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**PETROLOGIA MAGNÉTICA E QUÍMICA MINERAL DOS
GRANITOIDES MESOARQUEANOS DE OURILÂNDIA DO
NORTE (PA) - PROVÍNCIA CARAJÁS**

Dissertação apresentada por:

ALINE COSTA DO NASCIMENTO

Orientador: Prof. Dr. Davis Carvalho de Oliveira (UFPA)

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ALINE COSTA DO NASCIMENTO**

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“Ser estudante é não perder a esperança e ânimo
quando tudo parece ser tão irrecompensável
É vencer o cansaço depois de um dia de rotina
É vencer obstáculos sem medo de errar
É repousar no desejo de que a vida para ser edificada
Precisa ser enfrentada dia a dia
É ter sabedoria para trilhar um caminho ético e digno
Apesar de nem sempre ter exemplos éticos de professores
É construir suas próprias opiniões e saber transmiti-las com êxito
Ser estudante é muito mais que aceitar o conhecimento imposto
É refletir e ter senso crítico sobre a vida”.

Essa mensagem ainda é válida e foi escrita pela autora durante a graduação em Geologia para retratar as dificuldades enfrentadas e os momentos de retrocesso na educação brasileira.

Aline Costa do Nascimento

RESUMO

A área de Ourilândia do Norte está situada na porção centro-oeste da Província Carajás, no limite entre os domínios Rio Maria (DRM) e Carajás (DC), onde afloram três principais grupos de granitoides mesoarqueanos (2,92-2,88 Ga), assim distinguidos: (i) leucogranitos e granodiorito alto-Ti associado – compreendem monzogranitos equi- a heterogranular e granodiorito porfirítico enriquecido em titanita. Ambos apresentam biotita como principal fase máfica, ausência de anfibólio, além de xenólitos do embasamento TTG; (ii) sanukitoides – constituídos por granodioritos (equigranular, heterogranular e porfirítico), com tonalito, quartzo monzodiorito e quartzo diorito subordinados. Caracterizam-se pela presença de hornblenda como mineral varietal e inúmeros enclaves máficos; e (iii) trondhjemitos - representado como um granitoide porfirítico com finos enclaves máficos. A partir do estudo de suscetibilidade magnética (SM) estes granitoides foram divididos em três populações magnéticas: (i) baixos valores de SM (A; SM varia de $0,05 \times 10^{-3}$ a $0,57 \times 10^{-3}$ SI) – caracteriza-se pela escassez de fases opacas, onde há predominância de sanukitoides e trondhjemitos; (ii) valores intermediários de SM (B; SM entre $0,59 \times 10^{-3}$ a $2,35 \times 10^{-3}$ SI) – o conteúdo modal de ilmenita prevalece sobre o de magnetita, e há variáveis proporções de sanukitoides e leucogranitos; e (iii) altos valores de SM (C; SM $2,35 \times 10^{-3}$ a $17,0 \times 10^{-3}$ SI) – é constituída essencialmente por magnetita, e a ilmenita ocorre subordinada como os tipos texturais em treliça e composta; e os leucogranitos e granodiorito alto-Ti predominam sob os sanukitoides. Os anfibólios foram classificados como magnesio-hornblenda, razão $Mg/(Mg+Fe^{+2}) \geq 0,70$, com subordinada ocorrência de ferropargasita e actinolita-hornblenda. No trondhjemitos, o anfibólio ocorre como mineral acessório, e é classificado como magnesio-hornblenda e tschermakita. A biotita apresenta razão $Fe^{+2}/(Mg + Fe^{+2}) < 0,6$ nos leucogranitos e granodiorito alto-Ti, e $\leq 0,4$ nos sanukitoides e trondhjemitos. O plagioclásio foi classificado como oligoclásio, com menor ocorrência de albita, sem significativa variação composicional entre fenocristais e matriz; comumente é encontrado com alteração para sericita. Epidoto e titanita ocorrem sob a forma de quatro tipos texturais, porém foram analisados dois principais tipos texturais, o primeiro associado aos minerais ferromagnesianos e atribuído a origem magmática e o segundo ocorre nos planos de clivagem de biotita, de origem tardi-magmática. Em termos do conteúdo de pistacita no epidoto $\{Ps = [Fe^{+3}/(Fe^{+3} + Al)] \times 100\}$, valores entre Ps 25 a 36 %, 26 a 36 %, e 22 a 30 %, foram estimados para os leucogranitos, sanukitoides e trondhjemitos, respectivamente, além de $TiO_2 \leq 0,137$ %. Tais valores indicam origem magmática. Estimativas de temperatura baseadas na saturação de zircão (T_{Zr}) e apatita (T_{Ap})

em rocha total variam de T_{Zr} 841-990 °C e T_{Ap} 884-979 °C (leucogranitos e granodiorito alto-Ti), T_{Zr} 826-972 °C e T_{Ap} 864-886 °C (sanukitoides) e T_{Zr} 853-977 °C e T_{Ap} 909 °C (trondhjemitos), interpretadas como próximo ao *liquidus*. Geotermômetros e barômetros baseados no conteúdo de alumínio no anfibólio indicam temperaturas entre 738-811 °C (sanukitoides) e 779-892 °C (trondhjemitos), com pressão entre 100 a 280 MPa, representando condições de crosta superior. Entretanto, os valores abaixo de 800 °C denotam que recristalização dinâmica pode ter ocorrido a temperaturas próximas a do *solidus*, conforme a natureza sintectônica destas rochas. Admite-se que as temperaturas e pressões mais baixas estimadas correspondam a condições de abertura do sistema magmático relacionado à deformação. Apesar dos leucogranitos e granodiorito alto-Ti apresentarem relativo enriquecimento de #Fe (rocha total), os mesmos são rochas de afinidade cálcico-alcalina, superpondo-se aos granitos Cordilheiranos com $SiO_2 > 70 \%$, de baixo HFSE (*high field strength elements*), magnetita primária, e elevada SM. Isto é indicativo de que as mesmas foram formadas em condições oxidantes (provavelmente no domínio do tampão $\Delta_{NNO}+2,8$). Os sanukitoides apresentam $FeOt/(FeOt + MgO)$ em rocha total, anfibólio e biotita inferior a 0,7, e moderada a baixa SM, com formação atribuída a condições menos oxidantes (no domínio do tampão $\Delta_{NNO}+1,0$). Admite-se que estas rochas se formaram em tais condições, porém para as variedades de sanukitoides equigranulares e o trondhjemitos estimam-se condições próximo a do tampão $\Delta_{FMQ}+0,5$). A baixa SM e baixo conteúdo de magnetita reportada para os sanukitoides equigranulares e trondhjemitos também pode ser atribuída à formação precoce do epídoto e processos tardi-magmáticos responsável pela desestabilização de magnetita. Conclui-se que o magma precursor dos sanukitoides era hidratado ($H_2O > 4-7 \%$), enquanto $H_2O < 4-7 \%$ foi admitido para os magmas formadores dos leucogranitos e granodiorito alto-Ti; e trondhjemitos, como indicado pela ausência ou escassez de anfibólio e minerais hidratados na paragéneses. Tais resultados são comparados aqueles estimados para rochas cálcico-alcalinas da Suíte Rio Maria na Província Carajás e membros oxidados de outros terrenos Arqueanos a Paleoproterozoicos do Cinturão Báltico, orógeno Sarmatiano (Europa Ocidental), granitos tipo-*Closepet* e granodioritos alto-Mg do plúton Matok (Cinturão Limpopo – África do Sul).

Palavras-chave: Granitoides. Petrologia Magnética. Química Mineral. Arqueano. Província Carajás.

ABSTRACT

The Ourilândia do Norte area is located in the midwestern portion of the Carajás province, whose tectonic segment is comprised between the Rio Maria (RMD) and Carajás domains (CD), where outcrop three main Mesoarchean (2.92-2.88 Ga) granitoids: (i) leucogranite and associated high-Ti granodiorite – are constituted by equi- to heterogranular monzogranites and associated granodiorite with high titanite contents. Both of them have biotite as an essential mafic phase, lack amphibole and host TTG basement; (ii) sanukitoids – are represented by granodiorites (equigranular, heterogranular and porphyritic), with subordinate tonalite, quartz monzodiorite and quartz diorites occurrences. These rocks are characterized by the presence of hornblende as an essential mineral and associated mafic enclaves; and (iii) trondhjemite – represented by porphyritic granitoids with fine-grained mafic enclaves. Based on magnetic susceptibility (MS) studies these granitoids were distinguished into three magnetic populations: (i) lowest magnetic values (A; MS ranging from 0.05×10^{-3} to 0.57×10^{-3} SI) – characterized by rare opaques phases, predominant sanukitoids and trondhjemite; (ii) moderate magnetic values (B; MS 0.59×10^{-3} to 2.35×10^{-3} SI) – the modal ilmenite contents prevails over magnetite, with variable proportions of sanukitoids and leucogranites; and (iii) high magnetic values (C; MS 2.35×10^{-3} to 17.0×10^{-3} SI) – characterized by the highest magnetite contents, with subordinate ilmenite occurrence as *trellis* and composite textural types. The leucogranites and associated high-Ti granodiorite predominate over porphyritic sanukitoid. Amphiboles classify as magnesio-hornblende, characterized by $Mg/(Mg+Fe^{+2})$ ratio ≥ 0.70 , and minor occurrence of ferropargasite e actinolite-hornblende. For the trondhjemite, amphibole occurs as an accessory mineral and corresponds to magnesio-hornblende and tschermakite. Biotite crystals have $Fe^{+2}/(Mg + Fe^{+2})$ ratio down 0.6 in leucogranites and associated high-Ti granodiorite, and lower values (≤ 0.4) in sanukitoids and trondhjemite. Plagioclase crystals are predominantly oligoclase, without significant compositional variations between phenocrysts and matrix, and are frequently replaced by sericite. Although there are four distinct textural types of epidote and titanite, were investigated two main textural types: the former has magmatic origin and the latter indicate late-magmatic origin. In terms of the pistacite molecule contents in epidote $\{Ps = [Fe^{+3}/(Fe^{+3} + Al)] \times 100\}$, Ps values of 25 to 36 %, 26 to 36 % and 22 to 30 % were estimated for the leucogranites, sanukitoids and trondhjemite, respectively, along with TiO_2 contents ≤ 0.137 , suggesting magmatic origin. Temperature estimative based on zircon (T_{Zr}) and apatite saturations (T_{Ap}) are in the range T_{Zr} 841-990 °C and T_{Ap} 884-979 °C (leucogranite and associated high-Ti granodiorite), T_{Zr} 826-972 °C and T_{Ap} 864-886 °C (sanukitoids) and,

finally, T_{Zr} 853-977 °C and T_{Ap} 909 °C (trondhjemite), which all of them are interpreted as close to *liquidus*, with pressure estimates in general between 100 and 280 MPa, akin to upper crust conditions. Geothermometers and barometers based on aluminium contents in amphibole indicate temperature around 738-811 °C (sanukitoids) and 779-892 °C (trondhjemite). The lower temperatures (< 800 °C) is assumed as resulted of opening magmatic system related to deformation, and denote that dynamic recrystallization may have occurred at temperatures close to *solidus*, indicative of a syntectonic nature. Although the leucogranites and associated high-Ti granodiorite present relative enrichment of #Fe in whole-rock, are calc-alkaline affinity granitoids, overlapping the Cordilleran granites with $SiO_2 > 70\%$, low HFSE (*high field strength elements*) abundances, magmatic magnetite and high MS, pointing to oxidized crystallization conditions (probably at $\Delta_{NNO}+2.8$). Sanukitoids varieties have $FeOt/(FeOt + MgO) < 0.7$ in whole-rock, amphibole and biotite, low MS, indicating less oxidized crystallization conditions ($\Delta_{NNO}+1.0$); however, the equigranular varieties and trondhjemite probably are formed in conditions relatively close to the $\Delta_{FMQ}+0.5$. The lower MS and lower magnetite contents reported for the sanukitoids and trondhjemite can also be attributed to the earlier epidote formation and to the late magmatic processes, which are responsible by the magnetite instability. It is concluded that the precursor magma of the sanukitoids are hydrated ($H_2O > 4-7\%$), whereas lower water contents in *melt* ($H_2O < 4-7\%$) are suggested for the leucogranites and associated high-Ti granodiorite; and trondhjemite, as indicated by their amphibole absence and accessory amphibole contents, respectively, along with low contents of hydrated mineralogy. These results are compared to those estimated for calc-alkaline rocks of the Rio Maria suite from the Carajás province and oxidized members from other Archean to Paleoproterozoic terrains such as Baltic Belt, Sarmatian orogen (Western Europe), Closepet-type granites and high-Mg granodiorites of the Matok pluton (Limpopo Belt – South Africa).

Keywords: Granitoids. Magnetic Petrology. Mineral Chemistry. Archean. Carajás province.

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CAPÍTULO 1 INTRODUÇÃO

1.1 APRESENTAÇÃO E LOCALIZAÇÃO

A integração de dados de suscetibilidade magnética (SM), petrografia de minerais opacos e química mineral em silicatos e óxidos de Fe-Ti tornou-se uma poderosa ferramenta para determinação dos parâmetros de cristalização em sistemas magmáticos tais como pressão, temperatura, fugacidade de oxigênio e conteúdo de água (P, T, fO_2 , xH_2O) (Clark 1999, Spencer & Lindsley 1981). Nas últimas décadas, esta abordagem foi aplicada em granitoides da Província Carajás, principalmente em granitos tipo-A (alto-HFSE), o que permitiu contribuir com significativas informações sobre as condições de cristalização destas rochas (Cunha *et al.* 2016, Dall'Agnol *et al.* 1988, 1997, Magalhães & Dall'Agnol 1992, Mesquita *et al.* 2018, Oliveira *et al.* 2018). No entanto, sua aplicação torna-se escassa quando se trata de granitoides cálcio-alcalinos arqueanos, como associações TTG, sanukitoides e leucogranitos (e.g. Gabriel & Oliveira 2014, Oliveira *et al.* 2010).

Nos últimos anos, trabalhos envolvendo mapeamento geológico em escala de semi-detalhe (1:50.000), estudos petrográficos, geoquímicos e geocronológicos foram realizados em granitoides da região de Ourilândia do Norte (Santos *et al.* 2013b, Santos & Oliveira 2016, Silva *et al.* 2018, Silva & Oliveira 2019, Silva *et al.* 2019), localizada na porção centro-oeste da Província Carajás, no sudeste do estado do Pará (Figura 1.1). Tais estudos indicaram que este segmento de crosta é formado por um magmatismo mesoarqueano diversificado (~2,92-2,88 Ga; Silva *et al.* 2019), representado por três principais grupos de granitoides, até então indiferenciados em trabalhos regionais (Araújo & Maia 1991, Avelar *et al.* 1999, Vasquez *et al.* 2008). Assim temos: (i) leucogranitos e granodiorito alto-Ti associado - compreendem monzogranitos equi- a heterogranular e granodiorito porfirítico enriquecido em titanita; (ii) sanukitoides – constituídos predominantemente por granodioritos (equigranular, heterogranular e porfirítico), com tonalito, quartzo monzodiorito e quartzo diorito subordinados e; (iii) trondhjemitos - representado por trondhjemitos porfiríticos, levemente deformados e com finos enclaves máficos.

Paralelamente ao desenvolvimento desta dissertação, as rochas estudadas são alvo de investigação da tese de doutorado de Luciano Ribeiro da Silva, também vinculada ao Programa de Pós-Graduação em Geologia e Geoquímica (PPGG) da UFPA. Esta visa aprofundar o entendimento petrogenético e o significado tectônico destas rochas, com base em dados geoquímicos, estruturais e isotópicos (Pb-Nd-Hf). Além disto, foi desenvolvido um Trabalho de Conclusão de Curso (TCC), vinculado a Faculdade de Geologia da UFPA e

voltado para uma caracterização preliminar da natureza magnética e dos minerais opacos dos granitoides de Ourilândia do Norte (Sacramento 2018). No entanto, apesar do avanço no entendimento geológico e tectônico destas rochas, ainda não haviam estudos voltados para a classificação dos silicatos e óxidos de Fe-Ti, tampouco sobre uma abordagem integrada envolvendo a assinatura magnética, petrografia de minerais opacos e dados de química mineral que possibilitassem discutir as condições de cristalização dos seus magmas geradores. Tais atividades fazem parte da linha de pesquisa Petrologia e Evolução Crustal do PPGG, desenvolvidas pelo Grupo de Pesquisa Petrologia de Granitoides (GPPG) e vinculadas às metas e objetivos propostos pelo projeto “Origem e história tectônica dos granitoides arqueanos do Domínio Carajás, SE do Craton Amazônico” (CNPq Nº 28/2018 – processo 435552/2018-0).

Os resultados obtidos durante o desenvolvimento desta dissertação são apresentados na forma de dois artigos científicos, precedido por um capítulo introdutório (Capítulo 1), que retrata a localização da área de estudo, o contexto geológico regional da Província Carajás, a problemática, os objetivos, e os materiais e métodos empregados. O Capítulo 2 refere-se ao artigo intitulado “*Magnetic petrology of the Mesoarchean granitoids from Carajás province: magnetic signature and its implications for oxidation degree of mantelic and crustal origin rocks*”, o qual expõe os principais resultados obtidos referentes à caracterização mineralógica e textural dos óxidos de Fe-Ti, definições das populações magnéticas interpretadas a partir dos dados de suscetibilidade magnética (SM), e suas relações com o conteúdo mineralógico e geoquímico. Isto permitiu discutir sobre as condições de oxidação dos granitoides estudados, e ainda, propor uma sequência de cristalização para as fases opacas. O Capítulo 3 contempla o segundo artigo intitulado “*Mineral thermobarometry and its implications for petrological constraints on Mesoarchean granitoids from the Carajás province (Brazil)*” que aborda a classificação mineralógica dos silicatos (anfíbólio, biotita, titanita, epidoto) e óxidos de Fe-Ti (magnetita e ilmenita) com as análises pontuais quantitativas obtidas por microsonda eletrônica. Com base nestes dados foi possível a discussão dos parâmetros de cristalização dos granitoides de Ourilândia do Norte (T, P, fO_2 e xH_2O), suas relações com eventos deformacionais, além da comparação com granitoides geoquimicamente similares de outros crátons e da própria província. Ambos os artigos serão submetidos para publicação no periódico *Journal of South American Earth Sciences* ou outro de classificação similar (Qualis/CAPES). O Capítulo 4 contempla as conclusões desta dissertação e sintetiza os principais resultados obtidos de forma a contribuir para o aprofundamento do conhecimento geológico na região de Ourilândia do Norte (PA).

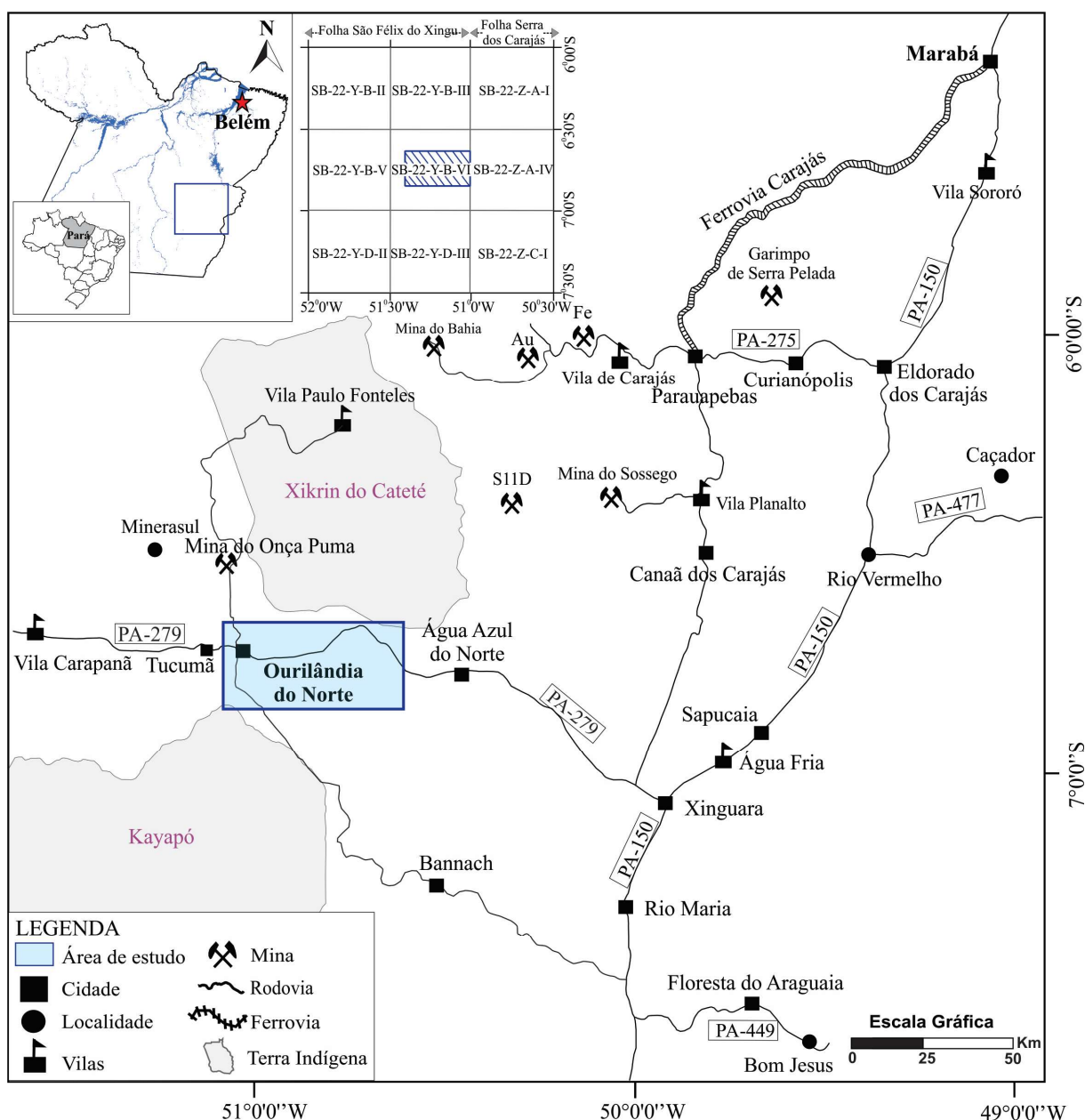


Figura 1.1 - Mapa de localização e acesso de Ourilândia do Norte, sudeste do estado do Pará.

