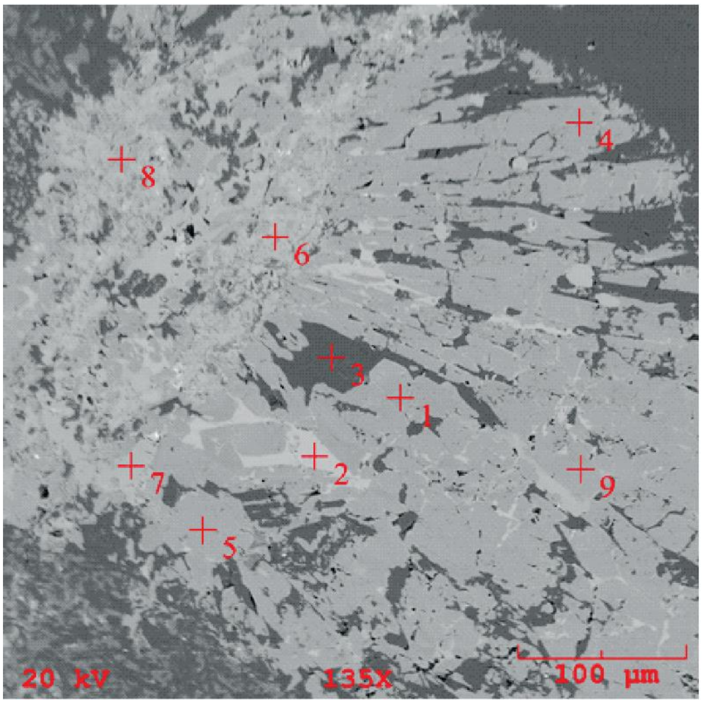


Figure 3 – Photomicrographs depicting the propylitic alteration that affected the Sobreiro Formation. A) Propylitic alteration represented by abundant epidote in dacite; B) Amygdale filled with epidote in plagioclase dacite; C) Epidote and sericite replacing a plagioclase phenocryst in plagioclase-amphibole-phyric andesite; D) Prehnite-pumpellyite filling a fracture in amphibole-plagioclase-clinopyroxene-phyric basaltic andesite.

Epidote replaces partially to completely plagioclase, amphibole, and clinopyroxene phenocrysts, and it is associated with clinozoisite and sericite, especially when dispersed in the groundmass. Usually epidote forms medium-sized, euhedral to anhedral crystals, which locally develop clusters together with chlorite and quartz. Clinozoisite forms euhedral to subhedral prismatic crystals, normally associated with anhedral carbonate and chlorite grains. Complementary EDS backscattered-electron analysis shows the hydrothermal texture of epidote as a constituent of the propylitic association (Fig. 4).



Plagioclase-phyric dacite						
Point	Mineral	% Element				
		O	Al	Si	Ca	Fe
5	Epidote	38,427	12,513	20,145	17,809	11,106

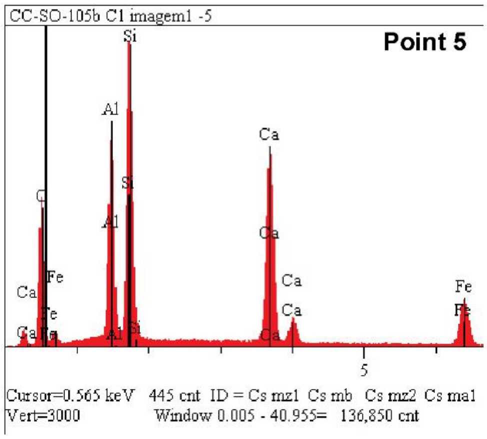
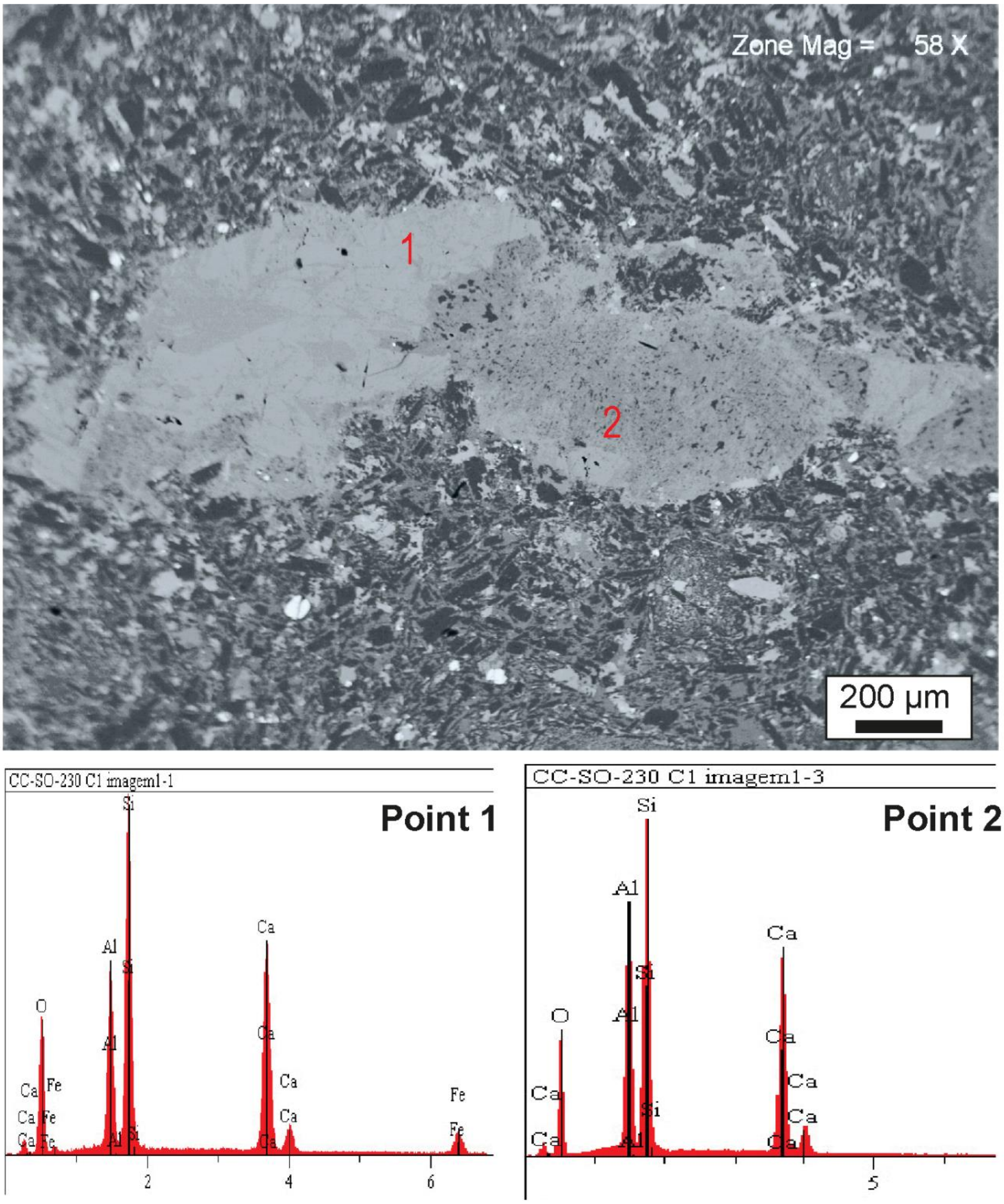


Figure 4 – Back-scattered electron image by SEM showing pervasive propylitic alteration, as well the spectrum with the respective values of the EDS analysis for epidote.