1.2 CONTEXTO GEOLÓGICO REGIONAL

O Cráton Amazônico é considerado um dos mais expressivos segmentos crustais de idade Arqueana/Proterozoica, e está situado na porção norte da Plataforma Sul-Americana (Almeida *et al.* 1981). Na porção sudeste do cráton, encontra-se o seu maior núcleo arqueano preservado, representado pela Província Carajás (PC) (Figura 1.2a). Tal província é reconhecida mundialmente pela sua ampla importância metalogenética marcada pelas ocorrências de depósitos minerais de alto teor de Cu, Fe, Au, Mn e Ni (DOCEGEO 1988, Vasquez *et al.* 2008). Apesar do potencial metalogenético e a intensa atividade de pesquisa mineral realizada nos últimos 40 anos, a província ainda permanece, em sua maior parte, com

conhecimento geológico limitado a trabalhos de escala regional, quando comparada à outros crátons arqueanos.

No trabalho de Santos (2003), o Serviço Geológico do Brasil (CPRM) oficializou a Província Carajás como uma província arqueana independente. Entretanto, Tassinari & Macambira (2004) optaram por manter este segmento de crosta como um bloco inserido no contexto da Província Amazônia Central. Estudos geofísicos, geológicos e estruturais realizados nas últimas décadas, contribuíram para a individualização de unidades geológicas até então consideradas como pertencentes ao Complexo Xingu (Silva *et al.* 1974). Tais estudos promoveram o desenvolvimento de várias propostas de compartimentação tectônica para a província, dividindo-a em distintos segmentos crustais (Althoff *et al.* 2000, Costa *et al.* 1995, Dall'Agnol *et al.* 2006, 2013, Feio & Dall'Agnol 2012, Souza *et al.* 1996). Inicialmente, a porção sul da província foi denominada de Terreno Granito *Greenstone* de Rio Maria (TGGRM), o qual corresponderia a rochas mais antigas e de características ígneas preservadas, enquanto que a porção mais ao norte foi representada por uma vasta sequência vulcanossedimentar e intrusões de granitoides sintectônicos afetados por eventos tectonotermiais de idade neoarqueana (Souza *et al.* 1996). O limite entre estes domínios ainda é controverso, alguns autores têm enfatizado que ele pode estar situado imediatamente a sul do Granito Xinguara ou a norte do *Greenstone Belt* de Sapucaia (Dall'Agnol *et al.* 2006, Souza *et al.* 1996). Dall'Agnol *et al.* (1997) sugeriram que a região entre Xinguara e o sul da Serra dos Carajás corresponderia a uma zona de transição, pois foi afetada pelos eventos atuantes no Bloco Carajás, denominando informalmente esta porção de Domínio de Transição e posteriormente redefinido como Subdomínio de Transição por Feio & Dall'Agnol (2012). O Serviço Geológico do Brasil, seguindo a proposta previamente estabelecida por Santos (2003), subdividiram a província em dois domínios tectônicos principais (Vasquez *et al.* 2008): (i) **Domínio Rio Maria (DRM)**, de idade mesoarqueana (3,0 – 2,87 Ga), e (ii) **Domínio Carajás (DC)**, de idade Meso- a Neoarqueana (3,0 – 2,76 Ga). Com o avanço do conhecimento geológico-tectônico na província, pesquisadores do GPPG (Grupo de Pesquisa Petrologia dos Granitoides) da UFPA mostraram que a área considerada como embasamento da Bacia Carajás (antigo Domínio de Transição), que se estenderia desde a sua borda sul até o limite com o TGGRM, não corresponderia a uma crosta tectonicamente homogênea, o que levou à adoção das denominações subdomínios Canaã dos Carajás (SCC) e Sapucaia (SS) para as porções norte e sul deste segmento crustal da província, respectivamente (Figura 1.2b; Dall'Agnol *et al.* 2013). Com base nesta configuração tectônica serão abordados a seguir uma síntese das principais unidades geológicas que compõe a Província Carajás.

1.2.1 Domínio Rio Maria (DRM)

O Domínio Rio Maria está situado na porção sul da Província Carajás, de idade Mesoarqueana (3,0 - 2,85 Ga), corresponde as rochas mais antigas aflorantes na província. É formado por associações *greenstone belts* do Supergrupo Andorinhas (3,0 – 2,9 Ga) e o Grupo Tucumã (Avelar 1996, Lafon *et al.* 2000, Macambira & Lancelot 1991, Pimentel & Machado 1994, Rolando & Macambira 2003, Souza *et al.* 2001), além de uma diversidade de granitoides arqueanos, representados pelas suítes TTGs, sanukitoides e leucogranitos potássicos, além de variedades híbridas (Almeida *et al.* 2011, 2013, Avelar *et al.* 1999, Leite *et al.* 2004, Pimentel & Machado 1994, Macambira & Lafon 1995, Macambira & Lancelot 1996, Rolando & Macambira 2003). O Grupo Tucumã, anteriormente integrado ao Supergrupo Andorinhas (DOCEGEO 1988), foi diferenciado e denominado formalmente por Araújo & Maia (1991). Corresponde a rochas metaultramáficas, metamáficas, metavulcânicas intermediárias e ácidas intercaladas com metassedimentares clásticas e químicas. Os principais grupos de granitoides aflorantes no DRM são descritos abaixo:

(a) **Série TTG** (2,98 - 2,92 Ga): ocorre em dois momentos de cristalização, com a formação das rochas mais antigas do Tonalito Arco Verde e Trondhjemitó Mogno (2,98 e 2,96 Ga) (Almeida *et al.* 2010, 2011, Macambira & Lafon 1995, Rolando & Macambira 2003), e uma cristalização mais nova, marcada pelo Complexo Tonalítico Caracol, Tonalito Mariazinha e Trondjemito Água Fria, com idades entre 2,94 e 2,92 Ga (Almeida *et al.* 2011, Leite *et al.* 2004). Almeida *et al.* (2010) interpretaram que as suítes TTGs foram formadas por fontes similares aos metabasaltos do Supergrupo Andorinhas, diferenciando-as em três grupos: (a) grupo de alta razão La/Yb, Sr/Y e Nb/Ta, referente a geração em altas pressões (> 1,5 GPa) e fonte com granada e anfibólio no resíduo; (b) grupo com média razão La/Yb, formado em pressão intermediária (~ 1,0-1,5 GPa), mas ainda no campo de estabilidade da granada; e (c) grupo com baixa razão La/Yb, Sr/Y e Nb/Ta, formado a baixa pressão ($\leq$ 1,0 GPa), com plagioclásio no resíduo;

(b) **Suíte *Sanukitoide* Rio Maria** (~2,89 - 2,85 Ga): caracteriza-se por granitoides cálcico-alcalinos alto-Mg, representados pelo Granodiorito Rio Maria e rochas associadas (Medeiros & Dall'Agnol 1988, Oliveira *et al.* 2009, 2011, Santos *et al.* 2013a, Santos & Oliveira 2016). Além destes, também fazem parte o Granito Rancho de Deus (Dias 2009) e a unidade anteriormente definida como Tonalito Parazônia (DOCEGEO 1988, Huhn *et al.* 1988), e posteriormente redefinida como Quartzo-Diorito Parazônia (~ 2,87 Ga – Guimarães 2009);

(c) **Leucogranitos potássicos de afinidade cálcico-alcalina** (~2,86-2,87 Ga): São

representados pelo Granito Mata Surrão e rochas associadas (Almeida *et al.* 2010, Lafon *et al.* 1994). O Granito Mata Surrão tem idade 2,88-2,87 Ga obtido por Pb-Pb em zircão e rocha total (Lafon *et al.* 1994, Rolando & Macambira 2003), é caracterizado por monzogranitos com restrita ocorrência de granodioritos;

(d) **Leucogranodioritos-granitos de alto Ba-Sr** (~2,87-2,86 Ga): São representados pelo Granodiorito Grotão e a Suíte Guarantã, sendo esta última formada por três plútons (Guarantã, Azulona e Trairão, com restritas ocorrências também identificadas na região de Bannach e Xinguara) (Almeida *et al.* 2010, Almeida *et al.* 2013, Almeida *et al.* 2017, Althoff *et al.* 2000, Guimarães 2009). Estas rochas foram interpretadas como produto de mistura em diferentes proporções de magmas de composição trondhjemitica do tipo TTG e leucogranítica rica em Ba e Sr (Almeida *et al.* 2010). As rochas pertencentes ao evento magmático mais jovem registrado no DRM (~ 2,87 Ga) indicam a última fase de cratonização do domínio, marcado por eventos tectonotermiais. Tais rochas são recobertas por rochas sedimentares clásticas, transgressivas do Grupo Rio Fresco (DOCEGEO 1988), que posteriormente, foram intrudidas por granitos tipo-A paleoproterozoicos (~ 1,88 Ga) da Suíte Jamon (Dall'Agnol *et al.* 2005, Dall'Agnol & Oliveira 2007) e diques de diferentes composições (Rivalenti *et al.* 1998, Silva Junior *et al.* 1999, Silva *et al.* 2016).

1.2.2 Domínio Carajás (DC)

1.2.2.1 Subdomínio Canaã dos Carajás (SCC)

Localizado ao norte da Província Carajás, o Subdomínio Canaã dos Carajás (SCC) está compreendido entre a Bacia Carajás (BC), no extremo norte, e o Subdomínio Sapucaia (SS), ao sul. Caracteriza-se por apresentar ocorrências de granitos *stricto sensu* e charnokitos, com raros granitoides TTGs. Granulitos máficos (3,05-2,93 Ga) e félsicos (2,89-2,84 Ga) têm sido reportados na área de Ouro Verde por Marangoanha *et al.* (2019b), os quais foram considerados o embasamento da Bacia Carajás. Unidades de afinidade sanukitoides ainda não foram descritas neste domínio, entretanto, tonalitos com anfibólio geoquimicamente distintos das séries TTGs tem sido encontrado (Feio *et al.* 2013, Moreto *et al.* 2011). Recentemente, na transição entre o DC e o DRM também foram descritos ortopiroxênio-granodioritos, clinopiroxênio- e/ou anfibólio-monzogranitos, e gabronoritos, os quais foram relacionados à série de rochas gabronorito-charnockito-granito (Felix *et al.* 2020).

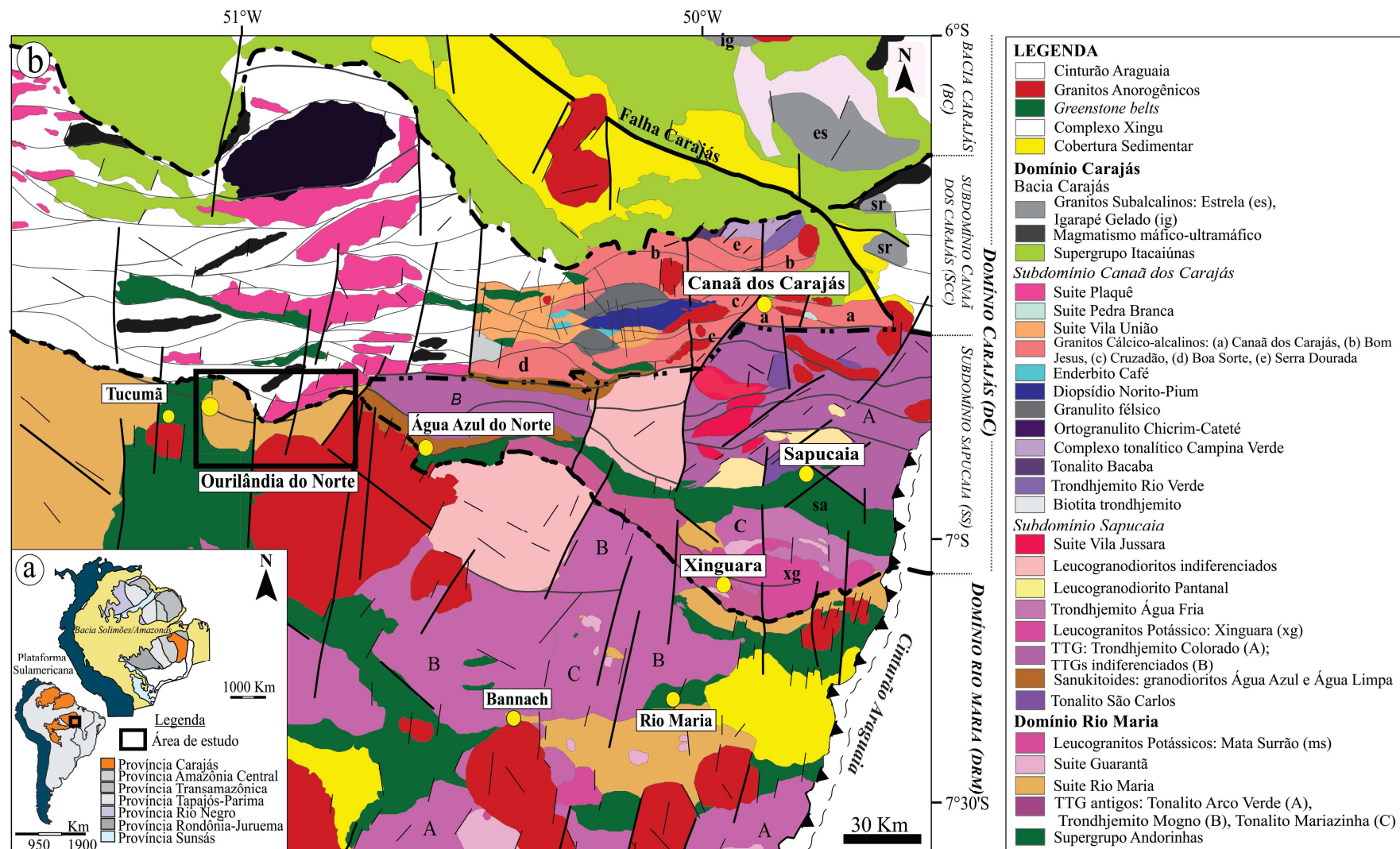


Figura 1.2 -Mapa da compartimentação tectônica e geológico regional: a) Cráton Amazônico na Plataforma Sul-Americana, com a localização da Província Carajás (Tassinari & Macambira 2004); b) Mapa geológico da Província Carajás. Modificado de Feio *et al.* (2013), Gabriel & Oliveira (2014), Guimarães *et al.* (2012), Marangoanha *et al.* 2020, Oliveira *et al.* (2010), Santos & Oliveira (2012), Silva *et al.* (2020) e Vasquez *et al.* (2008). À direita é exibida a mais recente compartimentação tectônica para a Província Carajás (Dall'Agnol *et al.* 2013).

Admite-se que o SCC preserva os sucessivos eventos de retrabalhamento meso- e neoarqueanos, os primeiros referentes à processos de espessamento crustal e ao pico de metamorfismo regional (2,89 - 2,84 Ga – Delinardo 2018, Marangoanha 2018), enquanto o segundo refere-se ao fechamento da Bacia Carajás (Feio *et al.* 2013, Martins *et al.* 2017, Marangoanha *et al.* 2019a,b, Marangoanha *et al.* 2020, Oliveira *et al.* 2018, Santos *et al.* 2013b, Tavares 2015, Tavares *et al.* 2018). Desta forma, o SCC é constituído por seis grupos de rochas principais, a saber:

(a) As **rochas granulíticas** são representadas pelo: (i) Ortogranulito Chicrim-Cateté (Vasquez *et al.* 2008), constituído por rochas de alto grau metamórfico que são associados aos charnockitos do Diopsídio-Norito Pium. Santos *et al.* (2013b) e, posteriormente, Marangoanha *et al.* (2020), definiram o Diopsídio-Norito Pium com idade Neoarqueana, sendo uma unidade composta por rochas ígneas; (ii) núcleos granulíticos da Vila Ouro Verde, formado por ortogranulitos máficos (3,05 - 2,93 Ga) e félsicos (2,89 - 2,84 Ga), que foram considerados o embasamento da Bacia Carajás (Delinardo *et al.* 2015, Delinardo 2018, Marangoanha 2018, Marangoanha *et al.* 2019b, 2020);

(b) Os **tonalitos com anfibólio** designados pelo: (i) Tonalito Bacaba (~ 3,0 Ga – Moreto *et al.* 2011) e; (ii) Complexo Tonalítico Campina Verde (2,87 - 2,85 Ga - Feio *et al.* 2013). O primeiro é composto por tonalitos de granulação fina, com hornblenda e biotita, e o segundo, por biotita-hornblenda ou biotita tonalitos, com dioritos, granodioritos e monzogranitos subordinados (Feio *et al.* 2013);

(c) O **Granito Canaã dos Carajás** (2,95 Ga – Feio *et al.* 2013) é constituído por monzogranitos e granodioritos subordinados, de assinatura cálcio-alcálica e afinidade sódica, fortemente deformados;

(d) **Associações TTGs** – apesar de raras no SCC, são representadas pelo Trondhjemito Rio Verde (2,92-2,86 Ga – Feio *et al.* 2013) e pelos protólitos granulíticos Chicrim-Cateté (3,0 Ga – Vasquez *et al.* 2008) e o da região da Vila Ouro Verde (3,05-2,93 Ga – Delinardo 2018, Marangoanha 2018, Marangoanha *et al.* 2019a,b);

(e) Os **leucogranitos potássicos** – Representam as unidades mais expressivas do SCC e são representadas pelo: (i) Granito Cruzadão (2,84 Ga – Feio *et al.* 2013); Granito Boa Sorte (2,85 Ga – Rodrigues *et al.* 2014); (iii) Granito Bom Jesus (2,83 Ga – Feio *et al.* 2013); e (iv) Granito Serra Dourada (2,86 Ga e 2,83 Ga – Feio *et al.* 2013 e Moreto *et al.* 2011);

(f) **Associações neoarqueanas** – São representadas por uma diversidade de rochas, a saber: (i) Suíte Intrusiva Cateté (2,76 Ga – Lafon *et al.* 2000) constituída pelos plútons Serra da Onça, Serra do Puma, Serra do Jacaré, Serra do Jacarezinho, Igarapé Carapanã, Fazenda

Maginco, Ourilândia e Vermelho, e outros sem denominação formal; (ii) Gabro Santa Inês (DOCEGEO 1988), embora posicionado no Neoarqueano, permanece com idade incerta (Vasquez *et al.* 2008); (iii) Diopsídio-Norito Pium (2,74 Ga – Ricci & Carvalho 2006, Santos *et al.* 2013a); (iv) Suíte Pedra Branca (2,76 Ga por TIMS – Sardinha *et al.* 2004) e 2,75 Ga (Feio *et al.* 2013); (v) Enderbito Café (2,75-2,73 Ga – Marangoanha *et al.* 2019b); (vi) Granitoides da Vila União (2,75-2,73 Ga – Oliveira *et al.* 2018, Marangoanha *et al.* 2019a,b); (vii) Suíte Planalto (2,74 e 2,71 Ga – Feio *et al.* 2013, Galarza *et al.* 2017, Gomes 2003, Huhn *et al.* 1999, Oliveira *et al.* 2010, Sardinha *et al.* 2004); e (viii) Suíte Plaquê (2,73 Ga - Avelar *et al.* 1999).

1.2.2.2 Subdomínio Sapucaia (SS)

O Subdomínio Sapucaia está compreendido entre o SCC e o DRM. É caracterizado por rochas de idade Meso- a Neoarqueana, comumente deformadas, intrudidas por rochas pertencentes às suítes Vila Jussara e Planalto. As principais associações que compõe este domínio são os *greenstones belts*, anfibolitos, TTG's, sanukitoides, leucogranitos potássicos, leucogranodioritos-granitos alto Ba-Sr, além de granitoides subalcalinos tipo-A (Dall'Agnol *et al.* 2017, Gabriel *et al.* 2010, Gabriel & Oliveira 2014, Leite *et al.* 2004, Leite-Santos & Oliveira 2014, 2016, Marangoanha & Oliveira 2014, Santos *et al.* 2010a, 2010b, Santos *et al.* 2013b, Santos *et al.* 2018, Silva 2010a,b, Sousa *et al.* 2014, Souza *et al.* 2010, Teixeira *et al.* 2013, Sousa *et al.* 2014, Souza *et al.* 2017).