Chlorite is usually yellow-greenish in natural light. The common filling of millimetric to centimetric-thick fractures by chlorite, prehnite, epidote, carbonate, quartz, and hematite accounts for this fracture-controlled style of chlorite occurrence.

The prehnite-pumpellyite association is fine-grained and shows radiated habit when dispersed in the groundmass of andesites. Locally it occurs as fracture filling minerals (Fig. 3D). Locally, it is observed chlorite pseudomorphosed by the prehnite-pumpellyite association. Figure 5 shows an EDS backscattered-electron image and the composition of these minerals in fractures.

Calcite forms fine, anhedral grains, and locally amorphous aggregates, which fill intergranular spaces irregularly. It generally replaces amphibole crystals, commonly associated with sericite, chlorite, and oxide minerals. Hematite is essentially a veinlet constituent. Barite, pyrite, and manganese oxides occur associated with the groundmass of the andesites.



Amphibole-plagioclase-clinopyroxene-phyric basaltic andesite						
Point	Mineral	% Element				
		O	Al	Si	Ca	Fe
1	Pumpellyite	40,52	10,84	23,02	20,27	5,345
2	Prehnite	41,39	14	23,9	20,72	

Figure 5 – Back-scattered electron image by SEM of prehnite-pumpellyite association with their spectra and EDS analysis.

5.1.2 **Sericitic alteration**

The sericitic alteration is represented by the assemblage sericite (fine-grained muscovite grains) + quartz + carbonate ± muscovite and replaces plagioclase phenocrysts and the groundmass (Figs. 6A, B). It occurs mainly in volcaniclastic rocks and mafic crystal tuffs, and reveals incipient to pervasive styles, although locally is fracture-controlled. Less significant than the propylitic type, the sericitic alteration is superimposed upon it, as shown by the chlorite and epidote remains of the previous stage, and obliterated partially to completely the rock texture, of which the sericitized plagioclase pseudomorphs are the only record left.

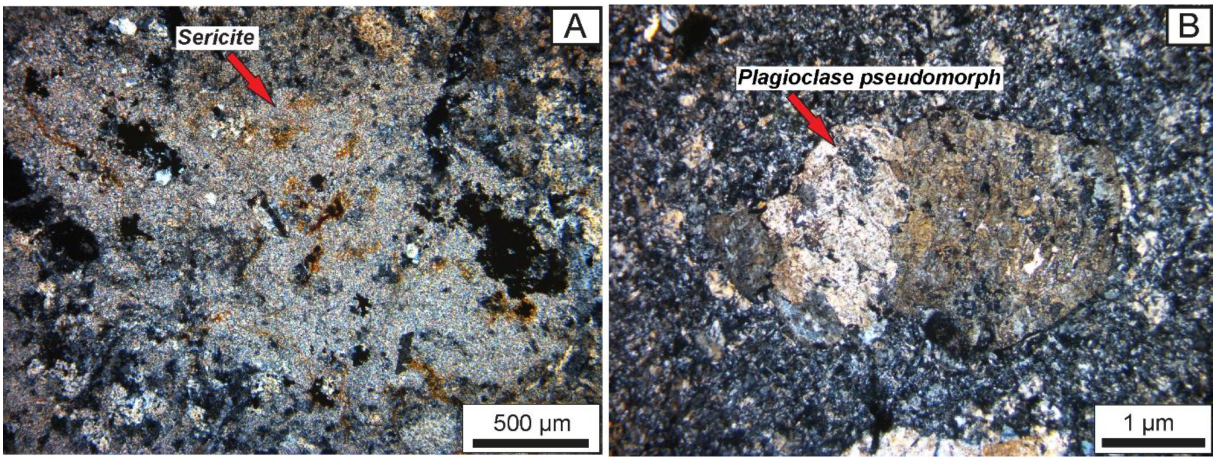


Figure 6 – Photomicrographs depicting the hydrothermal alteration sericitic that affected the Sobreiro Formation. A) and B) Plagioclase pseudomorphs after pervasive sericitic alteration in quartz-phyric rhyodacite and plagioclase-quartz-potassic feldspar-phyric dacite, respectively.

Very fine-grained sericite/muscovite lamellae resulted from the partial to total alteration of plagioclase crystals. Quartz occurs as anhedral crystals, locally rounded, exhibiting undulose extinction and usually develops ribbons and fine-grained crystals. Quartz veins are texturally diverse, the comb type being a common feature, especially in samples from outcrops with stockwork structures. Carbonate usually replaces the plagioclase of the groundmass. Locally, it fills fractures associated with quartz.

5.1.3 **Potassic alteration**

In some samples, the potassic metasomatism is evident in mesoscopic scale, since it dyed the andesites with a reddish color, which has arisen from the growth of hydrothermal potassic feldspar. This metasomatism represents the final stage of the hydrothermal alteration in the area and may be related to fluids sourced from more evolved magmas, probably with a geochemical signature similar to that of the upper Santa Rosa Formation.

Based on textural features, temporal relationships were defined for the hydrothermal minerals (Fig. 7). After the magmatic stage, hydrothermal alteration caused the propylitization of clinopyroxene and amphibole, producing epidote, calcite, chlorite, clinozoisite, opaque minerals, and quartz. Sericitic alteration is developed next, breaking down partially plagioclase and potassic feldspar phenocrysts as well as the groundmass minerals. At last, local potassic alteration was set forth, but apparently did not affect all rock types.

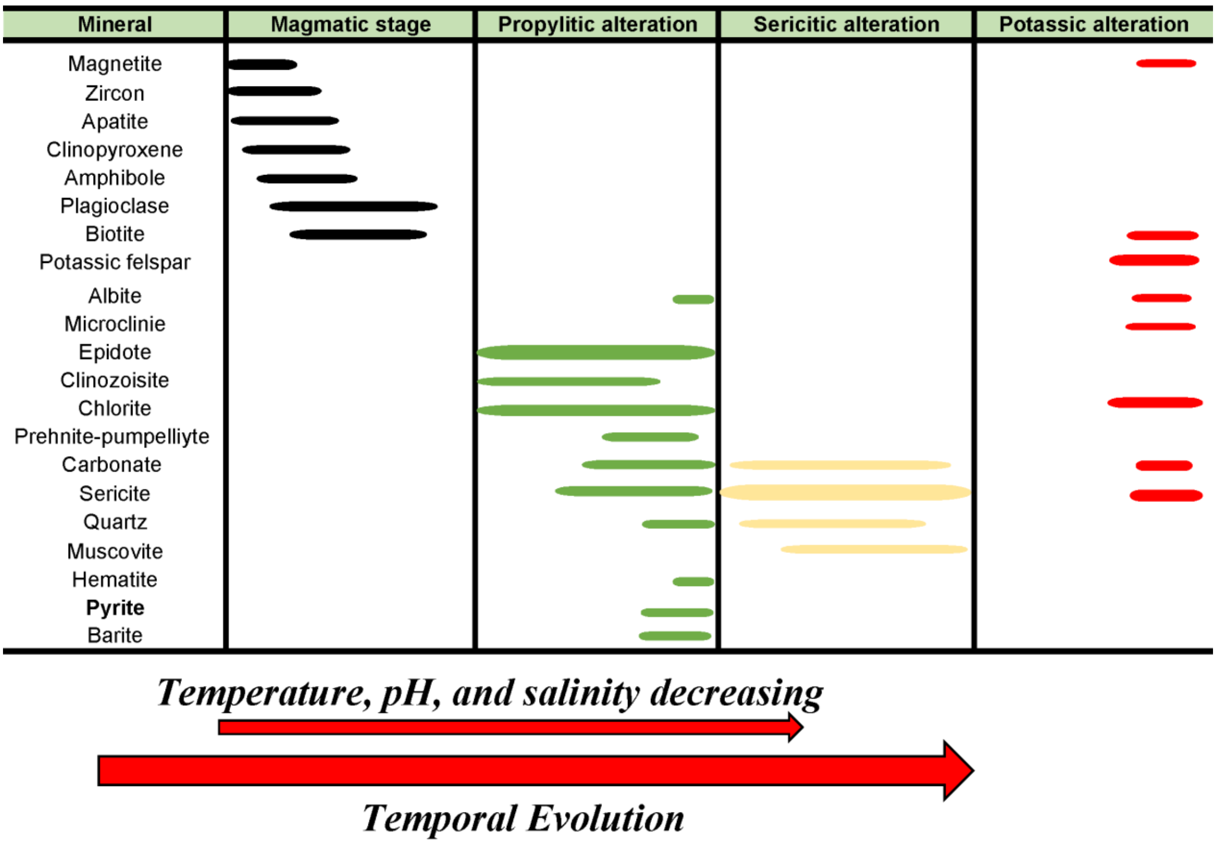


Figure 7 – Sketch with temporal evolution of the hydrothermal alterations related to Sobreiro Formation. The physico-chemical changes are inferred from mineral stability fields.
Font: (Pirajno, 2009).

5.2 SANTA ROSA FORMATION

5.2.1 **Potassic alteration**

The potassic alteration is subordinate and represented by the assemblage microcline + biotite + magnetite. It normally occurs in granitic porphyries and, less commonly, in rhyolites. Locally it develops fracture-controlled style mainly in the granitic porphyries. This type of alteration is responsible for the reddish color of the rocks due to the growth of hydrothermal microcline (Figs. 8C, D).