(a) Os *greenstones belts* são representados por metamafitos, metaultramafitos e metassedimentares de fácies xisto verdes a anfibolito percententes ao Grupo Sapucaia (Costa *et al.* 1994, DOCEGEO 1988, Hirata *et al.* 1982). Sousa *et al.* (2014) propuseram que o Grupo Sapucaia representa resquícios de platôs ou ilhas oceânicas gerados durante o Mesoarqueano;

(b) Os **TTG's mesoarqueanos** (2,98-2,92 Ga) compreendem os TTGs mais antigos aflorantes neste domínio, e integram o Tonalito Caracol e um corpo de composição tonalítica com estruturação planar N-S semelhante ao Tonalito Mariazinha. O Tonalito Caracol ocorre na porção noroeste de Xinguara, com idade de cristalização de 2,94-2,93 Ga (Almeida *et al.* 2011, Leite *et al.* 2004). É composto por biotita tonalitos e /ou trondhjemitos fortemente deformados. Mais recentemente, Santos *et al.* (2018) identificaram na região de Água Azul do Norte um corpo de composição trondhjemítica de afinidade TTG (~ 2,93 Ga), ainda sem denominação formal. Ainda, há ocorrência de anfibólio-biotita tonalitos do Tonalito São Carlos (Silva *et al.* 2014);

(c) **Granitoides de afinidade *Sanukitoides*** são representados pelos granodioritos Água Azul e Água Limpa, de idade 2,88-2,87 Ga (Gabriel *et al.* 2010, Gabriel & Oliveira 2014, Santos *et al.* 2013a, Souza *et al.* 2010). Caracterizam-se predominantemente por biotita-anfibólio granodiorito porfirítico, e subordinada ocorrência de biotita granodiorito e biotita-anfibólio tonalito;

(d) Os **TTG's jovens** são representados pelos trondhjemitos Água Fria (2,86-2,84 Ga – Almeida *et al.* 2011, Leite *et al.* 2004) e trondhjemitos Colorado (~ 2,87 Ga – Silva *et al.* 2010a). O primeiro é intrusivo na associação de rochas que compõem os *greenstone belts* de Sapucaia e o Tonalito Caracol. Já a sua relação espacial com o Granito Xinguara é de contemporaneidade, sendo cortado por diques e veios leucograníticos (Leite & Dall'Agnol 1997);

(e) Os **leucogranitos potássicos** de afinidade cálcico-alcálica são compostos pelo: (i) Granito Xinguara (2865±1 Ma - Leite *et al.* 2004); e pelo (ii) Leucogranito Velha Canadá (2,74 e 2,73 Ga – Santos *et al.* 2010b, Santos & Oliveira 2012, Souza *et al.* 2010). O primeiro é constituído por monzogranitos e sienogranitos, cuja relação de contato é intrusiva nos *greenstones belts*, no Tonalito Caracol e no Granodiorito Rio Maria (Leite 2001);

(f) Os **Leucogranodioritos-granitos de alto Ba-Sr** são rochas afins à Suíte Guarantã, no qual são representadas pelo: (i) leucogranodioritos Nova Canadá (Leite-Santos & Oliveira 2014) e Pantanal (Teixeira *et al.* 2013).

Novos eventos sintectônicos produziram magmatismo Neoarqueano subalcalino do tipo-A, onde foram formados diversos granitoides geneticamente diferentes entre si, e diferenciados na **Suíte Vila Jussara** e **Suíte Planalto**. A primeira caracteriza-se por granitos *strictu sensu* portadores de anfibólio, com tonalitos e granodioritos subordinados de idade de 2,74-2,75 Ga (Oliveira *et al.* 2010, Silva *et al.* 2010b, Souza *et al.* 2010, Silva *et al.* 2020), distinguindo-se da segunda por apresentar caráter oxidante e maior diversidade modal (Dall'Agnol *et al.* 2017). Adicionalmente, o **Leucogranito Velha Canadá** (2,73 e 2,74 Ga – Santos *et al.* 2010b, Souza *et al.* 2010), é constituído por granodioritos cálcico-alcálico alto-K, geoquimicamente similares aos leucogranitos potássicos mesoarqueanos.

1.2.2.3 Bacia Carajás (BC)

A Bacia Carajás (BC) corresponde a rochas supracrustais pertencente ao Domínio Carajás, é constituída por rochas metavulcanossedimentares (metagrauvas, metarcóseos, vulcanoclásticas, metabasaltos toleíticos), xistos pelíticos e formações ferríferas bandadas, além de ocorrências de paragnaisses, anfibolitos, riolitos, metamorfizadas em fácies xisto

verde e anfíbolito, de idade entre 2,77-2,73 Ga (DOCEGEO 1988, Galarza *et al.* 2008, Hirata *et al.* 1982, Machado *et al.* 1991, Tallarico *et al.* 2005, Trendall *et al.* 1998). Compõe a bacia rochas pertencentes aos grupos Grão Pará, Igarapé Salobo, Igarapé Pojuca, Igarapé Bahia, Rio Novo, Aquiri, São Félix e São Sebastião, que anteriormente integravam o Supergrupo Itacaiúnas (DOCEGEO 1988, Vasquez *et al.* 2008). No Paleoproterozoico (~ 1,88 Ga), o terreno compreendido pela BC e o SCC foi intrudido pelos granitos anorogênicos da Suíte Serra dos Carajás (Dall'Agnol *et al.* 2006, Teixeira *et al.* 2017). Estes granitos anorogênicos possuem similaridades com àqueles afins já descritos na província, em especial no Domínio Rio Maria, porém apresentam peculiaridades geoquímicas que sugerem fontes e história de cristalização distinta entre eles (Dall'Agnol *et al.* 1994).

1.3 PROBLEMÁTICA E JUSTIFICATIVA

Trabalhos que envolvem uma abordagem integrada de petrologia magnética e química mineral têm sido desenvolvidos nas últimas décadas na Amazônia, especialmente em granitos tipo-A da Província Carajás (Cunha *et al.* 2016, Dall'Agnol *et al.* 1988, 1997, Magalhães & Dall'Agnol 1992, Mesquita *et al.* 2018, Oliveira *et al.* 2018), o que permitiu estimar e discutir as condições de cristalização destas rochas. Entretanto, esta técnica ainda é pouco empregada em granitoides calc-alcalinis arqueanos, como associações sanukitoides e leucogranitos, além de rochas pertencentes à suíte TTG (e.g. Gabriel & Oliveira 2014, Oliveira *et al.* 2010). Neste contexto, para os granitoides mesoarqueanos de Ourilândia do Norte, apesar do avanço em seu entendimento geológico e tectônico (Santos & Oliveira 2016, Silva *et al.* 2018), estudos voltados para a classificação dos silicatos e óxidos de Fe-Ti até então eram inexistentes, assim como uma abordagem integrada envolvendo a assinatura magnética, petrografia de minerais opacos e dados de química mineral que viabilizassem discutir as condições de cristalização dos magmas geradores destas rochas. Com base nisto, é possível destacar algumas lacunas ainda existentes sobre as condições de cristalização destes granitoides, dentre as quais podemos mencionar:

- (i) inexistência de classificação mineralógica dos silicatos (plagioclásio, hornblenda, biotita, epídoto, titanita) e óxidos de Fe-Ti (magnetita, ilmenita);
- (ii) ausência de um estudo integrado entre dados de SM (Suscetibilidade Magnética) e aqueles de química mineral;
- (iii) inexistência de informações sobre as condições de cristalização (T, P, fO_2 e xH_2O) dos granitoides mesoarqueanos de Ourilândia do Norte.

1.4 OBJETIVOS

Levando-se em consideração o que foi apresentado acima, o objetivo geral deste trabalho visou definir os principais parâmetros de cristalização (T , P , fO_2 e xH_2O) dos granitoides mesoarqueanos de Ourilândia do Norte, sendo que para isto, tornou-se necessário atingir os seguintes objetivos específicos:

- (i) estimar a sequência de cristalização dos minerais opacos;
- (ii) relacionar a variação da SM com o conteúdo mineralógico e geoquímico dos granitoides estudados;
- (iii) classificar a mineralogia dos silicatos (plagioclásio, hornblenda, biotita, epídoto, titanita) e óxidos de Fe-Ti (magnetita, ilmenita), a partir da composição quantitativa por análise em microsonda eletrônica;
- (iv) integrar os resultados de petrologia magnética com aqueles de química mineral, a fim de investigar em que condições de oxidação do magma estes granitoides foram gerados;
- (v) estimar os parâmetros de cristalização dos granitoides estudados (T , P , fO_2 e xH_2O), e discutir suas implicações em eventos deformacionais;
- (vi) comparar a química dos minerais formadores destas rochas com aqueles de granitoides análogos da Província Carajás e de outros terrenos arqueanos, assim como avaliar contrastes ou afinidades entre eles.

1.5 MATERIAIS E MÉTODOS

As amostras utilizadas durante esta dissertação foram obtidas durante o mapeamento geológico de semi-detulhe realizado por Santos & Oliveira (2016) e Silva *et al.* (2018). O leitor é convidado a consultar estes trabalhos para um maior detalhe acerca dos dados de mapeamento, coleta de amostras, geoquímica e afinidades petrológicas.

1.5.1 Pesquisa Bibliográfica

Durante o desenvolvimento desta dissertação foi realizado um levantamento bibliográfico referente ao contexto geológico regional da Província Carajás, assim como aqueles referentes ao contexto geológico local de Ourilândia do Norte, com o intuito de compreender a petrogênese, natureza e afinidades geoquímicas de leucogranitos, sanukitoides e trondhjemitos. Adicionalmente, artigos científicos com ênfase em petrologia magnética e química mineral foram consultados, contribuindo para o entendimento acerca das aplicações da suscetibilidade magnética, tampão experimental de fugacidade de oxigênio e calibrações de geotermobarometria em rochas graníticas.

1.5.2 Petrografia de minerais opacos

Foi realizado um estudo petrográfico detalhado das fases opacas sob luz refletida em 14 lâminas polidas representativas de leucogranitos, sanukitoides e trondhjemitos, com ênfase na identificação e descrição sistemática dos aspectos texturais, relações de contato, intercrescimentos, exsolução e/ou substituição dos óxidos de Fe-Ti, e sua relação com os demais minerais, procurando esclarecer a sua provável condição e ordem de cristalização. Em termos microestruturais, foi realizado o reconhecimento das microestruturas magmáticas e submagmáticas, e de recristalização relacionadas à deformação (Best 2003, Vernon 2004, Trouw *et al.* 2010).

1.5.3 Petrologia Magnética

Os valores de SM foram obtidos com o suscetibilímetro SM-30 fabricado pela *ZH Instruments* (limite de detecção máxima 1×10^{-7} SI) no Laboratório de Petrologia Magnética do Instituto de Geociências (IG) da Universidade Federal do Pará (UFPA). As medidas foram realizadas em superfícies regulares e sem evidências intempéricas, com uma média de três medidas em seções distintas da amostra, totalizando 141 medidas de SM. Os valores foram plotados em gráficos e histogramas de frequência utilizando o *software Minitab 18 (versão gratuita)*. A caracterização textural e mineralógica dos óxidos de Fe-Ti foram realizadas em luz polarizada e refletida em 14 lâminas polidas representativas de cada variedade de rocha estudada. Complementar aspecto textural dos óxidos de Fe-Ti foi adquirido com o Microscópio Eletrônico de Varredura (MEV) modelo LEO-1430 equipado com um espectrômetro de energia dispersiva (EDS) no Laboratório de Microanálises do Instituto de Geociências da UFPA. As condições de operação analítica das análises por EDS foram 20 kV para a coluna de aceleração. O *software GCDKit (versão 6.0 gratuita)* foi utilizado para confecção de diagramas comparativos entre SM e geoquímica.

1.5.4 Química Mineral

As análises quantitativas de química mineral foram realizadas em seções pré-selecionadas de silicatos (biotita, hornblenda, epídoto, titanita e plagioclásio) e óxidos de Fe-Ti (magnetita, ilmenita), onde, sempre que possível, foi analisado o núcleo e a borda de cada cristal para obtenção de sua composição química mais detalhada e observação de contrastes existentes entre eles. O equipamento utilizado nesta fase foi a microsonda eletrônica JEOL JXA-8230 equipada com cinco espectrômetros de energia dispersiva de raio-X (*Wavelength Dispersive Spectroscopy* – WDS), no Laboratório de Microanálises do IG/UFPA. As condições analíticas de operação do equipamento foram tempo de aceleração de 15 kV,

corrente de 20 nA, tempo de análise de 20 segundos para os elementos maiores e 40 segundos para os elementos menores. A metodologia segue padrão de correção LIFH (*lithium fluoride*) para V, Mn, Fe, Ni e Ba; PETJ (*pentaerythritol*) para K, Ca, Ti e Sr; TAP (*thallium acid phthalate*) para Na, Si, Al e Mg; LDE1 (*layered dispersion element*) para F. Os padrões utilizados para calibração do instrumento foram andradita (Si e Ca), microclina (Al e K), hematita (Fe), olivina (Mg), albita (Na), pirophanita (Ti e Mn), vanadinita (V e Cl), topázio (F). A precisão analítica é de $\pm 1\%$ e $\pm 10\%$ para os elementos maiores e menores, respectivamente. Todas as amostras selecionadas para química mineral apresentam geoquímica de rocha-total disponível, compiladas dos trabalhos de Santos & Oliveira (2016) e Silva *et al.* (2018).

1.5.5 Classificação mineral e geotermobarometria

Para a obtenção das fórmulas estruturais e classificação de anfibólio foram consultados os trabalhos de Leake *et al.* (1997) e Hawthorne *et al.* (2012), com partição de ferro calculado a partir do método de Schumacher (Leake *et al.* 1997). Os critérios de classificação de biotita foram baseados em Rieder (1998), com diagramas complementares de Deer *et al.* (2013), Foster (1960) e Nachit *et al.* (1985, 2005). Para a obtenção da composição e classificação dos demais minerais (plagioclásio, titanita, epídoto) foram utilizados os diagramas propostos por Aleinikoff *et al.* (2002), Deer *et al.* (2013), Kowallis *et al.* (1997), e Tulloch (1979). A discussão acerca dos parâmetros de temperatura foi baseada em geotermômetros formulados a partir do conteúdo de alumínio no anfibólio (Ridolfi *et al.* 2010, Ridolfi & Renzulli 2012, Putirka 2016). Adicionalmente, geotermômetro de saturação de apatita e zircão propostos por Harrison & Watson (1984), Watson & Harrison (1983), Boehnke *et al.* 2013, Gervasoni *et al.* (2016) foram empregados a partir de geoquímica em rocha-total. Para estimativa de pressão das rochas estudadas foram consultados Anderson & Smith (1995), Hammarstrom & Zen (1986), Hollister *et al.* (1987), Johnson & Rutherford (1989), Mutch *et al.* (2016), Ridolfi *et al.* (2010), Schmidt (1992), e finalmente, o cálculo de fugacidade de oxigênio e conteúdo de água em rochas ígneas foi baseado na paragênese em equilíbrio Titanita + Magnetita + Quartzo (Wones 1989), mineralogia e aspectos texturais, comparação com estudos experimentais, além de estimativas quantitativas pelo método de Ridolfi *et al.* (2010).

CAPÍTULO 2 MAGNETIC PETROLOGY OF THE MESOARCHEAN GRANITOIDS FROM CARAJÁS PROVINCE: MAGNETIC SIGNATURE AND ITS IMPLICATIONS FOR OXIDATION DEGREE OF MANTELIC AND CRUSTAL ORIGIN ROCKS

Artigo a ser submetido para uma revista indexada da área

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ABSTRACT

This paper investigates the oxidation conditions in the magmatism involved on formation of the Mesoarchean granitoids (2.92-2.88 Ga) from Ourilândia do Norte (PA) situated on the midwestern portion of the Carajás province (Brazil). It was based on magnetic susceptibility (MS), opaques petrography and qualitative estimates of crystallization conditions considering oxygen fugacity (fO_2) and temperature (T). Previous studies have classified Ourilândia granitoids into three associations: (i) leucogranites (equi- and heterogranular monzogranites) and high-Ti granodiorite, which commonly have hosted tonalitic xenoliths; (ii) sanukitoids are formed by granodiorites (equigranular, heterogranular and porphyritic), with minor occurrence of tonalite, quartz monzodiorite and quartz diorite; and (iii) porphyritic trondhjemite, represented by a small undeformed stock. From MS study was possible to distinguish three magnetic fields: (i) low MS field (A; MS range from 0.05×10^{-3} to 0.57×10^{-3} SI) whose sanukitoids and trondhjemite are predominants, characterized by rare opaque minerals; (ii) moderate MS field (B; MS 0.59×10^{-3} to 2.35×10^{-3} SI) which shows variable proportion of sanukitoids and leucogranites; and ilmenite prevailing in relation to magnetite contents; and (iii) high MS field (C; MS 2.35×10^{-3} to 17.0×10^{-3} SI) where leucogranite and high-Ti granodiorite, and minor porphyritic sanukitoid are predominants. It was admitted an oxidized crystallization conditions for the leucogranites ($\Delta_{NNO}+2.8$) whereas a less oxidizing condition was considered for the heterogranular and porphyritic sanukitoids ($NNO+1.0$). Thus, for the equigranular sanukitoids and trondhjemite is indicated crystallization conditions in the $\Delta_{NNO}+0.5$. The precursor magma of the sanukitoids was hydrated ($H_2O > 4-7\%$), meanwhile, $H_2O < 4-7\%$ are proposed for the leucogranites and high-Ti granodiorite, and trondhjemite, as indicated by the absence or scarcity of hydrated minerals and amphibole in their paragenesis.

Keywords: Magnetic Susceptibility. Magnetite. Granitoids. Archean. Carajás.

2.1 INTRODUCTION

Magnetic petrology investigates the process and factors that control the opaques phases equilibrium balance during magmatic evolution and which are intrinsically associated with the source and oxygen fugacity of the magma, hydrothermal alteration and metamorphism (Frost 1991b, Frost & Lindsley 1991, Clark 1999). Ishihara (1981) and Clark (1999) reported that a direct correlation between the oxidation state of magmas and formation of mineralizations in granitic rocks is generally observed. Based on this premise, when relating the Fe-Ti oxide mineralogy, magnetic susceptibility (MS), geochemical and petrological affinities of a granitic rock association, is possible to understand its magnetic signature, which can be used for interpretations of geological and metallogenic models (Clark 1999). Granitoids crystallized from intensely oxidized magmas have high magnetite, titanite and magnesian biotite contents and are representative of igneous suites related to porphyry-type deposits (Cu-Au). However, rocks formed under reduced conditions are generally associated with deposits of Sn and greisens-W, characterized by high ilmenite and sulfides contents (Ishihara 1981). Therefore, magnetic petrology is a complementary methodology to classic petrology studies, becoming an indirect tool for metallogenetic researches.

In the Amazonian craton, this methodology has been widely disseminated in A-type granites from the Carajás province since the 1980s (Dall'Agnol *et al.* 1988, Magalhães & Dall'Agnol 1992, Magalhães *et al.* 1994, Dall'Agnol *et al.* 1997, 2005, Oliveira *et al.* 2002), however, there are few studies related to magnetic petrology applications in sanukitoid affinity rocks and Archean leucogranites in the province (e.g. Gabriel & Oliveira 2014). In recent years, studies involving semi-detail geological mapping in the Ourilândia do Norte area, southeastern of Pará state (Brazil), have allowed the characterization of a diverse postcollisional mesoarchean plutonism (2.92-2.88 Ga - Silva & Oliveira 2019), subdivided into three main granitoid associations (Santos *et al.* 2013a, Santos & Oliveira 2016, Silva *et al.* 2018, 2019, Silva & Oliveira 2019): (i) leucogranite and associated high-Ti granodiorite: the former is constituted by monzogranites (equi- to heterogranular) and the latter has porphyritic texture, and commonly hosts tonalitic xenoliths; (ii) sanukitoids: constituted mainly of granodiorites (equigranular, heterogranular, porphyritic), frequently present mafic enclaves, and tonalite, quartz-monzodiorite and quartz-diorite are subordinate lithotypes; and (iii) porphyritic trondhjemite: occurs as a moderated formed stock.

Although previous reseachers in Ourilândia do Norte area have advanced in the discussions on the origin, nature and tectonic style of the Mesoarchean granitoids no study involving an integrated approach of magnetic susceptibility (MS) data, opaque mineral

petrography and geochemistry would make possible the discussion of the active oxidation conditions during the formation and evolution of the magmas that generate sanukitoids, leucogranites and trondhjemite, along with a crystallization sequence model of their opaque minerals. In this way, the correlation between these data allow to estimate the temperature and oxygen fugacity conditions (fO_2) of the three main associations of mesoarchean granitoids on Ourilândia do Norte area, as well as to discuss the implications regarding their nature, source, magmatic evolution and also reflect the role of deformation in the late- to postmagmatic opaque evolution and associated ferromagnesian minerals.

2.2 REGIONAL GEOLOGY

The Carajás province is recognized as a well-preserved Archean continental crust of the South American platform, which has been stable since the Neoproterozoic (Almeida *et al.* 1981) (Figure 2.1a). The province has been subdivided into two main tectonic domains (Santos 2003, Vasquez *et al.* 2008): (i) the **Rio Maria domain** is a Mesoarchean (3.0-2.87 Ga) terrane, situated in the south portion of the province, is composed of *greenstone belts* and four main groups of Archean granitoids: (a) the TTG series is represented by the Arco Verde and Mariazinha tonalites and Mogno trondhjemite; (b) the high-Mg granitoids and associated rocks of the Rio Maria suite; (c) the high-Ba-Sr leucogranodiorites of the Garantã suite; and (d) the potassic leucogranites forming the Mata Surrão granite (Oliveira *et al.* 2009, 2010, Almeida *et al.* 2011, Santos *et al.* 2013a, Almeida *et al.* 2013, Santos & Oliveira 2016, Almeida *et al.* 2017, Silva *et al.* 2018, Silva-Silva *et al.* 2020); (ii) the **Carajás domain** is dated from Meso- to Nearchean (3.0-2.76 Ga) and interpreted as a heterogeneous lithological crust by Dall'Agnol *et al.* (2013). The authors called its southernmost portion of *Sapucaia subdomain*, interpreted as similar to Rio Maria Domain; however, affected by Neoproterozoic events; and the northernmost portion of *Canaã dos Carajás subdomain*, which represents the basement of the Neoproterozoic Carajás basin (Figure 2.1b).