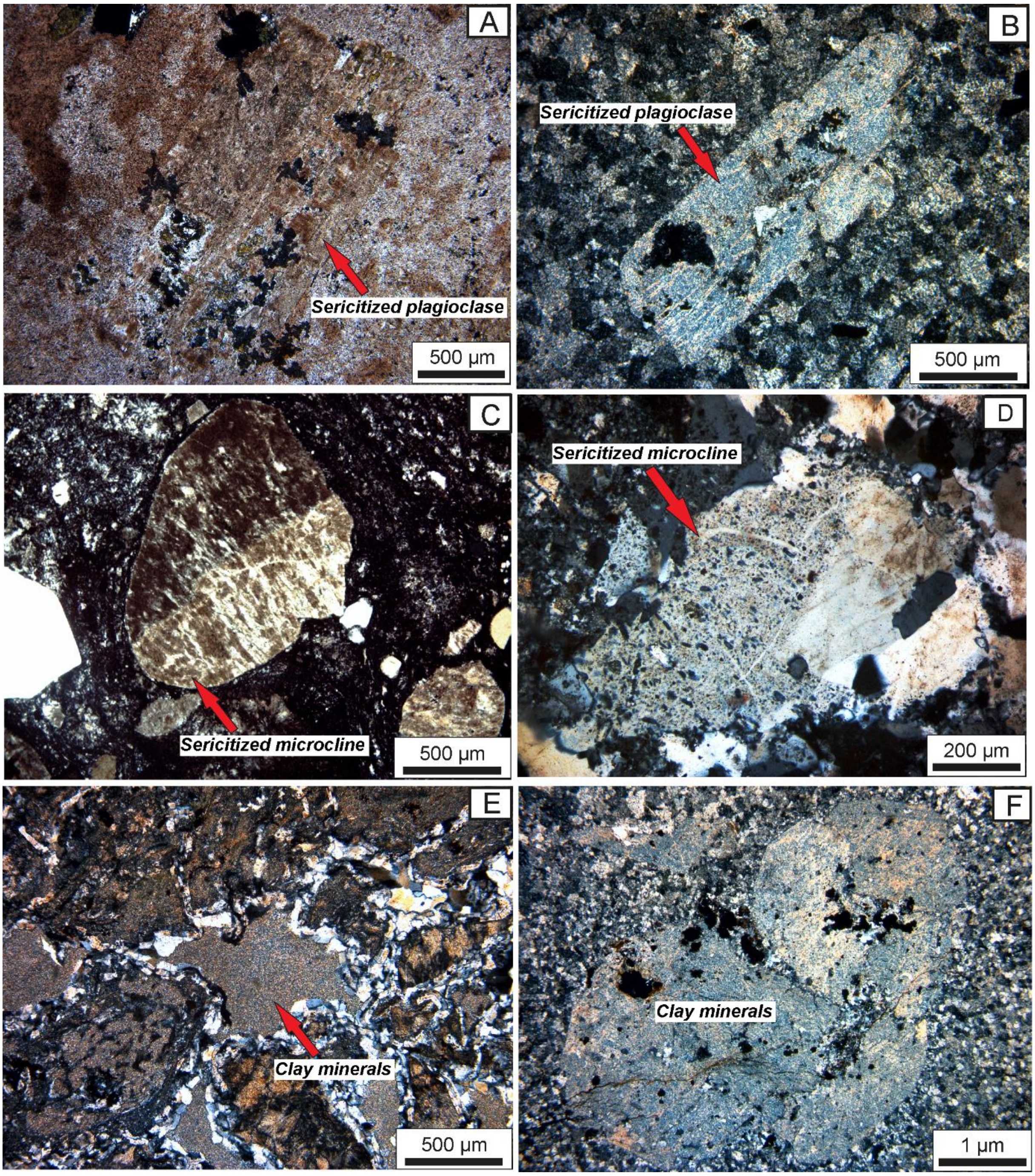


Figure 8 – Representative photomicrographs of alteration types that affect the Santa Rosa Formation. A) and B) Plagioclase pseudomorphs with pervasive sericite development; C) and D) Potassic alteration evidenced by sericitized microcline or hydrothermally generated grains; E) and F) Pervasive argillic alteration imposing total obliteration of the magmatic texture.

Hydrothermal microcline replaces partially to completely magmatic plagioclase and potassic feldspar. Microcline displays fine anhedral crystals that generally surround plagioclase and potassic feldspar phenocrysts, as well as plagioclase microlites of the groundmass. Usually microcline is associated with secondary quartz and is replaced by sericite-muscovite that stabilized in the next alteration stage.

Hydrothermal biotite forms fine, anhedral flakes that are either associated with or replaced by chlorite.

Magnetite grains vary from subhedral to anhedral and form fine aggregates scattered throughout the rock. They usually present exsolution lamellae of ilmenite, evidenced by the trellis texture, and association with titanomagnetite.

5.2.2 **Sericitic alteration**

It is the dominant alteration type identified in this unit. The rocks are variably altered by the assemblage sericite + quartz + carbonate ± potassic feldspar. Locally, the fracture-controlled style is recognized by the occurrence of veinlets that transect the rocks or just the phenocrysts (Figs. 8A, B). The groundmass is flooded with sericite, causing the rock to appear whitish in hand specimen.

Sericite occurs as aggregates of fine lamellae that replace partially to completely potassic feldspar and plagioclase phenocrysts, generating pseudomorphs. In the groundmass, it replaces plagioclase microlites and subordinate potassic feldspar or occurs dispersed in it. This mica is usually associated with quartz and carbonate. Its polycrystalline microgranular appearance makes it difficult to be distinguished from clay minerals in some samples. X-ray spectra highlight well-defined peaks of muscovite, quartz, and microcline (Fig. 9).

Secondary quartz crystals are also fine and often occur as aggregates in the mineral interstices. Carbonate is dispersed throughout the groundmass of rhyolites and granitic porphyries, normally as fine anhedral crystals. Locally, subhedral calcite crystals occur in felsic crystal tuff.

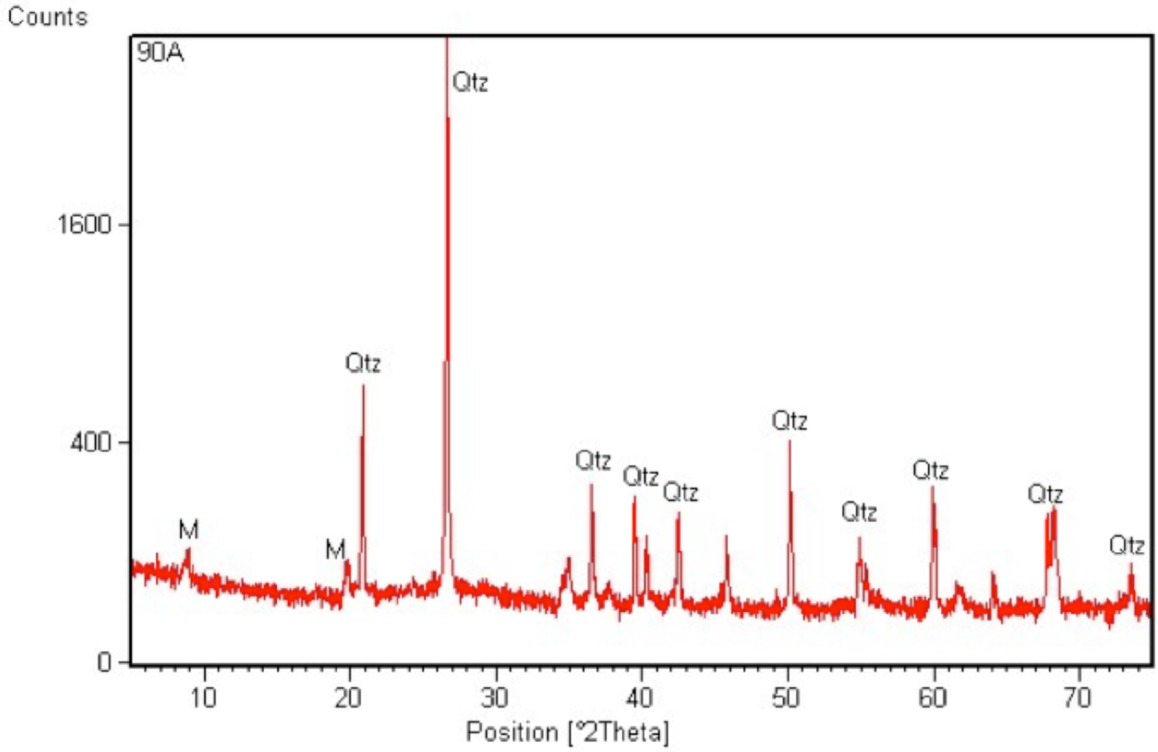


Figure 9 – X-ray diffractogram for potassic feldspar-phyric alkali rhyolite of the Santa Rosa Formation showing the occurrence of muscovite (M) and quartz (Qtz) in sericitic alteration zone.

EDS backscattered-electron analyses reveal also the occurrence of gold, rutile, Ce-monazite, and hinsdalite. They show varying shapes and are usually dispersed in the rock or present along micro-fractures (Fig. 10).

By the end of the sericitic alteration, special conditions, particularly fluids largely depleted in K, favored the formation of chlorite that replaced pre-existing minerals, notably hydrothermal biotite. Chlorite displays irregular shapes and radiating arrangements with typical anomalous blue birefringence and is generally associated with carbonate and quartz. Additional sampling is needed to assess whether or not chloritization is a local phenomenon.

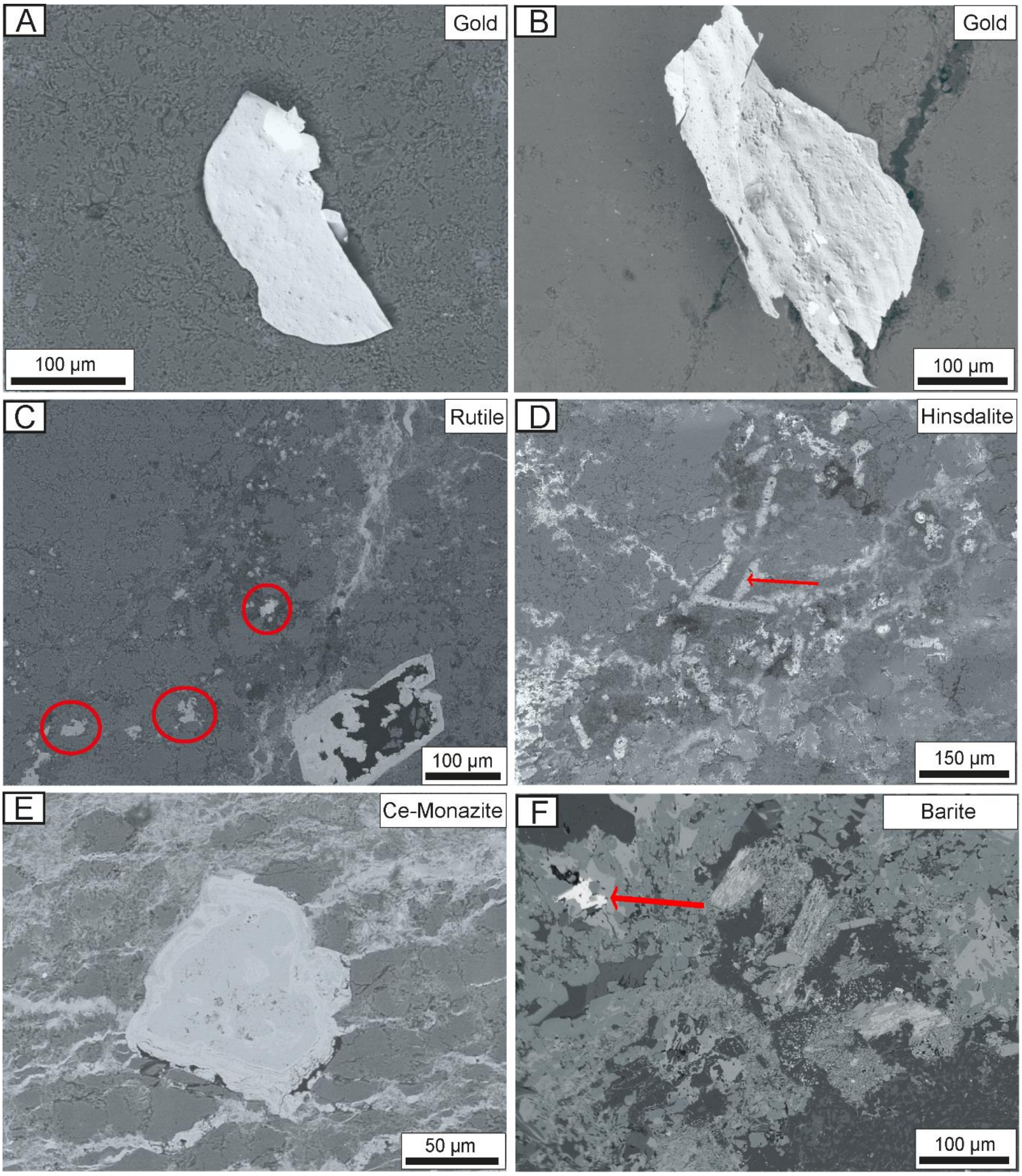


Figure 10 – Back-scattered SEM images showing rare and base metals related to the sericitic and propylitic alterations. A) and B) Gold particles in hydrothermalized rhyolite; C) Scattered rutile grains (red circles) in the rhyolite groundmass; D) Hinsdalite present in hydrothermalized aphyric rhyolite; E) Ce-monazite in rhyolite groundmass; and F) Barite crystals dispersed in hydrothermalized dacite groundmass.

5.2.3 **Intermediate argillic alteration**

The intermediate argillic alteration was recognized in rhyolites (Figs. 8E, F) and comprises montmorillonite + kaolinite + halloysite + illite + chlorite + sericite ± quartz ± hematite. The identification of the clay minerals was based on short-wave infrared spectroscopy data (Cruz *et al*. submitted). This alteration type is also texturally destructive and tinges the rocks white to pink-white, resembling macroscopically the sericitic alteration. Plagioclase and potassic feldspar phenocrysts, as well as microlites of the groundmass, are replaced by irregular masses of clay minerals, sericite, quartz, and ± chlorite. The clay minerals show low crystallinity and usually consist of a mixture of montmorillonite and illite. Figure 11 summarizes the temporal evolution of the hydrothermal alteration zones related to the Santa Rosa Formation.