The Sapucaia subdomain is dominated by (a) *greenstone belts* and amphibolites; (b) a TTG series composed of the Colorado, Água Azul do Norte and Nova Canadá trondhjemites; (c) the high-Mg Água Azul and Água Limpa granodiorites; (d) the high Ba-Sr Nova Canadá leucogranodiorite; (e) the potassic Xinguara and Velha Canadá granites; and (f) the high-HFSE granitoids of the Vila Jussara suite (Santos *et al.* 2013b, Teixeira *et al.* 2013, Silva *et al.* 2014, Gabriel & Oliveira 2014, Leite-Santos & Oliveira 2016, Dall'Agnol *et al.* 2017, Santos *et al.* 2018, Silva *et al.* 2020). Thus, the Canaã dos Carajás subdomain is formed essentially by (a) the Chicrim-Cateté and Ouro Verde granulites; (b) high-K leucogranites (Cruzadão, Serra Dourada, Boa Sorte and similar granites); (c) restricted TTG series (Rio

Verde trondhjemite) and amphibole-bearing tonalites (Campina Verde tonalitic complex); (d) high-HFSE granitoids (Planalto and Vila União suites); and (e) charnockites (Feio *et al.* 2012, 2013, Santos *et al.* 2013a, Rodrigues *et al.* 2014, Delinardo *et al.* 2015, Tavares *et al.* 2018, Marangoanha *et al.* 2019a, b, 2020, Felix *et al.* 2020) (Figure 2.1c).

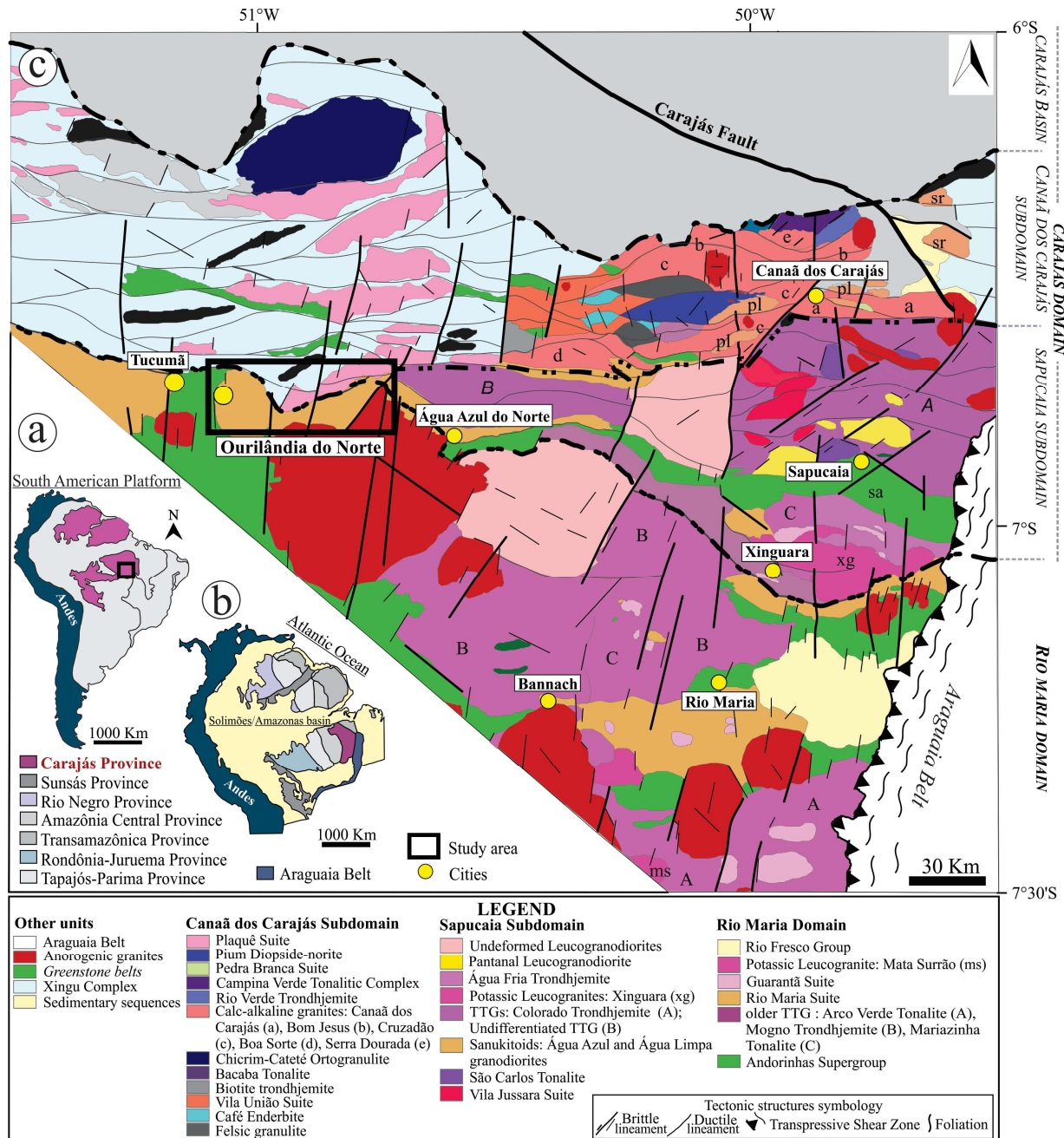


Figure 2.1 – Geological and tectonic context of the Carajás province: (a) Location map of Amazonian craton inserted into the South American Platform (Santos 2003, Santos *et al.* 2006); (b) Geochronological provinces based on Tassinari & Macambira (2004); (c) Geologic map of the Carajás province highlighting the Ourilândia do Norte area. Modified after Vasquez *et al.* (2008), Oliveira *et al.* (2010), Guimarães *et al.* (2012), Santos & Oliveira (2012), Feio *et al.* (2013), Gabriel & Oliveira (2014), Marangoanha *et al.* (2020), Silva *et al.* (2020). The most recent tectonic division of the Carajás province is showed in the right corner (Vasquez *et al.* 2008, Dall'Agnol *et al.* 2013).

At the end of the Archean, there was the youngest magmatic event of the Carajás province (Althoff *et al.* 2000, Souza *et al.* 2001) characterized by remarkable tectothermal events. The clastic sedimentary rocks of the Rio Fresco Group (DOCEGEO 1988) were subsequently deposited which later were intruded by Paleoproterozoic (1.88 Ga) A-type granites of the Jamon and Serra dos Carajás suite (Dall'Agnol *et al.* 2005, Dall'Agnol & Oliveira 2007) along with distinct compositional dikes (Rivalenti *et al.* 1998, Silva Junior *et al.* 1999, Silva *et al.* 2016).

2.3 MESOARCHEAN MAGMATISM OF THE OURILÂNDIA DO NORTE AREA

The semi-detail geological mapping (1:50,000) carried out on recent years in the eastern portion of the Ourilândia do Norte area contributed to characterize and individualize leucogranitic rocks, sanukitoid affinity granitoids, trondhjemites and microgranular mafic enclaves associations (Santos & Oliveira 2016, Silva *et al.* 2018). The spatial arrangement of these rocks agree with the tectonic regional foliation of E-W direction, commonly with dipping towards to the south and angle from moderate to high (65-90°). The plutonic bodies emplacements are conditioned by E-W directional transpressive shear zones, associated with the development of mylonitic foliations and compositional banding frequently affected by complex folds or sectioned by faults. Mingling processes are frequently observed between mafic and felsic associations, and indicates contemporaneity between compositionally distinct magmas. In the following topics a synthesis of the main geological characteristics, geochronological aspects and geochemical classification of these granitoids will be presented.

2.3.1 General aspects

2.3.1.1 Leucogranites and associated high-Ti granodiorite

The leucogranitic plutons of Ourilândia outcrop over a surface of 240 km². They are formed by two elongated batholiths arranged according to the main regional tectonic trend of E-W to SW-NE direction. These granitoids are limited to the southeast by the Seringa granites and Água Azul trondhjemite, to the north by the Xingu Complex and metavolcanic rocks of the Sapucaia Group, and to the west by granitoids of sanukitoid affinity (Figure 2.2). They are formed by equigranular monzogranites, with subordinate occurrence of heterogranular monzogranites and high-Ti porphyritic granodiorites (Figure 2.3a-d; Figure 2.4a), commonly are hosted by tonalitic xenoliths. In general are hololeucocratic rocks, where the heterogranular variety are characterized by the presence of mylonitic deformation structures (Figure 2.3a-b) and the porphyritic high-Ti granodiorite has centimetric potassium feldspar

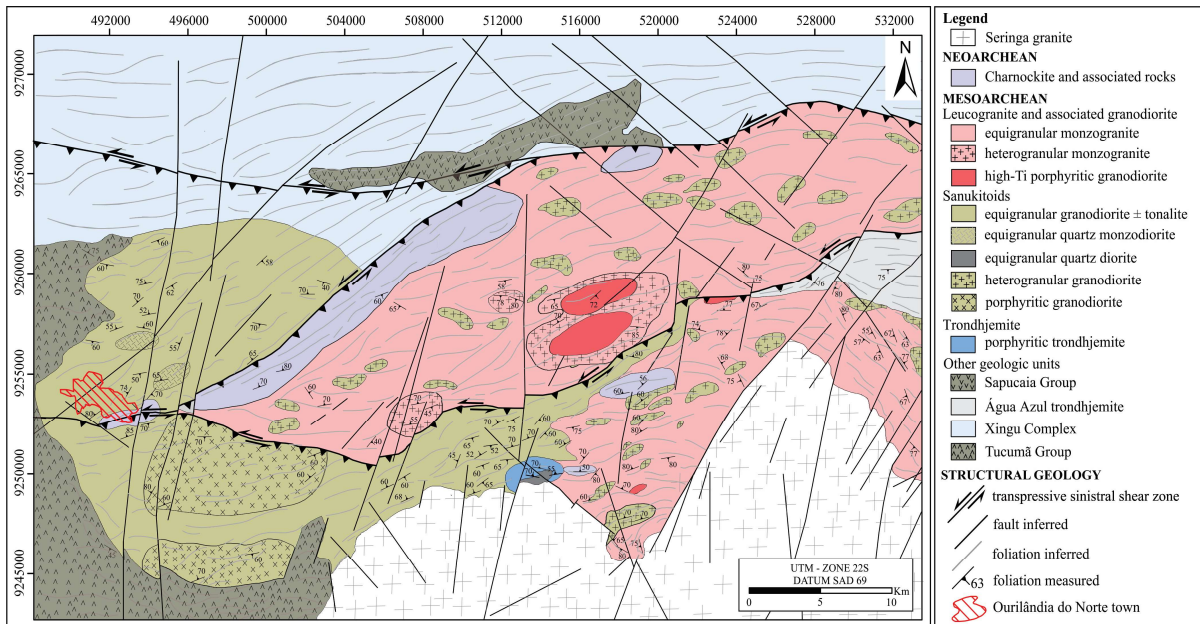


Figure 2.2 – Geologic map of the Ourilândia do Norte area (modified after Silva *et al.* (2019)).

(Afs) augen (1 - 2.5 cm) associated with titanite (Ttn) as an important accessory phase (Figure 2.3c-d). Biotite (Bt) is the chief ferromagnesian phase and hornblende (Hbl) is always absent in these granitoids. The primary accessory phases are represented by titanite (Ttn), epidote (Ep), apatite (Ap), zircon (Zrn), allanite (Aln) and opaque (Opq) minerals. The high-Ti porphyritic granodiorite has high modal contents of titanite (up to 2.5%) and was discriminated by Silva *et al.* (2018) as related to the Closepet-type granites from Craton Dhawar (Laurent *et al.* 2014).

The leucogranites show several lenses (or rounded enclaves) formed by sanukitoids affinity granitoids (heterogranular granodiorite), which indicates contemporary spacial relationships during the emplacement of the precursor magmas of these lithotypes. This is strengthened by their interdigitated behavior (Figure 2.2). U-Pb/SHRIMP geochronological data confirmed these observations and indicated that the leucogranites were crystallized at 2.88 Ga, simultaneously to the main generation of sanukitoid magmatism in the Ourilândia region (Silva & Oliveira 2019, Silva *et al.* 2019). Thus, from regional geologic context, this age was correlated with the main event of granulitization and crustal thickening (2.89-2.84 Ga; Marangoanha *et al.* 2019b), during the formation of the other potassic leucogranites in the Carajás province. In addition, Silva *et al.* (2019) obtained negative values of $\epsilon_{\text{Hf}(t)}$ (-4.10 and -0.78) and $\text{Hf-T}_{\text{DM}}^{\text{C}}$ Paleoproterozoic (3.53-3.33 Ga) for the leucogranites, which confirms origin involving reworking and a long crustal residence time for these rocks (> 500 Ma).

In the ternary diagram [$\text{Na}_2\text{O}/\text{K}_2\text{O}$ vs. $2\text{A}/\text{CNK}$ vs. 2FMSB] proposed by Laurent *et al.* (2014), leucogranites plot in the high alkali contents domain (pole A/CNK) and the high-Ti porphyritic granodiorite plots in the more magnesian field (pole FMSB - Figure 2.4b).

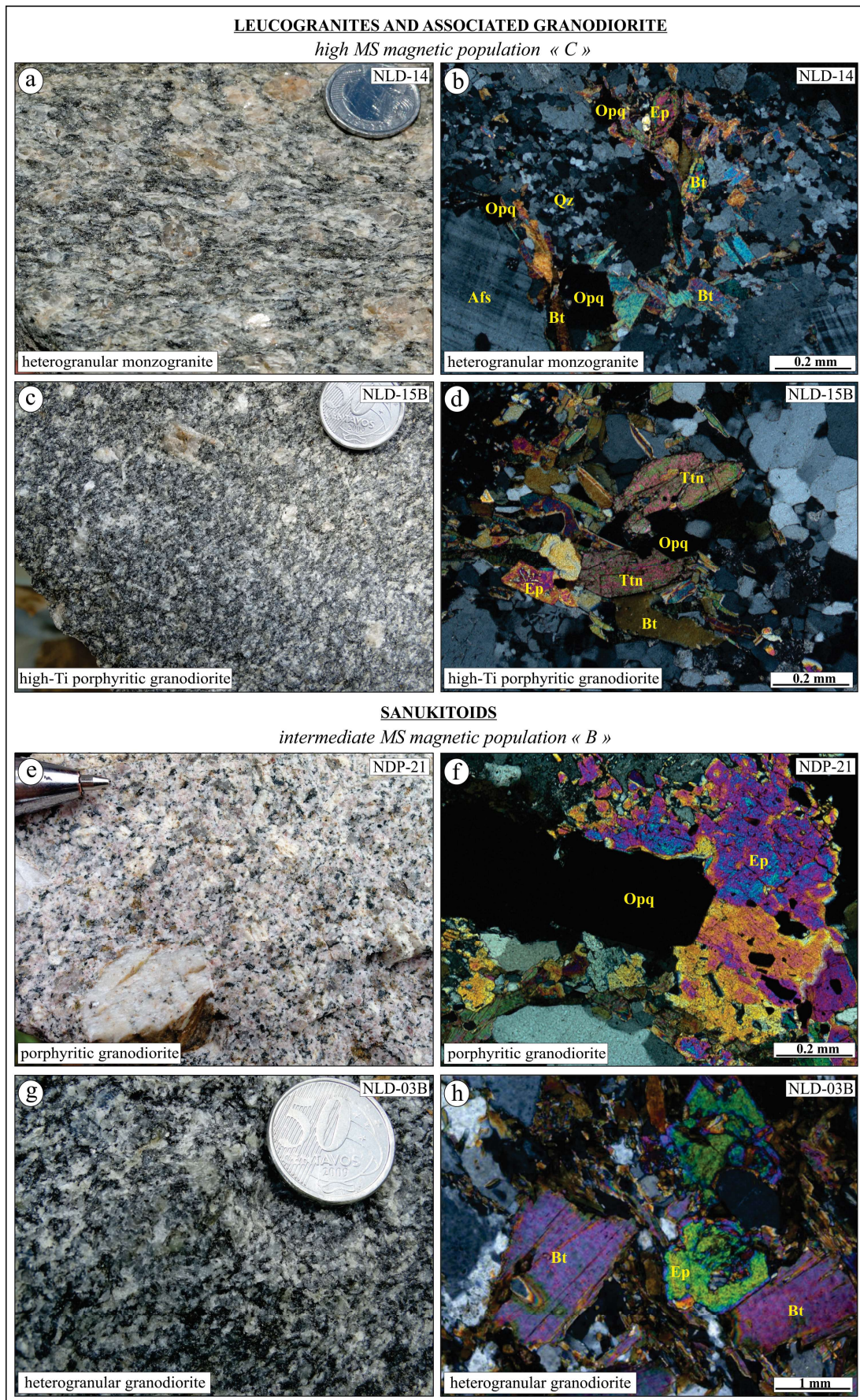


Figure 2.3 – Outcrop photos and photomicrographs of thin sections in crossed nicols (CN) of the textural aspects of the Ourilândia granitoids: *Leucogranites and high-Ti granodiorite* (a-b) heterogranular monzogranite with Afs phenocrysts alignment associated to mylonitic foliation; (c-d) *high-Ti porphyritic granodiorite*: medium-grained porphyritic texture; with Pl and Ttn phenocrysts immersed into fine-grained quartz feldspar matrix. *Sanukitoids* (e-f) *porphyritic granodiorite*: idiomorphic medium-grained Afs phenocrysts. It represents the unique sanukitoid variety with high content of Opq crystals; (g-h) heterogranular granodiorite: characterized by amphibole absence, and high epidote and biotite contents. Mineral abbreviations based on Whitney & Evans (2010).

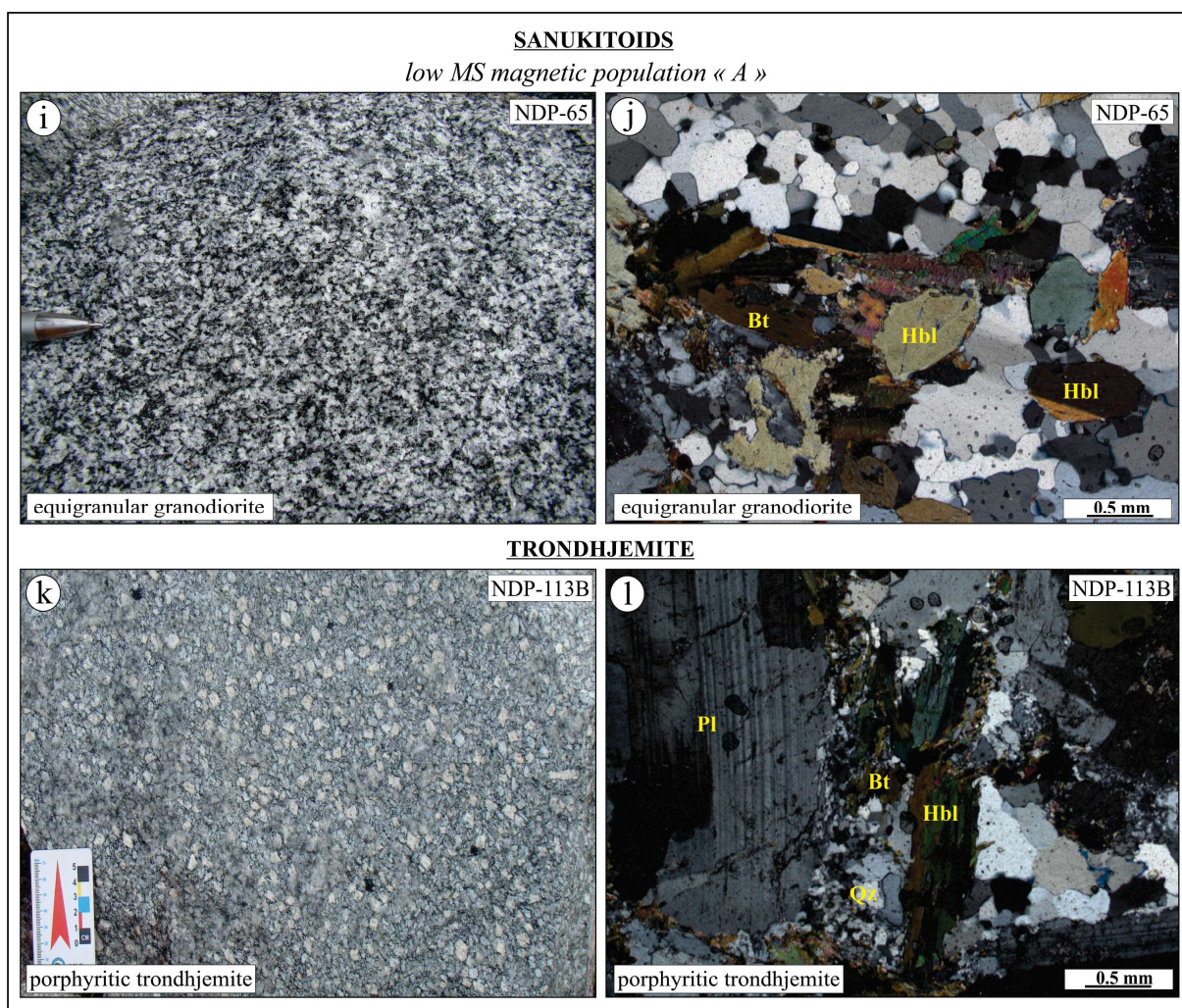


Figure 2.3 (*Continuation*) - Outcrop photos and photomicrographs of thin sections in crossed nicols (CN) of the textural aspects of the Ourilândia granitoids: (i-j) equigranular granodiorite: considered the major sanukitoid variety, commonly has idiomorphic Hbl crystals; (k-l) *Trondhjemite*: Pl partially replaced by sericite along cleavage planes and immersed into a finer matrix with recrystallized Qtz and chloritized Bt. The Hbl represents an accessory phase. Mineral abbreviations based on Whitney & Evans (2010).