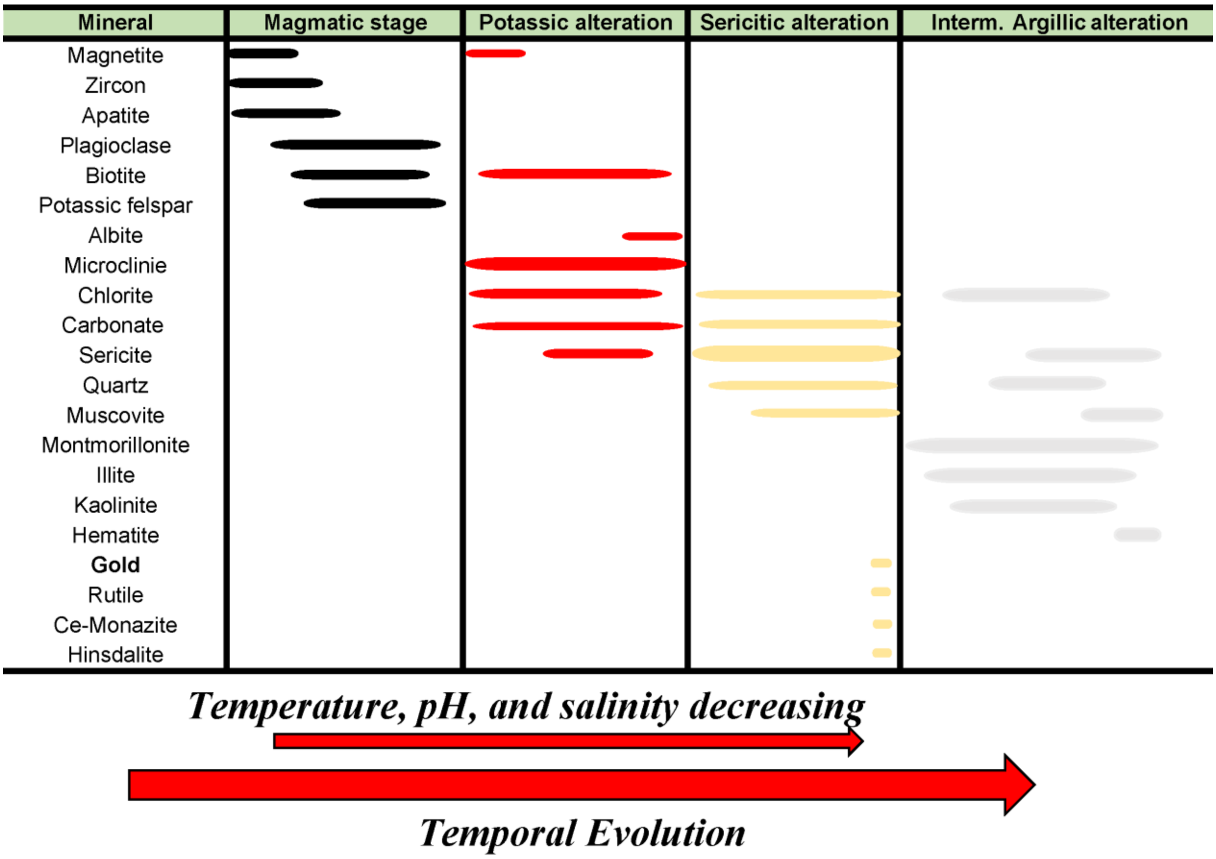


Figure 11 – Sketch with temporal evolution of the hydrothermal alterations related to Santa Rosa Formation. The physico-chemical changes are inferred from mineral stability fields.
Font: (Pirajno, 2009).

X-ray analyses detected also the occurrence of quartz, muscovite, and kaolinite (Fig. 12), reinforcing their presence in the mineral paragenesis of the intermediate argillic alteration in the Santa Rosa Formation. The identification of kaolinite by X-ray diffraction is not straightforward. The precise characterization of this phase is made when there is interplanar spacing of the main diffraction peak at 7 Å. However, uncertainties occur if minerals with interplanar spacing at 14 Å (main peak) are present, since they may produce secondary 7 Å peaks, a common fact when mixtures of phyllosilicates are involved. Anyway, the presence of kaolinite in some rocks has been confirmed by short wave infrared spectroscopy.

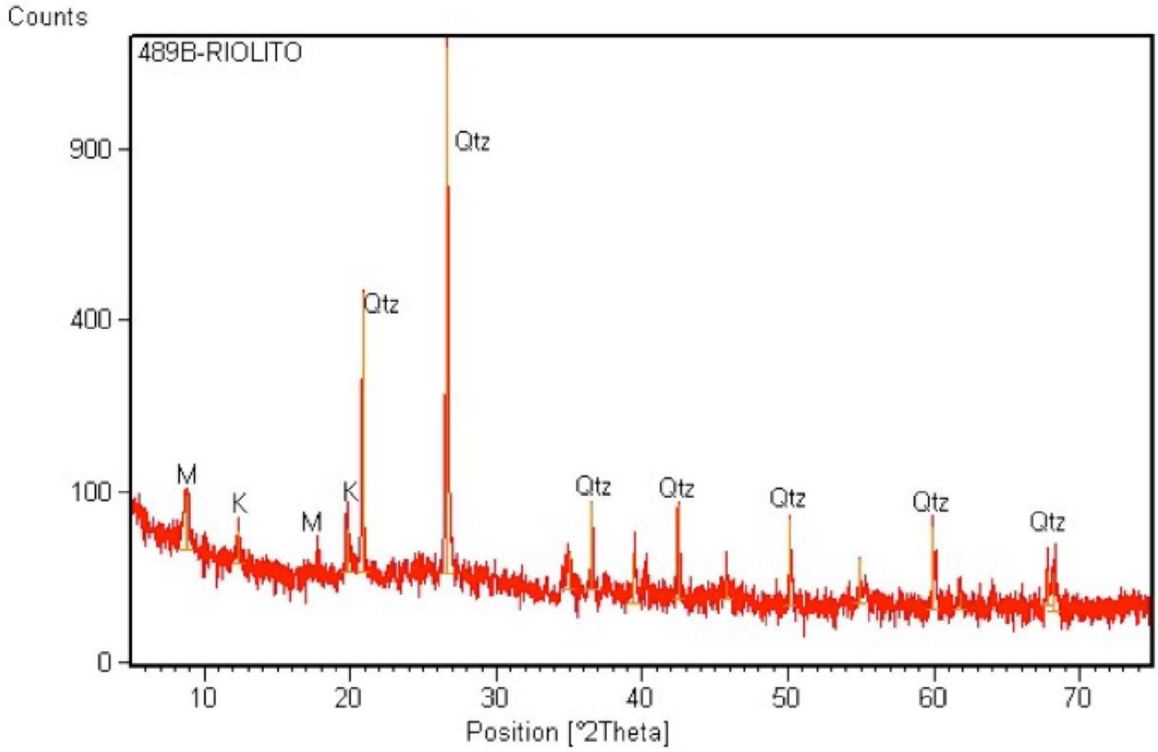


Figure 12 – X-ray diffractogram for aphyric rhyolite of the Santa Rosa Formation showing the presence of muscovite (M), quartz (Qtz), and kaolinite (K) in intermediate argillic alteration zone.

6 **DISCUSSION**

The volcano-plutonic rocks of the Sobreiro and Santa Rosa Formations have been hydrothermally altered at different degrees and extent. In general, the effects of the metasomatic processes are more evident in the Santa Rosa Formation. Mineralogical and textural data obtained in this study allowed defining not only the magmatic and hydrothermal associations, but also the paragenetic sequences developed in these units (Figs. 7 and 11). Thermal flow, induced by the cooling of magmas at depth, and the composition of both rocks and hypogene fluids mostly controlled the generation of the different types of hydrothermal alteration. Meteoric waters may have played an important role, given the near surface environment where the alteration processes took place.