Compared to leucogranites, the high-Ti granodiorite is less evolved ($\text{SiO}_2 = 68.08\text{--}66.34\%$) and has higher TiO_2 ($0.54\text{--}0.60\%$), CaO ($2.42\text{--}3.03\%$) and Al_2O_3 ($14.90\text{--}15.30\%$) contents. Although the analyzes of the high-Ti granodiorite plots on the magnesian field in the diagram of Laurent *et al.* (2014), unlike these, the high-Ti granodiorite has relatively moderate $\text{Fe} \# = \text{FeOt}/(\text{FeOt}/\text{MgO})$ ($0.5\text{--}0.9\%$), low $\text{Mg}\#$ ($< 0.4\%$) and K/Na ratio ranging from $0.8\text{--}1.5$ (Figure 2.4c). In the MALI diagram ($\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$) vs. SiO_2 , leucogranites and high-Ti granodiorite plot at the boundary between the alkali-calcic to calc-alkalic fields of Frost *et al.* (2001) (Figure 2.4d), with significant enrichment in SiO_2 ($69.30\text{--}74.69\%$) and K_2O ($3.83\text{--}5.37\%$).

2.3.1.2 Sanukitoids

These granitoids are composed of granodiorites (equigranular, heterogranular and porphyritic), and occurrence of associated tonalite, quartz-monzodiorite and quartz-diorite varieties (Figure 2.3e-j; Figure 2.4a). The batholith of the equigranular granodiorite $\pm$ tonalite

lithotypes has a notable surface in the central-western portion of the area. This batholith has an ellipsoidal shape area of 296 km² and a spatial arrangement that follows the main ductile regional structure directions (E-W).

The heterogranular granodiorite variety consists of small plutons across 2 Km² and occurs as inclusion in leucogranites. The porphyritic granodiorite occurs in the southwestern part of the area and comprises two circular batholiths of 35 km², separated by the equigranular granodioritic variety (Figure 2.2). The sanukitoids are characterized by dark-gray to light-gray color, medium- to coarse-grained texture, commonly with plagioclase (Pl) saussuritization and high mafic and epidote (Ep) contents (> 11 %). Biotite (Bt) and hornblende (Hbl) frequently occur as varietal minerals (Figure 2.3e-h). Accessory minerals are represented by titanite (Ttn), zircon (Zrc), apatite (Ap) and opaque (Opq) minerals. These rocks are moderately deformed, marked by the stretching of quartz crystals (*ribbon*) and bands of mafic minerals defining the foliation plane (Figure 2.3i-j).

Sanukitoids commonly present microgranular mafic enclaves oriented according to the general trend of foliations. Such enclaves have evidence of interaction with the equigranular granodiorite variety, and are rare in porphyritic granodiorites. Silva *et al.* (2019) obtained negative to positive values of $\epsilon_{\text{Hf}}(t)$ (-1.98 and +3.36) and $\text{Hf-T}_{\text{DM}}^{\text{C}}$ between 3.40 and 3.08 Ga for the equigranular sanukitoids, indicating mantle contributions to their origins. Thus, for the porphyritic sanukitoids (~ 2.92 Ga), these authors reported strictly negative values of $\epsilon_{\text{Hf}}(t)$ (-4.38 and -0.08) and $\text{Hf-T}_{\text{DM}}^{\text{C}}$ ranges from 3.58-3.31 Ga, indicating a greater participation of the crustal components in relation to the mantelic contributions for their genesis. In general, the sanukitoids present notable enrichment in mantle origin elements (Mg, Cr, Ni) and incompatible elements (K, Sr, Ba), which reflects their high Mg# contents ($0.44 < \text{Mg\#} < 0.69$) and low Fe# contents ($0.45 < \text{Fe\#} < 0.69$), plotting on the ternary diagram [$\text{Na}_2\text{O}/\text{K}_2\text{O}$ vs. $2\text{A}/\text{CNK}$ vs. 2FMSB] in the central portion and high ferromagnesian contents field (pole FMSB - Figure 2.4b). In general, they show Al_2O_3 contents ranging from 13.0-15.5 % and K/Na ratio ranging from moderate to high (0.31-1.41) (Figure 2.4c). In the MALI diagram, they plot predominantly in the calc-alkalic field (Figure 2.4d).

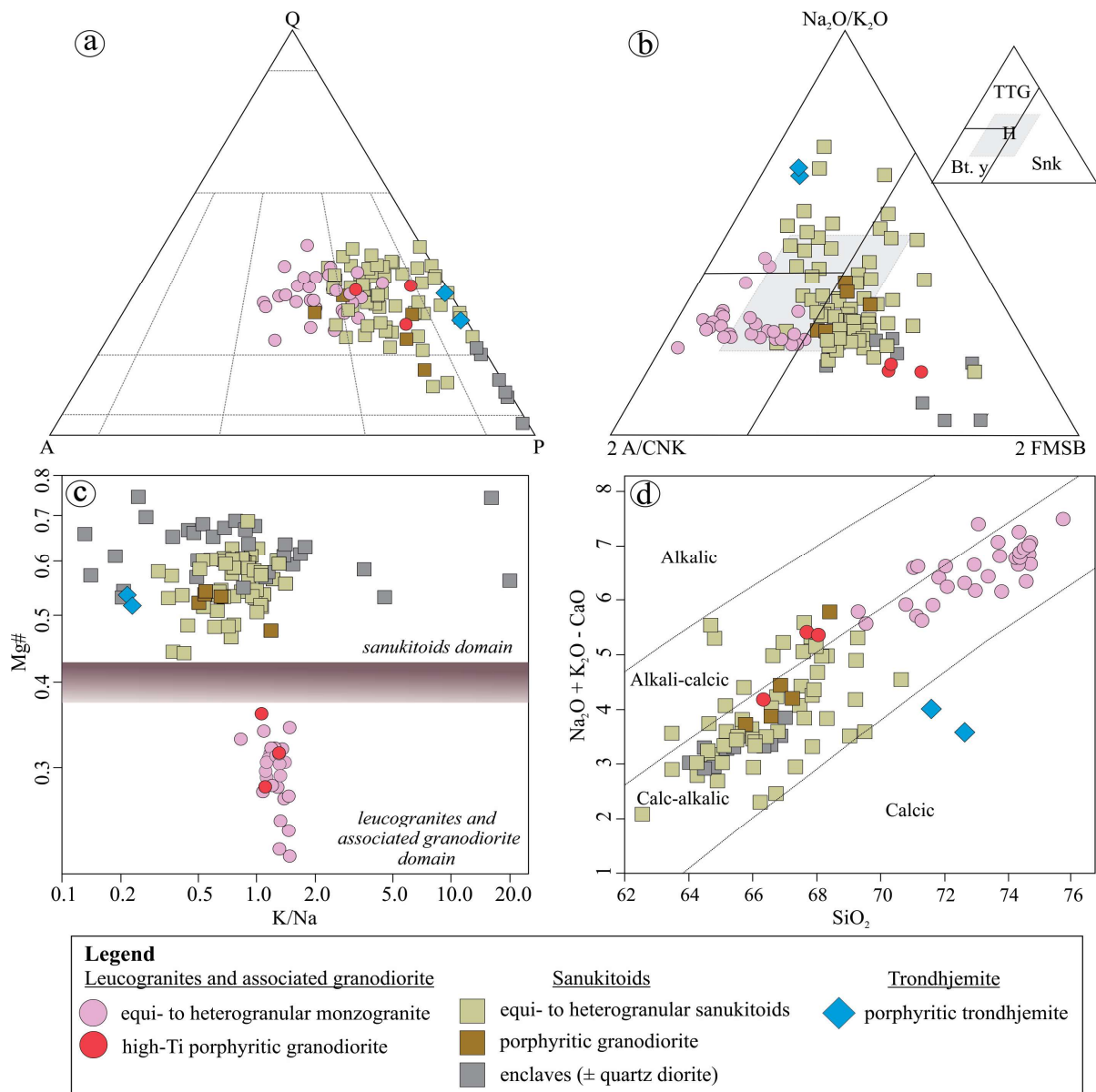


Figure 2.4 – Petrographic and geochemical classifications for the granitoids of the Ourilândia do Norte area: (a) modal analysis Q-A-P diagram according to the IUGS recommendations (Le Maitre *et al.* 2002); (b) ternary diagram [Na₂O/K₂O vs. 2A/CNK vs. 2FMSB]; where FMSB = (FeOt + MgO)wt.% * (Sr + Ba)wt.% (top right schematic triangle; Snk. = sanukitoids s.l., Bt.y = biotite- and two micas granites, H. = hybrids granites) (Laurent *et al.* 2014); (c) Mg# = MgO/(FeOt+MgO) vs. K/Na diagram (Moyen *et al.* 2003); (d) Na₂O+K₂O-CaO vs. SiO₂ diagram (Frost *et al.* 2001). Abbreviations: A = alkali feldspar, P = plagioclase, Q = quartz.

2.3.1.3 Trondhjemite

Trondhjemite outcrops in the central portion of the area, as a small ellipsoidal stock of 2 km wide and 1 km apart, associated with the quartz-diorite lithotype (Figure 2.2). It is characterized by undeformed medium-grained porphyritic texture (Figure 2.3k-l; Figure 2.4a). Its mineralogy is similar to those from sanukitoid varieties; however, it differs by a more intense plagioclase saussuritization, besides the higher epidote contents and rare opaque minerals (Figure 2.3l). The foliation plane is marked by the stretching of the biotite crystals and fine-grained quartz aggregates recrystallized mantling plagioclase porphyry. In the ternary classification diagram for Archean granitoids (Laurent *et al.* 2014), analyzes of the

trondhjemite plot in the field of TTGs, with a high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio (Figure 2.4b), high SiO_2 contents ($> 71\%$) and relatively low Mg# in a range of 0.51-0.53 (Figure 2.4c). In the MALI diagram, plots in the calcic field (Figure 2.4d). Silva *et al.* (2019) obtained an age of 2.92 Ga for the trondhjemite associated to values of $\epsilon\text{Hf}(t)$ ranging from negative to positive (-3.53 and +2.26) and $\text{Hf-T}_{\text{DM}}^{\text{C}}$ from 3.53-3.17 Ga.

2.4 MAGNETIC SUSCEPTIBILITY (MS)

2.4.1 Methodology

The samples came from the eastern portion of the Ourilândia do Norte town (southeast of the Pará state - Brazil), whose geological mapping was carried out between 2015 and 2017 in three different field stages, and represents 141 MS values (Figure 2.5). The weathered surface were broken off to reveal fresh samples surface. The susceptibility meter MS-30 manufactured by ZH Instruments (maximum detection limit 1×10^{-7} SI) was used during this stage at the Magnetic Petrology Laboratory of the Geosciences Institute of the Federal University of Pará. The measurements were performed on regular surfaces and without weather evidence, with an average of three measurements in different samples sections, which was considered the average as representative (see Table 2.1 to visualize the distributions of the MS values). The values were plotted on graphs and frequency histograms using the Minitab 18 software (free version). The opaque minerals textural and mineralogical characterization was carried out in reflected light using fourteen polished thin sections representatives of each petrographic variety. Prior to analysis by Scanning Electron Microscope (SEM), the thin sections were coated with carbon film to eliminate electrostatic charge-up on the sample surface. Back-Scattered Electron (BSE) images of the opaque minerals, textural aspects and their major element compositions, were obtained using a LEO-1430 Scanning Electron Microscope coupled with an Energy Dispersive X-ray Spectrometer, which operated at an accelerating voltage of 20 kV and 0.3 nA beam current at the Microanalysis Laboratory of the Geosciences Institute of the Federal University of Pará. All samples had available whole-rock geochemistry compiled from Santos & Oliveira (2016) and Silva *et al.* (2018). The GCDKit 6.0 (free version) was used to make diagrams between MS and geochemistry.

2.4.2 Dataset presentation

The MS arrangements can be seen in the geologic map (Figure 2.5). These values range from 0.05×10^{-3} (log -4.26) to 17.0×10^{-3} SI (log -1.77) (Table 2.1). The high MS values tend to be concentrated in the eastern portion of the map, while the intermediate and low MS values are distributed in the central and western portion, respectively. The probability graphs

show that the behavior of the MS values allows to separate three main magnetic fields, designated by the increasing order (A, B, C) (Figure 2.6a). In the frequency histograms, magnetic domain (A) is characterized by low MS values ranging from 0.05×10^{-3} to 0.57×10^{-3} SI (log -4.26 to -3.24), magnetic domain (B) has intermediate MS values in a range of 0.59×10^{-3} to 2.35×10^{-3} SI (log -3.22 to -2.62), and the magnetic domain (C) has high MS values ranging from 2.35×10^{-3} to 17.0×10^{-3} SI (or log -2.62 to -1.77) (Figure 2.6b-c).

2.4.2.1 Comparasion between MS distribution and the lithological varieties

The table 2.2 depicts the representative distributions of each lithological variety in the three distinct magnetic fields. Leucogranites and associated high-Ti granodiorite are distributed into the higher magnetic MS domain (C), which is consistent with their high modal contents of opaque minerals (magnetite) compared to the other lithological varieties. Its representative distributions decreases from magnetic field B, and reaches almost zero in the magnetic field A that indicates low MS values. The high-Ti porphyritic granodiorite differs from other leucogranitic varieties due its high MS values, which range from 11.3×10^{-3} SI (log -1.94) to 17.0×10^{-3} SI (log -1.76), and is distributed mostly in the magnetic domain (C).

The equigranular monzogranite presents MS values ranging from 2.38×10^{-3} SI (log -2.62) to 13.1×10^{-3} SI (log -1.88), whereas the heterogranular-type is distributed in a range of 5.11×10^{-3} SI (log -2.29) to 12.30×10^{-3} SI (log -1.92). In turn, the sanukitoids have a wide distribution, characterized by a significant concentration in the lower MS field (A), whose cumulative percentage corresponds to 87 % of total samples (Table 2.2). The quartz monzodiorite variety is distributed frequently in the lower magnetic field (A), whose MS values are represented by a range of 0.16×10^{-3} SI (log -3.79) to 0.17×10^{-3} SI (log -3.76). Thus, the porphyritic granodiorite (4.23×10^{-3} to 6.33×10^{-3} SI) and heterogranular-type (3.37×10^{-3} to 6.74×10^{-3} SI) have the highest MS values; the former has not representative samples distributions in low magnetic domain (A) whereas the latter has high to intermediate MS values (Figure 2.6c). Finally, the intermediate MS field concentrates variable proportions of leucogranites and sanukitoids lithotypes. However, unlike the leucogranite magnetic behavior, the occurrence of the sanukitoids varieties (except the porphyritic-type), trondhjemitic and mafic enclaves significantly increase towards lower MS values. Such varieties have low or zero magnetite modal contents (0.0-0.25 %), reflecting their lower MS values when compared with leucogranites.

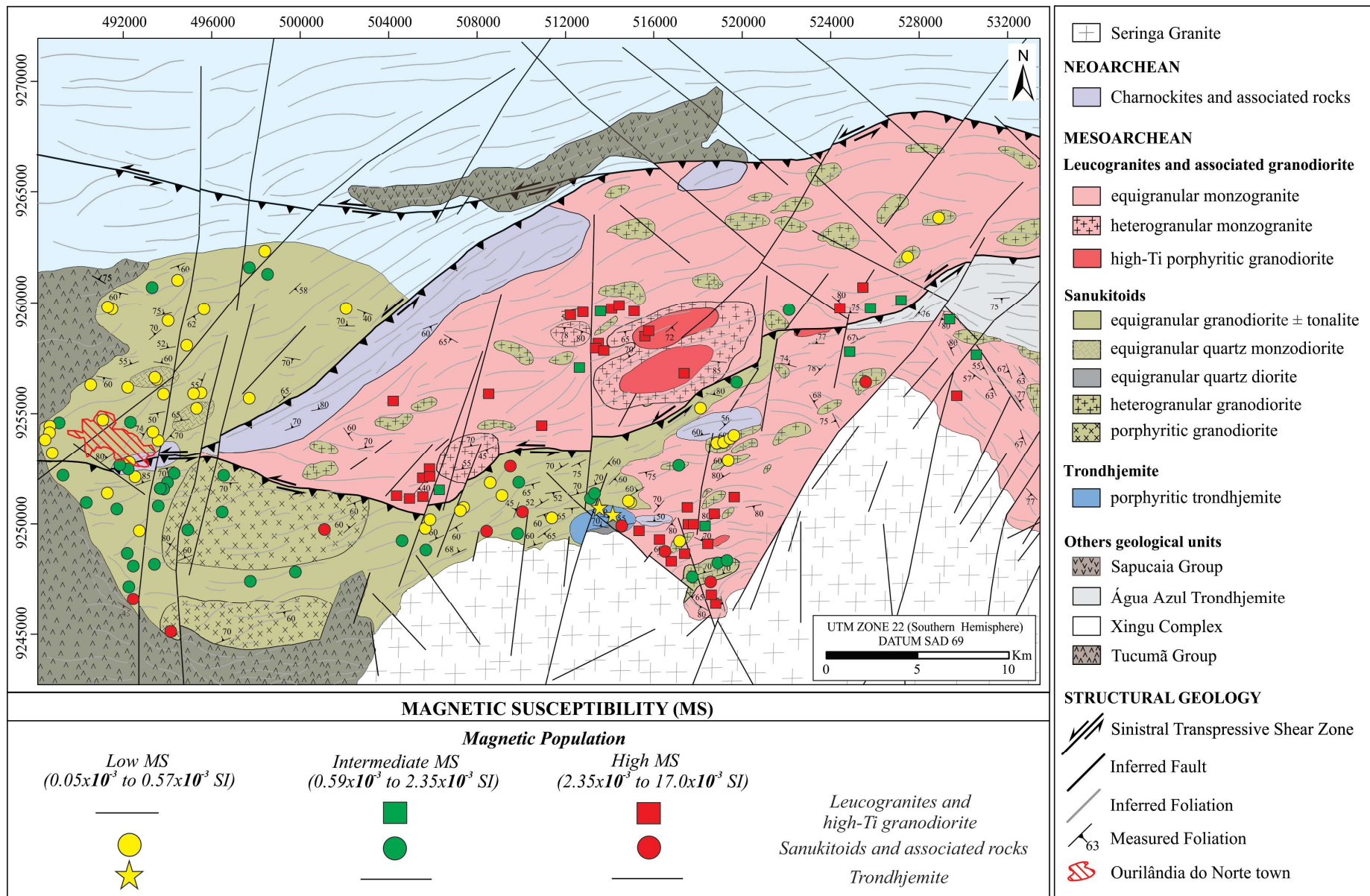


Figure 2.5 - Ourilândia do Norte geologic map showing the magnetic susceptibility measurements (MS) distributions according to the interpreted magnetic domains (modified after Silva *et al.* 2019). MS legend: leucogranite and associated high-Ti granodiorite represented by the squares; sanukitoids by circles; trondhjemite by the star, and the line shows absence of measures.

Table 2.1 - Magnetic susceptibility measurements (MS) in ascending order of the Mesoarchean granitoids from Ourilândia do Norte.