No drilling has been performed to date in the study area in the search for mineralized rocks. Gold particles have been found in a few outcrop samples, but they are rare and very fine (Figs. 10A, B). Nevertheless, the volcano–plutonic setting and the types of hypogene hydrothermal alterations already recognized highlight the potentiality for mineralizing systems associated with both the Sobreiro and Santa Rosa formations.

The fluids related to the propylitic assemblages in the Sobreiro Formation could represent a mixture of magmatic aqueous solutions and meteoric waters. Ancient Au-Ag-base metal intermediate- to low-sulfidation mineralizations have been described in modern geothermal fields and interpreted to be genetically associated with pervasive propylitic alteration, which normally marks the outer boundary of these hydrothermal systems (Einaudi *et al*. 2003, Sillitoe & Hedenquist 2003, Sillitoe 2010). Actually, the propylitic alteration is more pervasive towards the inner part of a hydrothermal deposit, whereas in the opposite direction it grades to unaltered or metamorphosed rocks with equivalent paragenesis of the propylitic alteration (Pirajno 2009). These required conditions are included in the assumed petrogenetic modeling for Sobreiro Formation that states its generation by mixing of calc-alkaline mantle-derived magmas and anatectic melts of Archean sources beneath the volcanic sequences in the São Félix do Xingu region and subsequent fractional crystallization (Fernandes *et al*. 2011).

Although further investigation is needed, the prehnite-pumpellyite phases that occurs associated with the propylitic alteration in the rocks of the Sobreiro Formation suggests low-grade metamorphic geothermal conditions related to the percolation of hydrothermal fluids (Frey & Robinson 1999). These conditions favor the stability of chlorite + epidote + quartz + carbonate. On the other hand, the absence of actnolite indicates that the temperature did not exceed 350 °C (Laird 1988). Propylitic alteration occurs under almost the same range of temperatures needed for prehnite-pumpellyite facies formation. Although, CO_2 pressures in propylitic alteration must be higher than those for low-grade geothermal metamorphism facies (Seki 1973). The well-defined stability fields of prehnite–pumpellyite make them very useful monitors of temperature and depth in epithermal and porphyry-type mineralizing systems (Sillitoe 2010), allowing to estimate the proximity to the heat source and metal deposition zone.

The potassic alteration, which predates the sericitic alteration in the Santa Rosa Formation, evolved at relatively greater depths and temperatures, and resulted most likely from the interaction between the volcanic rocks and residual aqueous fluids exsolved from magmas. The Santa Rosa Formation has been interpreted as having a fissure-controlled polyphasic origin, its magmatic chamber being recharged with successive pulses of exclusively crustal K-rich magmas until the total sealing of the system with granitic porphyries and equigranular granitic intrusions (Juliani & Fernandes 2010). The crystallization of these magmas surely released fluids with high a_{K+}/a_{H+} ratios that would be responsible for the potassic alteration of the volcanic pile.

As the fluid temperature and a_{K+}/a_{H+} (precipitation of potassic alteration minerals) decreased, the sericitic alteration was set forth, destroying preferentially the feldspars and releasing silica. The entry of meteoric water may have caused an increase in the fluid oxygen fugacity as evidenced by the formation of hematite that precipitated together with quartz in veins.

Later on, concomitantly with the continuous drop in temperature, the aqueous solutions became progressively less acid due to the large consumption of H^+ during the previous alteration stages. These solutions were still capable of destroying pre-existing minerals, mainly feldspars, leading to the partial leaching of alkalis from the system and the consequent formation of clay minerals. As a result, the rocks of the Santa Rosa Formation underwent an intermediate argillic alteration, which commonly develops at temperatures between 100 – 300 °C and fluid pH near neutrality (Gifkins *et al*. 2005, Pirajno 2009). These conditions and the resulting clay-mineral association (montmorillonite + kaolinite/halloysite + illite) are very similar to those described in low- and intermediate-sulfidation mineralization systems. Although the kaolinite/halloysite association can be produced by supergene processes, the occurrence of these clay minerals in the São Félix do Xingu region are restricted to the hydrothermalized centers, suggesting a hypogene origin.

Previous work in the São Felix do Xingu region (Lagler *et al*. 2011) describes fluorite, barite, alloclasite, sphalerite, and galena in rocks of the Sobreiro Formation, and colloidal pyrite, barite, sphalerite, chalcopyrite, and alloclasite associated with sericitic alteration, in addition to fluorite, phengite, silver inclusions in barite, and alunite in rocks of the Santa Rosa Formation. The present study records also gold, rutile, hinsdalite, Ce-monazite associated with sericitic alteration in the Santa Rosa Formation, and barite associated with propylitic alteration in the Sobreiro Formation. All these data, plus the occurrence of clay mineral-rich alteration zones, are suggestive that intermediate- to low-sulfidation epithermal systems may be hosted in these units, revealing their potential for mineral exploration.

Significantly, Paleoproterozoic high-sulfidation epithermal mineralization has been recorded in calc-alkaline felsic volcanic rocks of the Iriri Group (Juliani *et al*. 2005). More recently, a genetically related Au-(Cu, Mo) porphyry-type deposit was recognized in the calc-alkaline Paleoproterozoic Palito Granite (Juliani *et al*. 2012) in the Tapajós Mineral Province. Specifically in the case of the São Félix do Xingu region, the morphology and close arrangement of lava flow facies, granitic porphyry, equigranular granitic intrusions, and co-genetic volcaniclastic facies of the Santa Rosa Formation in some portions points to an evolution related to nested ash flow calderas, as proposed by Lipman (1984) elsewhere. This model could explain the episodic magmatic recharge and the potassic metasomatism that overprinted previous alteration zones in the volcanic rocks. Thus, the integration of the available data leads to the conclusion that similar mineralizations and hydrothermal alteration types have developed in the volcano–plutonic covers, which show geochemical signatures similar to those of the Iriri Group and Palito granite. The existence of potential high-sulfidation epithermal mineralizing systems related to the A-type fissure-controlled Santa Rosa Formation suggests that at least part of this unit shall have high-K calc-alkaline geochemical signature – one of the criteria used by Arribas Jr (1995) to characterize this type of mineralization.

Based on these constraints and interpretations, several prospective models can be proposed for other areas of the Amazon craton where Paleoproterozoic volcano–plutonism has taken place (Lamarão *et al*. 2002, Barros *et al*. 2009, Ferron *et al*. 2010).

7 **CONCLUSIONS**

The present study investigated the volcanic rocks that occur in the São Felix do Xingu region. The results allowed characterizing several hypogene hydrothermal alterations and evaluating its metallogenetic potential. The alteration types and styles suggest a genetic relationship with volcano–plutonic systems and possible meteoric water contribution, thus defining this region as a new horizon for mineral exploration of rare and base metals in the Amazonian craton, especially those related to epithermal and porphyry-type deposits. If successful, the prospective models could be tested in areas of similar geological and geochemical characteristics in large Proterozoic volcano–plutonic covers of the Amazonian craton.

Apparently, the Sobreiro and Santa Rosa formations triggered distinct hydrothermal systems, consonant with their different geological, geochemical, geochronological, and tectono-magmatic affinity characteristics. However, a unique hydrothermal paleo-system should not be discarded. Further investigation is needed to support either hypothesis.

The Sobreiro Formation shows mainly pervasive to fracture-controlled propylitic alteration, and minor sericitic and potassic alterations. The presence of the prehnite-pumpellyite association in this unit suggests low-grade metamorphic conditions similar to those observed in modern geothermal fields. In the Santa Rosa Formation, the most common hydrothermal alterations are potassic, intermediate argillic, and sericitic. The latter bears evidence of gold mineralization and accessory phases compatible with intermediate- to low-sulfidation epithermal mineralizing systems. The intermediate argillic alteration and fracture-filling textures suggest formation in brittle mechanical regime and possible ash flow caldera environment.

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CAPÍTULO IV

CONSIDERAÇÕES FINAIS

Na região do município de São Félix do Xingu, localizado na Província Mineral de Carajás, SE do Cráton Amazônico (Almeida *et al.* 1981), ocorrem extensos centros vulcano–plutônicos efusivos e explosivos paleoproterozoicos, agrupadas nas formações Sobreiro e Santa Rosa (Juliani e Fernandes 2010), que são unidades geológica-, geocronológica-, e petrologicamente distintas. Os resultados deste trabalho permitiram caracterizar várias alterações hipogênicas hidrotermais e avaliar o seu potencial metalogenético.

Na Formação Sobreiro propilitização é o processo de alteração mais importante reconhecido nesta unidade, apresentando ambos os estilos pervasivo e fissural. A paragênese resultante consiste de epidoto + clorita + carbonato + clinozoisita + sericita + quartzo ± albita ± hematita ± pirita, que é sobreposta por alteração potássica pervasiva ou controlado por fratura, representada principalmente por feldspato potássico + biotita ± hematita. Alteração sericítica é menos abundante, e é representada pela assembleia de sericita + quartzo + carbonato ± epidoto ± clorita ± muscovita que ocorre principalmente nas rochas vulcanoclásticas e tufos de cristal máfico. Seus estilos vão desde incipiente a pervasivo, sendo localmente controlado por fratura. Localmente, ocorre fratura com associação prehnita-pumpellyita precipitada que poderia estar relacionado com metamorfismo de baixo grau.

Os tipos de alteração hidrotermal mais comuns na Formação Santa Rosa são sericítica e potássicos, resultando em paragênese mineral representado por sericita + quartzo + carbonato ± feldspato potássico, e biotita + clorita + microclina + carbonato + sericita ± albita ± magnetita, respectivamente. Essas alterações são ambas pervasiva e onde, comumente se desenvolve padrão *stockwork* é controlado por fratura. Ouro, muito geralmente de grão fino, ocorre na zona sericítica e foi identificado por MEV (Microscopia Electrônica de Varredura), embora em algumas amostras de mão suas partículas são suficientemente grossas para ser observadas a olho nu. A alteração argílica intermediária também foi reconhecida, mas os minerais de argila são muito difíceis de ser devidamente identificados com técnicas de petrografia convencionais.

Trabalhos anteriores em São Felix do Xingu (Lagler *et al*. 2011) descreve fluorita, barita, alloclasita, esfalerita, e galena em rochas da Formação Sobreiro, e pirita coloidal, barita, esfalerita, calcopirita, e alloclasita associado com alteração sericítica, além de fluorita, fengita, inclusões de prata em barita, e alunita em rochas da Formação Santa Rosa. Os atuais registros do estudo também mostram a ocorrência de ouro, rutilo, hinsdalita, Ce-monazita associados com alteração sericítica na Formação Santa Rosa, e barita associada com alteração propilítica na Formação Sobreiro. Todos esses dados, além da ocorrência de zonas de alteração ricas em minerais de argila, são sugestivos de que sistemas epitermais de intermediária-baixa sulfidação pode ser hospedado nestas unidades, revelando seu potencial para a exploração mineral.

Significativamente, mineralização epitermal paleoproterozoica de alta sulfidação foi reconhecida em rochas vulcânicas cálcio-alcalinas félsicas do Grupo Iriri (Juliani *et al*., 2005). Mais recentemente, um depósito de Au- (Cu, Mo) do tipo pórfiro geneticamente relacionado foi reconhecido no Granito paleoproterozoico Palito, cálcio-alcalina (Juliani *et al*., 2012) na Província Mineral do Tapajós. Especificamente no caso da região de São Félix do Xingu, a morfologia e arranjo das fácies fluxo de lava, granito pórfiro, intrusões graníticas equigranulares, e fácies vulcanoclásticas cogenéticas da Formação Santa Rosa, em algumas partes aponta para uma evolução relacionada com um modelo de *ash-flow caldera*, como proposto por Lipman (1984) em outros lugares. Esse modelo poderia explicar a recarga magmática episódica e o metassomatismo potássico que secciona zonas de alteração anteriores nas rochas vulcânicas. Assim, a integração dos dados disponível conduz à conclusão de que a mineralização e tipos de alteração hidrotermal que se desenvolveram nas coberturas vulcano-plutônicas, mostram assinaturas geoquímicas semelhantes aos do Grupo Iriri e Granito Palito. A existência de potenciais sistemas de mineralização epitermal de alta sulfidação relacionados à Formação Santa Rosa fissural tipo-A, sugere que pelo menos parte desta unidade deverá ter assinatura geoquímica cálcio-alcalina alto-K, um dos critérios utilizados pelo Arribas Jr (1995) para caracterizar este tipo de mineralização.

Aparentemente, as formações Sobreiro e Santa Rosa desencadearam sistemas hidrotermais distintos, em consonância com a suas diferentes características de afinidade geológicas, geoquímicas, geocronológicas e tectono-magmática. No entanto, um único paleo-sistema hidrotermal não deve ser descartado. É necessário mais investigação para apoiar qualquer hipótese. Sabe-se, portanto, que os tipos e estilos de alteração sugerem uma relação genética com os sistemas vulcano-plutônicos e uma possível contribuição de água meteórica, definindo, assim, esta região como um novo horizonte para a exploração mineral de metais raros e de base no Cráton Amazônico, especialmente aqueles relacionados à depósitos epitermais e do tipo pórfiro.

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