Pop.	N°	Sample	K (SI)	Log K (SI)	Facies	Unit	Pop.	N°	Sample	K (SI)	Log K (SI)	Facies	Unit	Pop.	N°	Sample	K (SI)	Log K	Facies	Unit
A	1	NDP-115	0.05x10 ⁻³	-4.262	pTrd	Trondhjemite	B	49	NDP-39C	0.20x10 ⁻³	-3.697	eQzDrt	Enclave	C	97	NLD-30B	2.55x10 ⁻³	-2.593	eMzG	Leucogranite
	2	NDP-113B	0.06x10 ⁻³	-4.218	pTrd	Trondhjemite		50	NDP-108	0.21x10 ⁻³	-3.669	eTnl	Sanukitoid		98	NLD-06B	2.67x10 ⁻³	-2.573	eMzG	Leucogranite
	3	NDP-126	0.07x10 ⁻³	-4.119	hGrd	Sanukitoid		51	NDP-28A	0.21x10 ⁻³	-3.669	eGrd	Sanukitoid		99	NLD-19	2.69x10 ⁻³	-2.570	eMzG	Leucogranite
	4	NDP-124	0.07x10 ⁻³	-4.119	hGrd	Sanukitoid		52	NDP-89A	0.23x10 ⁻³	-3.638	eGrd	Sanukitoid		100	NLD-17B	2.90x10 ⁻³	-2.537	eMzG	Leucogranite
	5	NDP-98A	0.07x10 ⁻³	-4.113	eTnl	Sanukitoid		53	NLD-26ANT	0.23x10 ⁻³	-3.628	hMzG	Sanukitoid		101	NLD-10A	2.92x10 ⁻³	-2.534	eMzG	Leucogranite
	6	NLD-24C	0.08x10 ⁻³	-4.094	eGrd	Sanukitoid		54	NDP-38A	0.24x10 ⁻³	-3.627	eTnl	Sanukitoid		102	NDP-127	2.93x10 ⁻³	-2.533	eMzG	Leucogranite
	7	NDP-128	0.08x10 ⁻³	-4.086	hGrd	Sanukitoid		55	BRM-82A	0.24x10 ⁻³	-3.619	eGrd	Sanukitoid		103	NDP-62	3.01x10 ⁻³	-2.521	eTnl	Sanukitoid
	8	NDP-88A	0.09x10 ⁻³	-4.036	eGrd	Sanukitoid		56	BRM-66	0.24x10 ⁻³	-3.619	eGrd	Sanukitoid		104	NLD-20B	3.04x10 ⁻³	-2.517	eMzG	Leucogranite
	9	NDP-47	0.09x10 ⁻³	-4.013	eGrd	Sanukitoid		57	NDP-130	0.24x10 ⁻³	-3.614	hGrd	Sanukitoid		105	NLD-11A	3.37x10 ⁻³	-2.472	hGrd	Sanukitoid
	10	NLD-26B	0.09x10 ⁻³	-4.009	hGrd	Sanukitoid		58	NDP-121	0.25x10 ⁻³	-3.603	eGrd	Sanukitoid		106	NLD-04B2	3.45x10 ⁻³	-2.462	eMzG	Leucogranite
	11	NDP-122	0.09x10 ⁻³	-4.004	eGrd	Sanukitoid		59	BRM-38B	0.25x10 ⁻³	-3.602	Enclave	Enclave		107	NLD-24B	3.70x10 ⁻³	-2.431	eMzG	Leucogranite
	12	NDP-120	0.10x10 ⁻³	-4.000	eGrd	Sanukitoid		60	BRM-11B	0.27x10 ⁻³	-3.568	eGrd	Sanukitoid		108	NDP-112A	3.72x10 ⁻³	-2.429	Enclave	Enclave
	13	BRM-10A	0.10x10 ⁻³	-4.000	eGrd	Sanukitoid		61	BRM-116B	0.28x10 ⁻³	-3.552	Enclave	Enclave		109	NLD-17C	3.72x10 ⁻³	-2.429	eMzG	Leucogranite
	14	NDP-105	0.10x10 ⁻³	-3.991	eGrd	Sanukitoid		62	BRM-112	0.30x10 ⁻³	-3.522	eGrd	Sanukitoid		110	NLD-27	3.89x10 ⁻³	-2.410	eMzG	Leucogranite
	15	BRM-44	0.11x10 ⁻³	-3.958	eGrd	Sanukitoid		63	NDP-39B	0.30x10 ⁻³	-3.519	Enclave	Enclave		111	NDP-15B	4.00x10 ⁻³	-2.398	eTnl	Sanukitoid
	16	BRM-13	0.11x10 ⁻³	-3.958	eGrd	Sanukitoid		64	NDP 19A	0.31x10 ⁻³	-3.504	eGrd	Sanukitoid		112	NLD-03A2	4.02x10 ⁻³	-2.396	eMzG	Leucogranite
	17	NLD-04A1	0.11x10 ⁻³	-3.955	hGrd	Sanukitoid		65	NDP-26	0.31x10 ⁻³	-3.501	eGrd	Sanukitoid		113	NDP-117A	4.06x10 ⁻³	-2.391	hMzG	Leucogranite
	18	NDP-101	0.11x10 ⁻³	-3.947	hGrd	Sanukitoid		66	NDP-15C	0.32x10 ⁻³	-3.492	Enclave	Enclave		114	NDP-23	4.23x10 ⁻³	-2.374	pGrd	Sanukitoid
	19	NDP-20	0.12x10 ⁻³	-3.924	eGrd	Sanukitoid		67	NDP-104	0.33x10 ⁻³	-3.486	eTnl	Sanukitoid		115	NDP-42	4.28x10 ⁻³	-2.368	eMzG	Leucogranite
	20	BRM-31	0.12x10 ⁻³	-3.920	eGrd	Sanukitoid		68	NDP-15A	0.33x10 ⁻³	-3.481	eTnl	Sanukitoid		116	NDP-106	4.52x10 ⁻³	-2.345	eTnl	Sanukitoid
	21	NDP-01	0.12x10 ⁻³	-3.913	eGrd	Sanukitoid		69	NDP-08	0.35x10 ⁻³	-3.459	eTnl	Sanukitoid		117	NLD-21	4.84x10 ⁻³	-2.315	eMzG	Leucogranite
	22	NDP-125	0.12x10 ⁻³	-3.910	hGrd	Sanukitoid		70	NLD-06A	0.37x10 ⁻³	-3.435	hGrd	Sanukitoid		118	NDP-91	5.11x10 ⁻³	-2.291	hMzG	Leucogranite
	23	NLD-03B	0.13x10 ⁻³	-3.889	hGrd	Sanukitoid		71	NDP-55	0.37x10 ⁻³	-3.423	eTnl	Sanukitoid		119	NLD-18	5.44x10 ⁻³	-2.264	eMzG	Leucogranite
	24	NDP-51A	0.13x10 ⁻³	-3.882	eGrd	Sanukitoid		72	NLD-22	0.40x10 ⁻³	-3.394	eGrd	Sanukitoid		120	NLD-08	5.62x10 ⁻³	-2.250	eMzG	Leucogranite
	25	NLD-12	0.14x10 ⁻³	-3.863	hGrd	Sanukitoid		73	NDP-30A	0.42x10 ⁻³	-3.372	eGrd	Sanukitoid		121	NDP-89B	5.83x10 ⁻³	-2.234	eMzG	Leucogranite
	26	NDP-100	0.14x10 ⁻³	-3.854	hGrd	Sanukitoid		74	NDP-57B	0.42x10 ⁻³	-3.371	Enclave	Enclave		122	NDP-43A	6.15x10 ⁻³	-2.211	eMzG	Leucogranite
	27	NDP-81A	0.14x10 ⁻³	-3.854	eGrd	Sanukitoid		75	NDP-103	0.44x10 ⁻³	-3.353	Enclave	Enclave		123	NDP-86B	6.21x10 ⁻³	-2.207	Enclave	Enclave
	28	NDP-71	0.14x10 ⁻³	-3.847	hGrd	Sanukitoid		76	NLD-07A	0.46x10 ⁻³	-3.331	hGrd	Sanukitoid		124	NDP-25A	6.33x10 ⁻³	-2.198	pGrd	Sanukitoid
	29	NDP-49	0.14x10 ⁻³	-3.842	eGrd	Sanukitoid		77	NLD-02A	0.51x10 ⁻³	-3.286	hGrd	Sanukitoid		125	NLD-11B	6.45x10 ⁻³	-2.190	eMzG	Leucogranite
	30	NDP-45	0.14x10 ⁻³	-3.838	eGrd	Sanukitoid		78	NDP-57A	0.57x10 ⁻³	-3.240	eTnl	Sanukitoid		126	NDP-93	6.65x10 ⁻³	-2.177	hMzG	Leucogranite
	31	NDP-29	0.14x10 ⁻³	-3.835	eGrd	Sanukitoid		79	BRM-63	0.59x10 ⁻³	-3.229	eGrd	Sanukitoid		127	NDP-112B	6.74x10 ⁻³	-2.171	hGrd	Sanukitoid
	32	NDP-125	0.15x10 ⁻³	-3.829	hGrd	Sanukitoid		80	NDP-48	0.70x10 ⁻³	-3.156	eGrd	Sanukitoid		128	NDP-92B	6.93x10 ⁻³	-2.159	hMzG	Leucogranite
	33	NDP-32	0.15x10 ⁻³	-3.818	eGrd	Sanukitoid		81	NDP-118A	0.72x10 ⁻³	-3.139	eMzG	Leucogranite		129	NLD-07B	7.50x10 ⁻³	-2.125	eMzG	Leucogranite
	34	NDP-50A	0.16x10 ⁻³	-3.798	eGrd	Sanukitoid		82	NDP-58	0.77x10 ⁻³	-3.115	eGrd	Sanukitoid		130	NLD-16B	7.80x10 ⁻³	-2.108	hMzG	Leucogranite
	35	BRM-49	0.16x10 ⁻³	-3.795	eQzMzD	Sanukitoid		83	NDP-84A	0.81x10 ⁻³	-3.089	pGrd	Sanukitoid		131	NDP-95A	7.84x10 ⁻³	-2.105	hMzG	Leucogranite
	36	BRM-15	0.16x10 ⁻³	-3.795	eQzMzD	Sanukitoid		84	NLD-29	0.94x10 ⁻³	-3.028	eMzG	Leucogranite		132	NLD-14	8.53x10 ⁻³	-2.069	hMzG	Leucogranite
	37	NDP-68A	0.16x10 ⁻³	-3.795	eGrd	Sanukitoid		85	NLD-10B	0.99x10 ⁻³	-3.004	hGrd	Sanukitoid		133	NLD-28	8.91x10 ⁻³	-2.050	eTnl	Sanukitoid
	38	NLD-24A	0.16x10 ⁻³	-3.790	eGrd	Sanukitoid		86	NDP-70	1.07x10 ⁻³	-2.970	hGrd	Sanukitoid		134	NLD-11C	9.11x10 ⁻³	-2.040	hMzG	Leucogranite
	39	NDP-65	0.16x10 ⁻³	-3.782	eTnl	Sanukitoid		87	NLD-26A*	1.24x10 ⁻³	-2.906	eMzG	Leucogranite		135	NLD-04B1	10.00x10 ⁻³	-2.000	eMzG	Leucogranite
	40	NDP-53	0.17x10 ⁻³	-3.767	eGrd	Sanukitoid		88	NDP-21	1.33x10 ⁻³	-2.876	pGrd	Sanukitoid		136	NLD-16C	11.30x10 ⁻³	-1.947	pGrd	Leucogranite
	41	NDP-82A	0.17x10 ⁻³	-3.761	eQzMzD	Sanukitoid		89	NLD-25	1.52x10 ⁻³	-2.818	eMzG	Leucogranite		137	NLD-03A	11.40x10 ⁻³	-1.943	hMzG	Leucogranite
	42	NDP-37	0.17x10 ⁻³	-3.752	eGrd	Sanukitoid		90	NDP-86A	1.69x10 ⁻³	-2.772	eGrd	Sanukitoid		138	NLD-15B	11.80x10 ⁻³	-1.928	pGrd	Leucogranite
	43	BRM-14	0.18x10 ⁻³	-3.744	eTnl	Sanukitoid		91	NLD-30A	1.74x10 ⁻³	-2.759	eMzG	Leucogranite		139	NLD-20A	12.30x10 ⁻³	-1.910	hMzG	Leucogranite
	44	NDP-56	0.19x10 ⁻³	-3.725	eGrd	Sanukitoid		92	NDP-19B	1.84x10 ⁻³	-2.735	eGrd	Sanukitoid		140	NDP-54	13.10x10 ⁻³	-1.883	eMzG	Leucogranite
	45	NDP-39A	0.19x10 ⁻³	-3.709	eQzDrt	Enclave		93	NLD-16A*	1.90x10 ⁻³	-2.721	eMzG	Leucogranite		141	NLD-17A	17.00x10 ⁻³	-1.769	pGrd	Leucogranite
	46	NDP-44A	0.20x10 ⁻³	-3.703	eGrd	Sanukitoid		94	NLD-31B	2.35x10 ⁻³	-2.628	Enclave	Enclave							
	47	BRM-68A	0.20x10 ⁻³	-3.698	eGrd	Sanukitoid	C	95	NDP-116	2.35x10 ⁻³	-2.628	eGrd	Sanukitoid							
	48	NDP-31	0.20x10 ⁻³	-3.698	eGrd	Sanukitoid		96	NLD-23*	2.38x10 ⁻³	-2.623	eMzG	Leucogranite							

Abbreviations: pTrd = porphyritic trondhjemite; hGrd = heterogranular granodiorite; eTnl = equigranular tonalite; eGrd = equigranular granodiorite; eQzMzD = equigranular quartz-monzodiorite; pGrd = porphyritic granodiorite; eMzG = equigranular monzogranite; hMzG = heterogranular monzogranite.

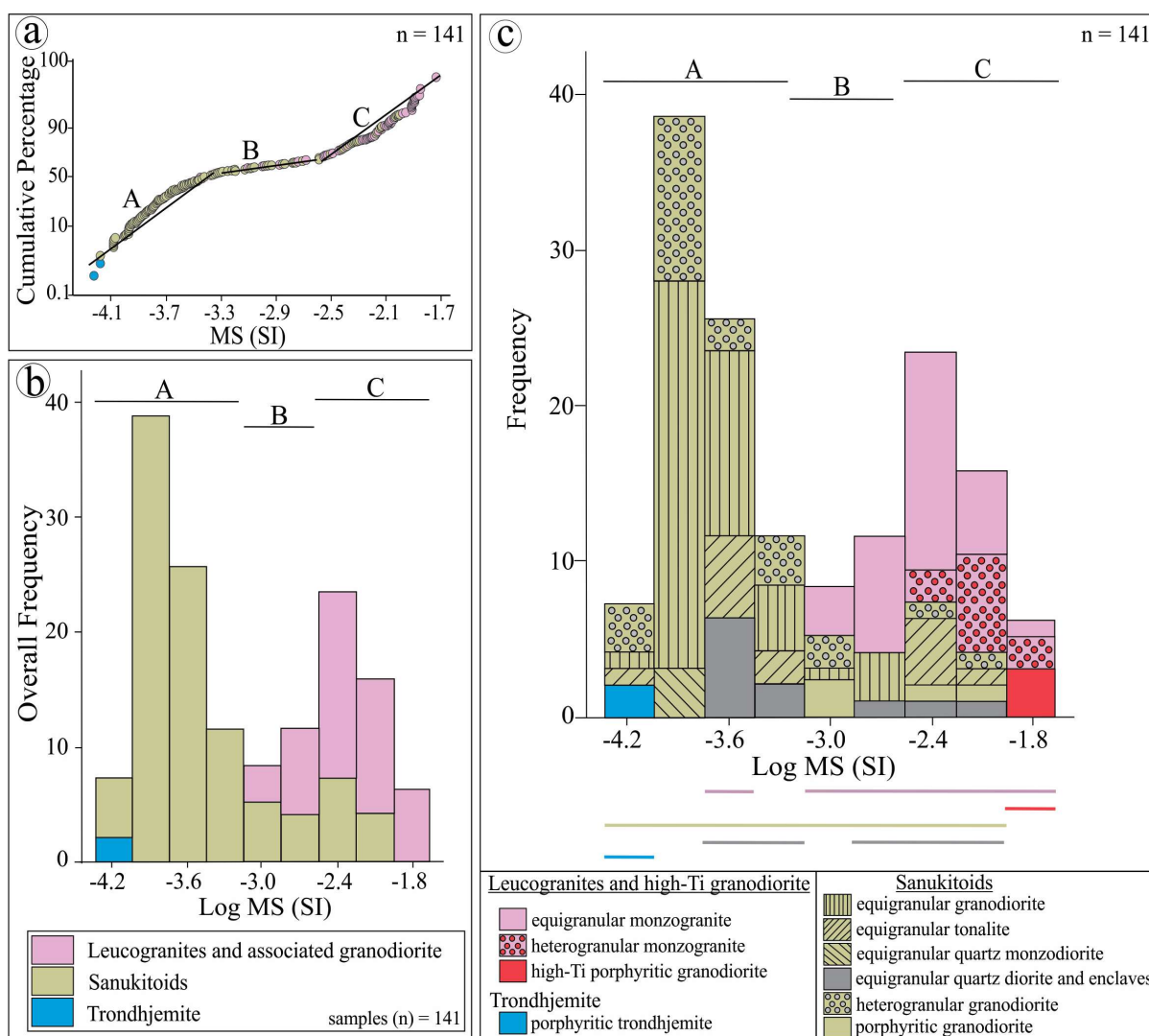


Figure 2.6 - Statistical graphs showing the frequency distributions of the MS in the lithotypes: (a) graph of cumulative percentage; (b) overall MS histogram; (c) MS histogram with the distribution of each lithological varieties.

Table 2.2 – Representative distribution of the lithotypes according to the MS values.

Geological units	Facies	Samples number	Magnetic Population (wt%)			MS K (SI)	
			A	B	C	Minimum	Maximum
Leucogranites and associated granodiorite	equi- to heterogranular MzG	41	0.0	30.9	86.3	0.23×10^{-3}	13.10×10^{-3}
	high-Ti porphyritic Grd	3	0.0	0.0	4.3	11.30×10^{-3}	17.00×10^{-3}
Sanukitoids	equi- to heterogranular sanukitoids	80	87.0	35.7	12.4	0.08×10^{-3}	8.91×10^{-3}
	porphyritic Grd	4	0.0	14.3	4.3	0.81×10^{-3}	6.33×10^{-3}
	equigranular QzDrt + Enclaves	11	10.0	7.2	4.3	0.19×10^{-3}	6.21×10^{-3}
Trondhjemitite	porphyritic Trd	2	3.0	0.0	0.0	0.05×10^{-3}	0.06×10^{-3}

Abbreviations: MzG = monzogranite; Grd = granodiorite; QzDrt = quartz-diorite; Trd = trondhjemitite.

2.4.2.2 Comparasion between MS distribution, and mineral and chemical contents

Ourilândia granitoids show high ferromagnesian mineral contents in sanukitoids and high-Ti granodiorite when compared with the monzogranites and trondhjemitites (Figure 2.7a). However, is noted that the sanukitoids display clusters of undefined MS trend, whereas leucogranites have a well-defined and positive MS trend; similar behavior is observed for the

opaque minerals contents, whose modal content is more expressive in the latter group. Note that opaque and ferromagnesian mineral contents control the MS values (positive correlation) in the leucogranite group and associated high-Ti granodiorite whereas undefined correlation can be indicated to the other granitoids associations (Figure 2.7b). Except for the porphyritic granodiorite which stands out for its higher opaque mineral contents in comparison with other sanukitoids varieties (Figure 2.7b). Trondhjemite is characterized by low opaque mineral contents which commonly is not plotted in the binary diagrams. Grant (1985) reported that MS measurements are dependent on the magnetite modal contents, whether other Fe-Ti oxide minerals. It is confirmed by the positive correlations between MS and opaque minerals, and negative in relation to the ferromagnesian mineral contents, and indicates the approach commonly identified in leucogranitic group whose magnetite is the chief Fe-Ti oxide mineral responsible for controlling the MS, on the other hand, lesser amounts of magnetite reflects in lower MS values in the sanukitoids varieties and trondhjemite.

The epidote modal contents are higher in sanukitoids, which, in general, show a clear negative correlation when compared with the MS values. For the leucogranitic group a dispersion of sample distributions is noted, which difficult a clear comparison with the MS behavior (Figure 2.7c). However, for the high-Ti granodiorite, epidote modal contents show a similar behavior from those identified for opaque minerals and other ferromagnesian minerals in relation to MS distributions (positive trend). For the sanukitoids and trondhjemite, epidote show high modal contents which commonly occurs mantling fine-grained magnetite crystals, and is frequently associated with chloritized biotite aggregates, amphibole and saussuritized plagioclase. These aspects suggest that the magnetite was an unstable mineral phase during late-magmatic stages, which would be responsible for the lower MS values ($< 2 \times 10^{-3}$ SI) in epidote-bearing varieties (Figure 2.7c). However, for the leucogranites and high-Ti granodiorite, the epidote does not occur associated with mafic minerals, and titanite tends to be more expressive in rocks with greater MS (Figure 2.7d). Ashwal *et al.* (1974) reconstructed the magnetic mineralogy using experimental studies and noted that an igneous protolith subjected to deformation and low-grade metamorphism conditions, Fe-Ti oxides formed commonly are replaced by new silicates phases (ferromagnesian minerals), where Fe^{+3} enters in the chemical epidote structure and hornblende; meanwhile Ti^{+4} enters in the structure of the hornblende and titanite. Therefore, the compositional contrasts noted among the three main granitoids associations reflect, in general, the distinct source and magma signatures which also is observed in the MS behaviors, as seen in the $\text{FeO}^* + \text{MgO} \%$ vs MS (SI unit) and $\text{SiO}_2 + \text{K}_2\text{O} \%$ vs. MS (SI unit) diagrams (Figure 2.7e-f).

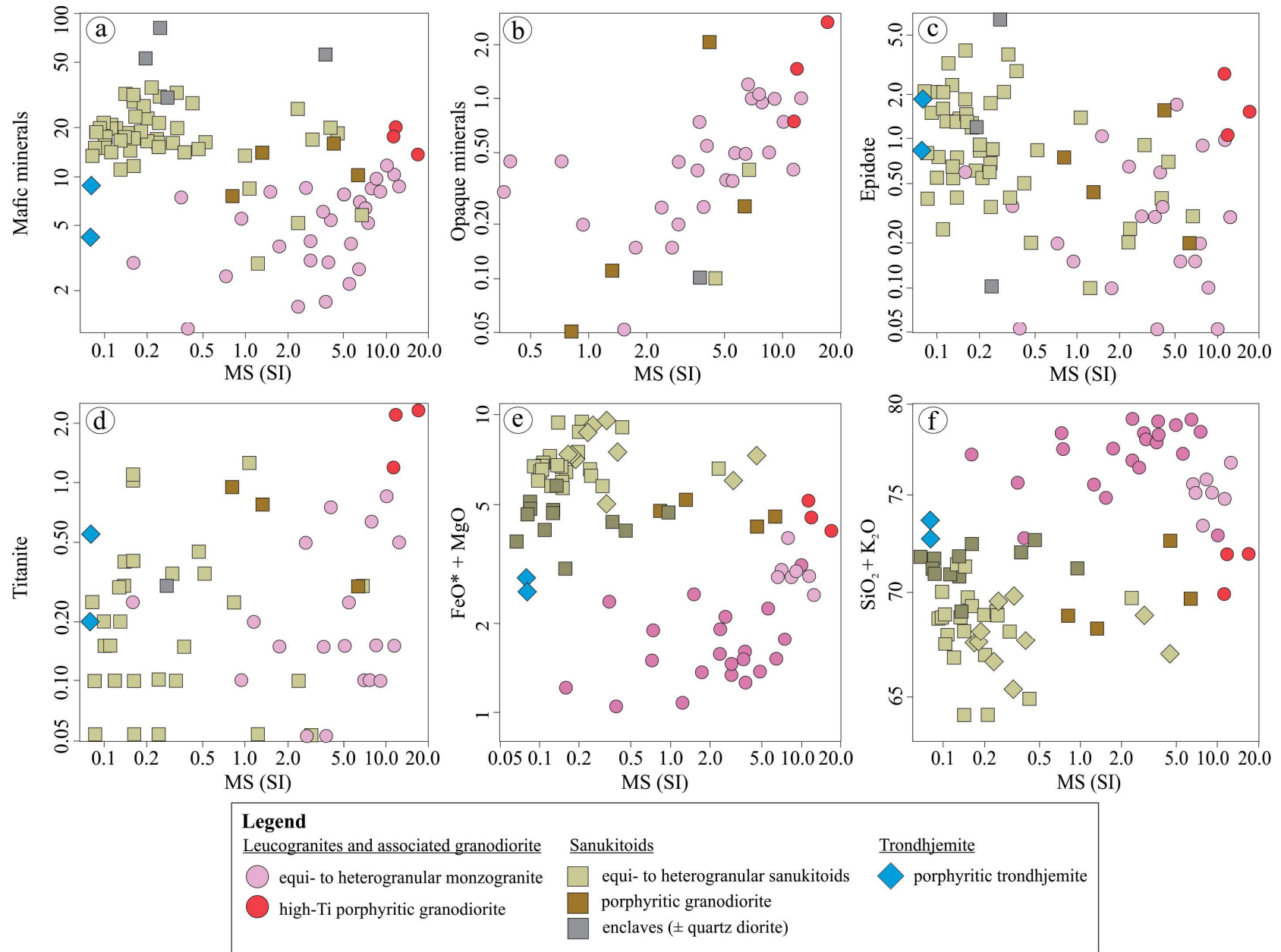


Figure 2.7 - Binary diagrams based on magnetic susceptibility, mineral and chemical contents showing correlation with: (a) mafic minerals; (b) opaque minerals; (c) epidote; (d) titanite; (e) $\text{FeO}^* + \text{MgO}$ %, (f) $\text{SiO}_2 + \text{K}_2\text{O}$ %.

Late-magmatic processes also can be responsible by the magnetite instability and contributes to the decreasing MS values in sanukitoids and trondhjemite. The magmatic epidote and other ferromagnesian minerals formations may inhibit the magnetite formations by the ferric iron capture during the early stages of magma crystallizations (Grant 1985).

2.5 OPAQUE MINERALS PETROGRAPHY

The Fe-Ti oxide minerals, sulfides and Fe-hydroxide identified in the Ourilândia granitoids are represented by magnetite, ilmenite, hematite, and in smaller proportions by chalcopyrite, pyrite and goethite. They occur as individual and/or fine-grained crystals aggregated, either as inclusion or in contact with ferromagnesian minerals. Although the studied granitoids show similarities regarding the opaque phase mineralogical associations, they differ in terms of their modal contents, textural aspects and degree of alteration and/or instability of opaque mineral phases by tardi-magmatic processes. Photomicrographs in reflected light (Figure 2.8a-l) and semi-quantitative SEM analyzes, along with their respective EDS spectra (Figure 2.9a-i), illustrate the textural and compositional aspects of Fe-Ti oxides minerals. For the leucogranites and associated high-Ti granodiorite, magnetite is the chief mineral Fe-Ti oxide where occurs as idio-hypidiomorphic fine- to medium-grained crystals with dimensions ranging from 1-1.5 mm (Figure 2.8a-d). They are slightly martitized (hematite alteration) and included in the biotite, or disseminated into a quartz-feldspar matrix, and occasionally has apatite inclusions and thin lamellae of ilmenite exsolution (Figure 2.9a-c). It may has straight contact or be mantling by titanite (Figure 2.8c-d, 2.9b), especially in the high-Ti granodiorite, and are rarely associated with epidote crystals. Ilmenite, in turn, occurs as oxy-exsolution lamellae into magnetite host, and according to the terminology proposed by Buddington & Lindsley (1964), Haggerty (1991) and Dall'Agnol *et al.* (1997), they classify as: i) ilmenite lattice (Ilm-T) which corresponds to thin submillimetric lamellae ($< 1\text{-}10\text{ }\mu\text{m}$) that develop into [111] plane and at the edges of the magnetite crystals; and ii) internal (Ilm-Cint) and external (Ilm-Cext) ilmenite-types that occur in contact with magnetite crystals. A third type is more common and occurs as thin individual and isolated crystals. Sulfides (pyrite and chalcopyrite) and goethite are rare.

For the sanukitoids, ilmenite has expressive modal content (0.15-0.25 %) and occurs as hypidiomorphic to xenomorphic crystals, with dimensions ranging from 1 to 2 mm (Figure 2.8i-j). They generally show individual fine-grained crystals, mantling by titanite (Figure 2.8i, 2.9e), or can occur as Ilm-T and Ilm-C types. For the equigranular variety, magnetite is a minor mineral phase and occurs as fine-grained crystals (0.5 mm) (Figures 2.8f-g, 2.9i),

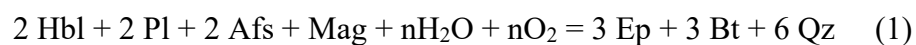
whereas for the porphyritic and heterogranular granodiorites, magnetite is the main Fe-Ti oxide mineral, has coarse-grained crystals (0.7 - 1.5 mm), and no martitization evidence (Figure 2.8e). It usually presents hypidiomorphic faces, occurs as inclusion into amphibole and biotite and presents very fine-grained apatite inclusions. When magnetite occurs associated with epidote crystals, displays signs of instability due to corrosion and a remarkable martitization degree (hematite) along [111] planes of the host mineral (Figure 2.8f, 2.9d, 2.9f-g). The occurrence of fine-grained disseminated crystals of pyrite mantling by goethite (corone-texture) is rare (Figure 2.8h, 2.8k, 2.9h). Opaque minerals are rare in trondhjemite (Figure 2.8l).

2.6 DISCUSSION

2.6.1 Nature and Fe-Ti oxide minerals formation sequence

Based on the textural characterization was possible to propose a formation sequence for the Fe-Ti oxides mineral assembly, as well as to infer its nature considering the reactions and processes widely disseminated on the literature (Buddington & Lindsley 1964; Spencer & Lindsley 1981; Haggerty 1991; Dall'Agnol *et al.* 1999).

Magmatic stage: Textural evidence, such as the cubic shape and straight contact of magnetite and ilmenite with the other primary ferromagnesian minerals, indicates that both are early phases in the crystallization process. According to the increase of oxygen fugacity (fO_2) in the magmatic system, occurs the inter-oxide rebalancing of the original titanomagnetite and contributes to the formation of pure magnetite crystals (poor-Ti content), represented by the formula Fe_3O_4 (Figure 2.9). The fact that magnetite occurs with inclusions of zircon and apatite, and ilmenite is free-inclusion, indicate that magnetite was formed shortly after the other primary accessories minerals, which are considered earlier in the crystallization history of granitic magmas. For the sanukitoids and trondhjemite, the earlier formation of magmatic epidote inhibits the formation of magnetite by ion exchange reactions involving hornblende, plagioclase, alkali-feldspar in the presence of a high H_2O contents and fO_2 . This contributes to the low magnetite contents and decrease in MS in these rocks. Schmidt & Poli (2004) reported that the formation of magmatic epidote in granitic rocks by the following reaction:



where Hbl (hornblende), Pl (plagioclase), Afs (alkali feldspar), Mag (magnetite), Ep (epidote), Bt (biotite), Qz (quartz).

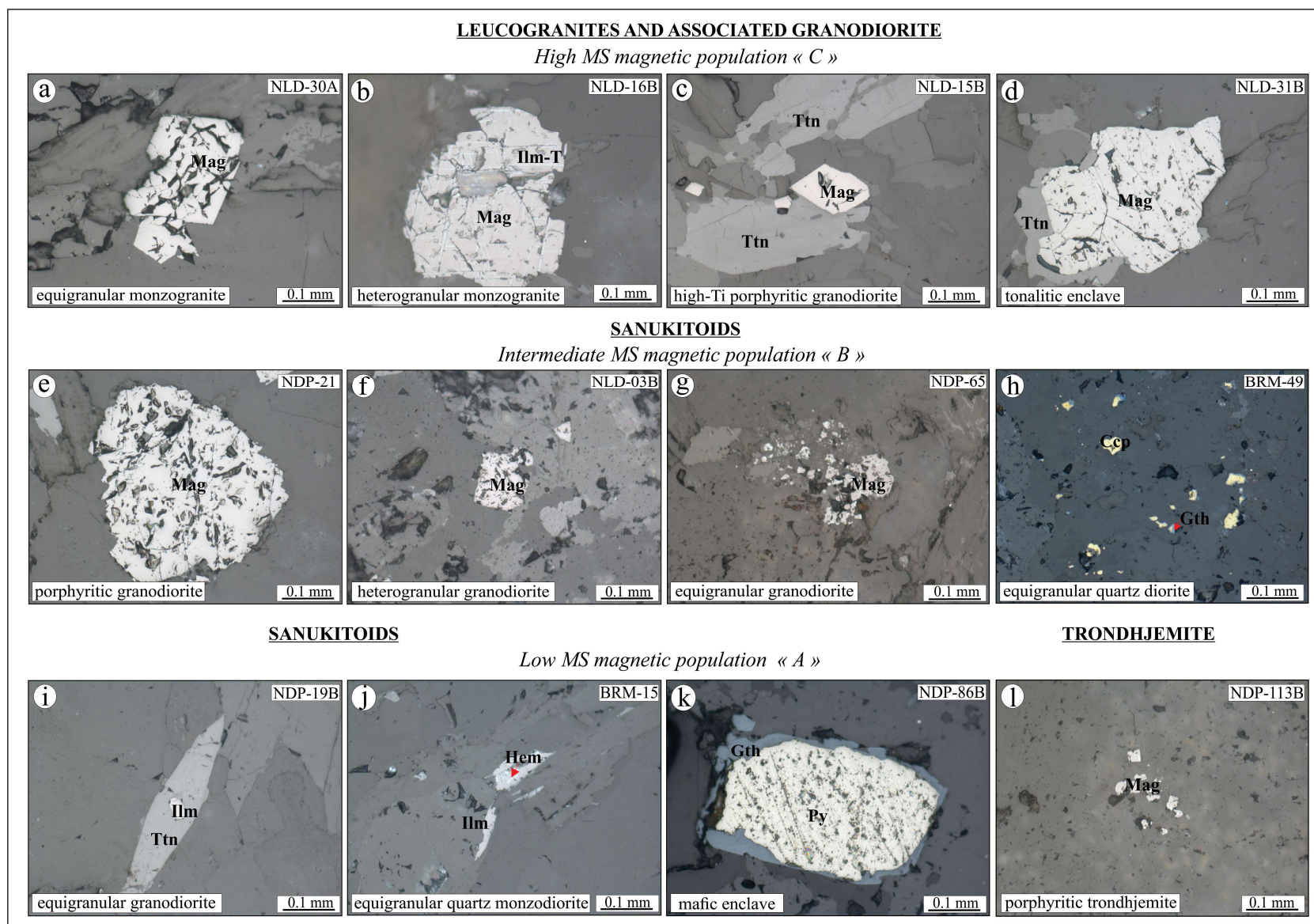


Figure 2.8 - Textural aspects under reflected light of the opaque phases. *Leucogranites and associated high-Ti granodiorite*: (a) euhedral coarse-grained individual magnetite (Mag) crystal; (b) thin lattice lamellae exsolution (Ilm-T) within Mag host; (c) cubic shape euhedral Mag showing straight contact with titanite (Ttn); (d) martitized Mag at the edges and mantling by Ttn; *Sanukitoids*: (e) subhedral Mag crystal; (f) fine-grained Mag crystal with intense martitization; (g) fine-grained Mag crystal replaced by ferromagnesian phase; (h) very fine-grained chalcopyrite (Ccp) and goethite (Gth) crystals; (i) subhedral ilmenite (Ilm) mantling by Ttn; (j) very-thin hematite lamellae (Hm) inclusions within fine-grained Ilm crystal; (k) subhedral pyrite (Py) mantling by Gth; *Trondhjemite*: (l) fine-grained Mag crystals which are rare in this variety. Mineral abbreviations based on Whitney & Evans (2010).

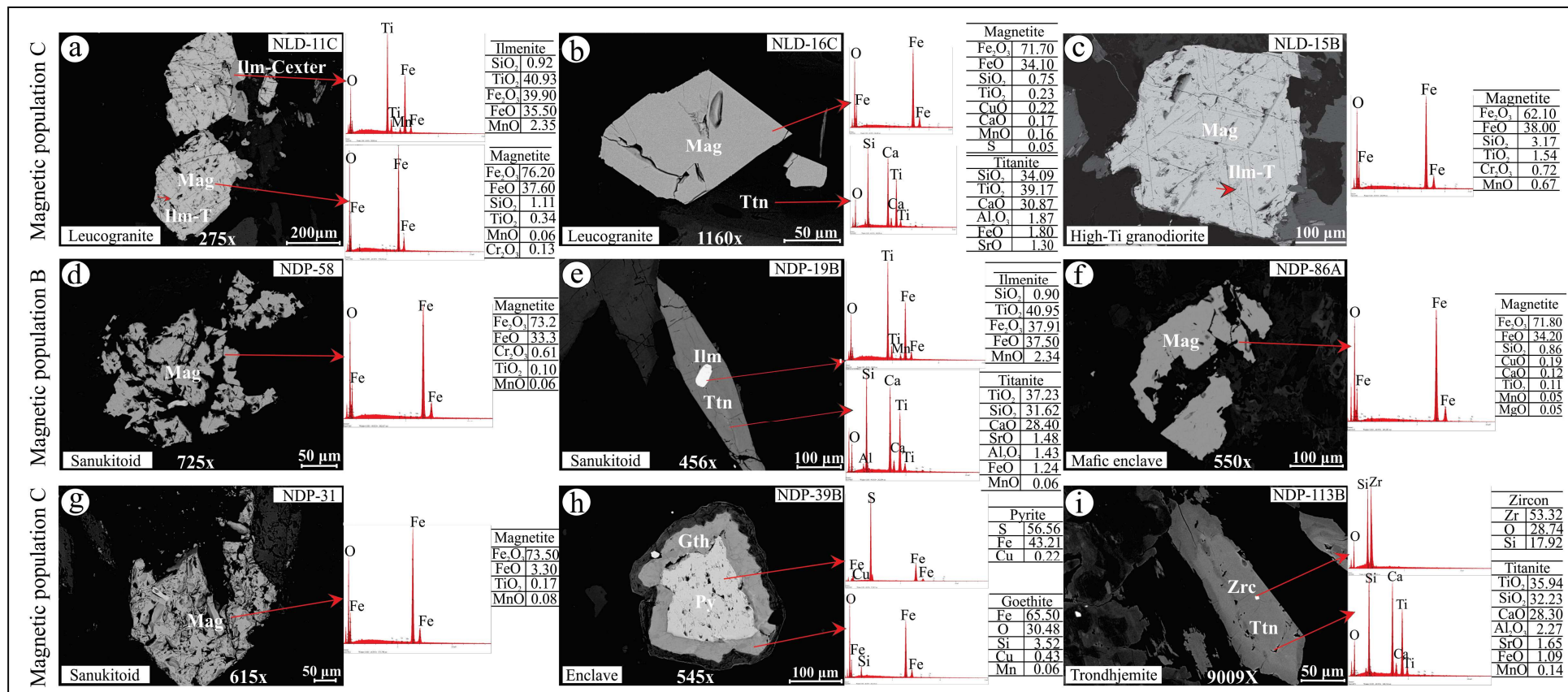
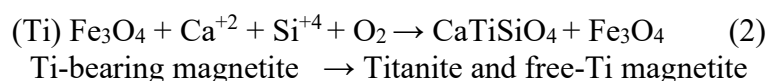


Figure 2.9 - Backscattered electron images obtained using a scanning electron microscope (SEM) and semiquantitative EDS spectra representative of the main opaque phases identified in the Ourilândia do Norte: (a) magnetite (Mag) associated with lattice ilmenite (Ilm-T) and composite ilmenite external (Ilm-Cexter); (b) magnetite (Mag) in straight contact with titanite (Ttn); (c) very-thin Ilm-T lammellae within magnetite (Mag) host; (d) corroded magnetite (Mag); (e) ilmenite (Ilm) mantling by euhedral titanite (Ttn); (f) magnetite (Mag) with fracture filled by epidote; (g) strongly deformed and martitized magnetite (Mag); (h) pyrite (Py) mantling by goethite (Gth); (i) euhedral titanite (Ttn) with inclusion of fine zircon (Zrc) crystal. Mineral abbreviation based on Whitney & Evans (2010).

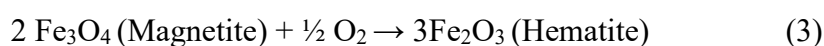
Hammarstron & Zen (1984), Naney (1983), Liebscher & Franz (2004) suggest that this process can occur in a temperature range from 600-700 °C (± 30 °C) under oxidizing conditions, depending on the H₂O contents available in magma. Through experimental studies, Schmidt & Thompson (1996) observed that in rocks with low epidote contents, the magnetite content increases proportionally (and vice versa), confirming the interrelationship between these minerals.

Tardi-magmatic stage: evidence of this stage corresponds to the development of Ilm-Cint and Ilm-Cext associated with magnetite crystals and the secondary titanite formation mantling ilmenite crystals. The formation of titanite is promoted by an enrichment of titanium in the system, which associated with the increasing Ca²⁺, Si⁴⁺, Al³⁺ availability from the amphibole to biotite disequilibria, contributes to the partial replacement of ilmenite by titanite. Corfu & Stone (1998) reported that the secondary titanite formation indicates crystallization during heating or fluid activity enrichments. Oliveira *et al.* (2002) represented this process by the following reaction:



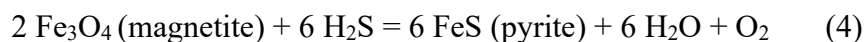
For the sanukitoids was indicated a restricted hematite dissolution formation within ilmenite crystals. Brownlee *et al.* (2010) reported that this texture occurs when there is a reheat in the magmatic system, affecting the temperature and fO_2 conditions. For the trondhjemite there is no textural evidence of this stage, such as the formation of titanite corone-texture and mineral dissolution evidences.

Postmagmatic stage: characterized by the greater intensity of the martitization processes, sulfides and goethite formations. For the leucogranites and high-Ti granodiorite, the martitization process is more incipient than from observed in sanukitoids and trondhjemite. The martitization process (change from magnetite to hematite) occurs due to increased oxidation, making the ferrous member (Fe²⁺) into ferric (Fe³⁺) in magnetite, as shown by the reaction below (Spencer & Lindsley 1981):



For the leucogranites and high-Ti granodiorite, there is rarely a xenomorphic epidote partially mantling by magnetite. However, in sanukitoids and trondhjemite, this contact relationship between magnetite and epidote is more frequent. In all studied varieties, sulfides (pyrite and chalcopyrite) are formed, mantling by goethite. The formation of these minerals is promoted by increasing of fluids circulation and oxygen fugacity, contributing to the

concentration of elements such as sulfur, copper and iron. The magnetite desestabilization process also can contribute to the pyrite formation, as can be expressed in the reaction:



In all granites from Ourilândia, Ilm-T can be formed within magnetite crystals. This process occurs under *subsolidus* conditions at temperatures below 620 °C (Spencer & Lindsley 1981), which titanium in the original titanomagnetite is removed by the reaction:

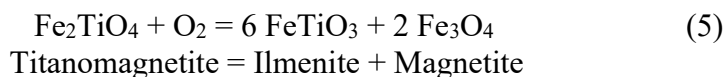


Figure 2.10 shows the sequence of Fe-Ti oxides and sulfides formations, and the main associated minerals. The pressure (P) and temperature (T) decrease from the magmatic to the postmagmatic stage, $f\text{O}_2$ and H_2O contents; viscosity and strain intensity increase in the opposite direction.

2.6.2 Crystallization conditions (T and $f\text{O}_2$)

In order to support the interpretation of the crystallization conditions of the Ourilândia do Norte granitoids, a compilation of the mineral chemistry data in amphibole and biotite was carried out (Nascimento, *in preparation*; see Chapter 3 for more details), and whole-rock geochemistry compiled from Santos & Oliveira (2016) and Silva *et al.* (2018). Complementary data, combined with mineralogical and textural aspects reported for the opaques and silicates phases, contributed to estimate the crystallization conditions of these granitoids in terms of temperature and $f\text{O}_2$.

The $f\text{O}_2$ is a thermodynamic parameter that controls the crystallization conditions of rocks, and is considered an important petrological marker, as it affects the equilibrium of Fe-Ti oxide minerals in the Fe-Si-O system, indicating whether the magma was oxidized or reduced (Wones 1989, Frost 1991a,b). This has both petrological and metallogenic implications for the concentration of mineral deposits (Clark 1999). The inter-correlation between this variable and the ferromagnesian silicates compositions (amphibole and biotite) have been studied in recent decades (Scaillet & Evans 1999, Ridolfi *et al.* 2010, Mutch *et al.* 2016 and references therein). For this effect, Ridolfi *et al.* (2010) proposed equations to estimate the temperature based on the magnesian amphibole compositions of calc-alkaline to alkaline rocks, crystallized under wide pressure, temperature, oxidation and water contents in magma conditions. Mutch *et al.* (2016) proposed an experimental geobarometer to estimate the pressure in bars applicable for shallower intrusions.

As the amphiboles found on sanukitoids and trondhjemite from Ourilândia do Norte are magnesian and satisfy the equations premises, the temperature and pressure calculated was used to estimate the fO_2 by the Wones (1989) equation:

$$\log (fO_2) = -30930 / T + 14.98 + 0.142 (P-1) / T \quad (6)$$

where T (in Kelvin) and P (in bars)

The fO_2 was also estimated using the equation proposed by Ridolfi *et al.* (2010). The methodology of analysis in amphibole and biotite are described in the article in preparation “*Mineral thermobarometry and its implications for petrological constraints on mesoarchean granitoids from the Carajás Province (Brazil)* (see Chapter 3). For estimates the fO_2 of leucogranites and associated high-Ti granodiorite was used the whole-rock compositions.

2.6.2.1 Leucogranites and associated high-Ti granodiorite

The leucogranites and high-Ti granodiorite present whole-rock $FeOt/(FeOt + MgO)$ ratio in a range of $0.69 > Fe^* > 0.89$, with SiO_2 % contents ranging from 66 – 76 %, plotting on the diagram of Frost *et al.* (2001) in the Cordilleran granites field (Figure 2.11a). Some monzogranites are chemically heterogeneous (NLD-26A*, NLD-23, NLD-05, NDP-68, NLD-16A); however, are characterized by Fe^* (0.89) and A_2O_3 % (13-15 %) consistent with magnesian calc-alkaline granitoids (Figure 2.11b). The oxidized nature is given by the dominant magnetite occurrence over ilmenite and its higher MS values (0.23×10^{-3} to 17.0×10^{-3} SI). These results are combined with the presence of magnesian biotite ($MgO > 10$ %) and $Fe/(Fe + Mg)$ ratio in biotite consistent with an oxidized nature. Considering that leucogranites have a crustal source origin (Silva *et al.* 2018), attributed to crust TTG anatexia (2.92-2.98 Ga; Almeida *et al.* 2011), probably they inherited the oxidized nature from the source itself. Although they do not have amphibole in their mineral assembly that allows crystallization temperature determinations, can be suggested that the leucogranites and high-Ti granodiorite were crystallized in high oxygen fugacity conditions (probably in the Δ_{NNO} - Figure 2.12a-b). The hematite exsolution presence indicates that the oxides crystallized under magnetite-ilmenite-hematite equilibrium conditions (Figure 2.12c). For the high-Ti granodiorite was indicated that partial melting of a enriched mantle contributed to the crustal anatexia (Silva *et al.* 2018). This interpretation integrated to the contemporary emplacement conditions show interaction with the magma-forming of the monzogranites, and therefore, is possible that the high-Ti granodiorite inherited/acquired an oxidized condition, contributing to the formation of magmatic magnetite, and this reflected in its high magnetic signature.

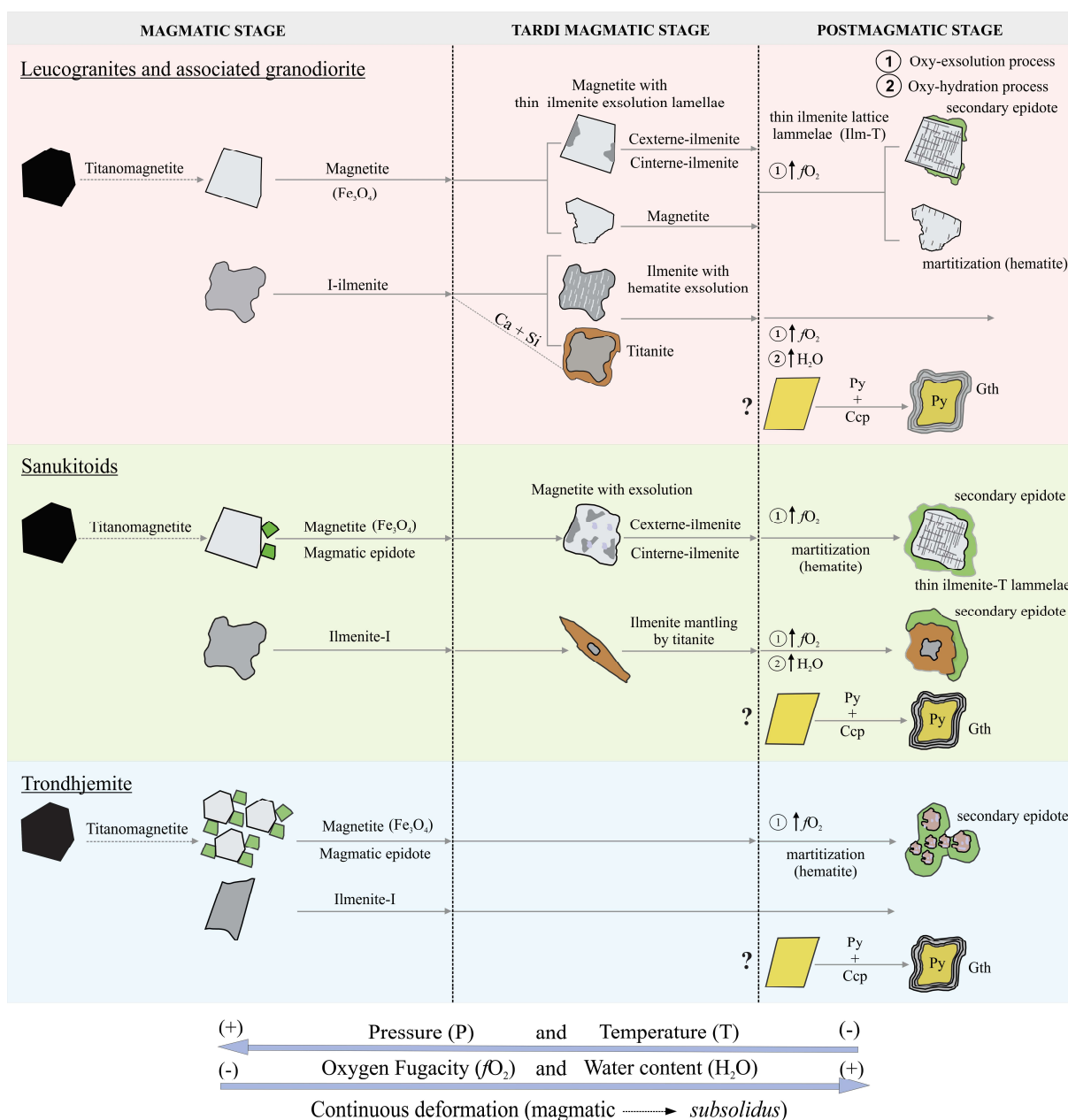


Figure 2.10 - Fe-Ti oxides and sulfides crystallization sequence showing the main magmatic stages differences. Abbreviations: Ilmenite-I (individual ilmenite crystals), Cexterne and Cinterne Ilm (external and internal composite ilmenite texture within magnetite host), Ilm-T (lattice ilmenite), Ca (Calcium), Si (Silicon), $f\text{O}_2$ (oxygen fugacity), H_2O (water content), Py (pyrite), Ccp (chalcopyrite), Gth (goethite).

2.6.2.2 Sanukitoids

Sanukitoids are typically magnesian rocks akin to the Cordilleran calc-alkaline granites, whose $\text{FeOt}/(\text{FeOt} + \text{MgO})$ ratio in whole-rock varies from $0.45 < \text{Fe}^* < 0.69$ (Figure 2.11a-b). Amphibole classify as magnesian-hornblende, $\text{Mg}/(\text{Mg} + \text{Fe}^{+2})$ ratio range 0.53 and 0.80. The biotite is magnesian and has a $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio lower than 0.40 (see Chapter 3). The $f\text{O}_2$ estimates in sanukitoids and associated rocks were performed based on the mineral assembly formed by titanite + magnetite + quartz and the equation proposed by Wones (1989).

The fO_2 values estimated by the Wones (1989) equation range from $\log fO_2$ -16.99 to -13.22, and plots close to the FMQ+1.0 (Fayalite-Magnetite-Quartz) up to values in the $\Delta_{NNO}+1.0$ (nickel-nickel oxide) (Figure 2.12a-b). Based on these results was assumed that these rocks evolved under fO_2 conditions ranging from low to moderately oxidized, with a variable T- fO_2 path slightly above FMQ+1.0 (equigranular granodiorite) up to the NNO+1.0 (porphyritic granodiorite). The fO_2 conditions for the equigranular variety is consistent with an enriched mantle source that contributed to the early formation of epidote, and influenced the reduction of the magnetite contents by iron capture, and consequently, would result in low MS values. However, the frequent presence of magnetite in the porphyritic granodiorite differs from other sanukitoid varieties and indicates differences in the compositions of their source, as reported by Silva *et al.* (2018). These compositional variations may have contributed to the magnetite formations in the porphyritic granodiorite due to greater crustal component participation during their formation, and contributing to a significant increase in MS. This interpretation is consistent with the higher fO_2 values obtained for the porphyritic granodiorite ($\log$ -13.22), suggesting its more oxidized nature compared to the other sanukitoid varieties.

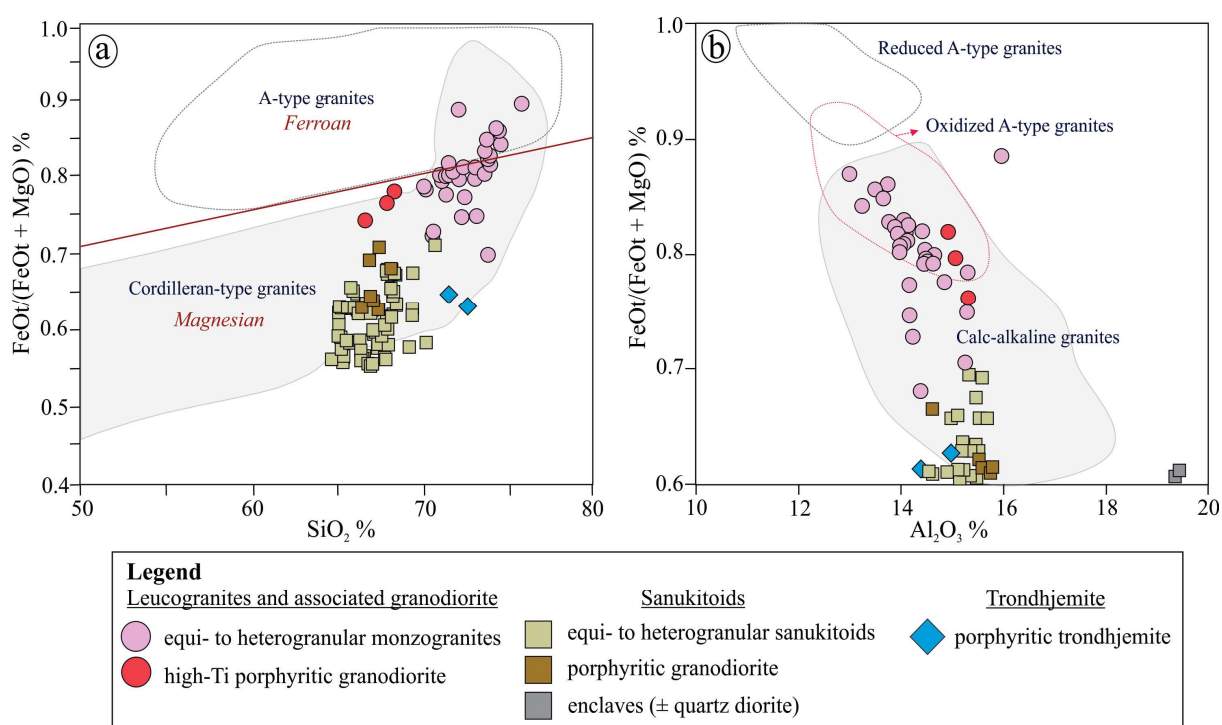


Figure 2.11 - Geochemical aspects of the Ourilândia do Norte granitoids: (a) $FeOt/(FeOt + MgO)$ vs. SiO_2 diagram showing that leucogranites characterized by $SiO_2 > 70 \%$ overlap with ferrous granites of type-A affinity, however, they are typically magnesian rocks and presents greater geochemical affinity with Cordilleran granites (Frost *et al.* 2001); (b) $FeOt/(FeOt + MgO)$ diagram vs. Al_2O_3 by Dall'Agnol & Oliveira (2007) confirming their calc-alkaline signature.

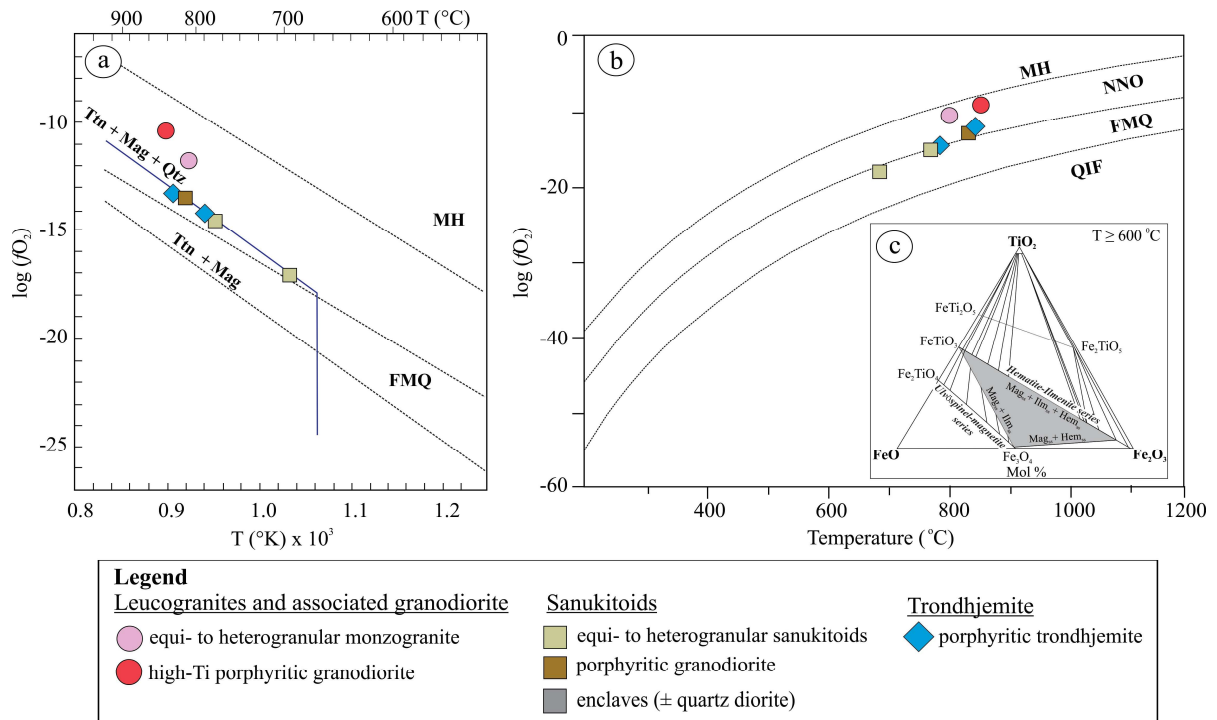


Figure 2.12 - Oxygen fugacity estimates: (a) temperature diagram (T °K) vs. oxygen fugacity (fO_2) based on Wones (1989) representing the approximate field of formation of the studied granitoids, with temperature and fO_2 calculated from the amphibole compositions using a microprobe; (b) fO_2 conditions based on Clark (1999) showing the estimated temperature and oxygen fugacity of the opaque phases. For the leucogranites and associated high-Ti granodiorite the fO_2 was estimated based on mineralogy (high magnetite content), high MS, and whole-rock compositions. Experimental buffers (Buddington & Lindsley 1964): MH - Magnetite Hematite, NNO - nickel-nickel oxide, FMQ - Fayalite Magnetite Quartz, QIF - Quartz-Ilmenite-Fayalite.

The sanukitoids of the Ourilândia do Norte have a geochemical signature similar to the Granodiorito Rio Maria, formed by the differentiation of parental mafic magma derived from partial melting of the mantle previously metasomatized (Silva *et al.* 2018). Geochronological data indicate that the porphyritic granodiorite (2.92 Ga) showed strictly negative ages and values of $\epsilon Hf(t)$ (-4.38 and -0.08) and $Hf-T_{DM}^C$ in a range of 3.58-3.31 Ga, indicating high crustal component participations in relation to the mantle, when compared with the equigranular sanukitoids (negative to positive values of $\epsilon Hf(t)$ -1.98 and +3.36 and $Hf-T_{DM}^C$ from 3.40 and 3.08 Ga; Silva *et al.* 2019). This confirms that the porphyritic granodiorite was formed by a magmatic pulse distinct from other sanukitoid affinity rocks as is indicated by its more oxidized nature.

2.6.2.3 Trondhjemite

They are Na-rich granitoids, characterized by $Fe/(Fe + Mg)$ ratio in biotite < 0.40 and in amphibole < 0.65 . The fO_2 estimates show values in a range of $\log -14.12$ to -13.17 (Figure 2.12), pointing to moderate to low oxidation conditions (FMQ+0.5). The fO_2 values, as well as the biotite and amphibole compositions, converge to their formations in moderately oxidized to low fO_2 conditions, which allowed the crystallization of rare crystals of magnetite.

Silva *et al.* (2019) reported a source formed by oceanic crust with participation of mantle liquids for the trondhjemites, which can influence in low fO_2 conditions.

2.7 CONCLUSION

The magnetic petrology study of the Mesoarchean granitoids from Ourilândia do Norte shows that the magnetic signature of these rocks is intrinsically related to the source and fO_2 crystallization conditions. Therefore, we admit that leucogranites and associated high-Ti granodiorite crystallized under high fO_2 conditions than sanukitoids and trondhjemite, probably in the $\Delta_{NNO}+2.8$. This is evidenced by the high content of primary magnetite and higher MS values, in addition to moderate FeOt/(FeOt + MgO) ratio in whole-rock (< 0.8) and the presence of magnesian biotite characterized by Fe/(Fe + Mg) ratio < 0.6 . These results are interpreted as source inheritance of a TTG crust. The equigranular sanukitoid variety and trondhjemite were formed in low to intermediate oxidizing conditions than those attributed to leucogranites; relatively above the FMQ buffer ($\Delta_{FMQ}+0.5$). For the heterogranular and porphyritic sanukitoids, crystallization conditions were estimated close to $\Delta_{NNO}+1.0$, in the magnetite stability field. These variations in the nature of the reservoirs source of the leucogranites (continental crust), sanukitoids (enriched mantle) and trondhjemite (oceanic crust), reflect the contrasts of their fO_2 . The low values of MS and the scarcity of magnetite reported for the equigranular sanukitoids and trondhjemite can be attributed to the early epidote formation, which inhibited the magnetite crystallization by iron capture during magmatic evolution, or even to the late magmatic processes, probably responsible for the magnetite destabilization. The frequent presence of magnetite in the porphyritic sanukitoid reinforces differences in the composition of its source in relation to the typical sanukitoids from Carajás Province already pointed out in previous geochemical and geochronological studies. Regarding the water contents, estimated from qualitative estimates, we can assume that the precursor magma of the sanukitoids was hydrated, which is indicated by its high amphibole contents, whereas low water contents were admitted for the leucogranites and trondhjemite, due to the absence of hydrated minerals in their paragenesis.

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CAPÍTULO 3 MINERAL THERMOBAROMETRY AND ITS IMPLICATIONS FOR PETROLOGICAL CONSTRAINTS ON MESOARCHEAN GRANITOIDS FROM THE CARAJÁS PROVINCE (BRAZIL)

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ABSTRACT

This paper is the first attempt to investigate the crystallization parameters of Mesoarchean granitoids from Ourilândia do Norte, located in the midwestern Carajás province. These rocks comprise coarse- to medium-grained leucogranites and associated high-Ti granodiorite, sanukitoid-related granitoids, and trondhjemitites. In the sanukitoids, amphibole is the chief mafic mineral, biotite is abundant; titanite and epidote are common accessory phases. Amphibole classifies as magnesiohornblende and biotite has magnesian composition. Epidote and titanite have predominantly magmatic origins, and magnetite is the principal Fe-Ti oxide mineral in leucogranites and porphyritic sanukitoid varieties, which show high magnetic susceptibility (MS) values. However, in equigranular sanukitoids and trondhjemitites, magnetite is rare, and ilmenite is dominant, resulting in low MS values. Geothermometers indicate temperatures from 738-892 °C and estimate pressures varying from 100-312 MPa. The lower pressure and temperature obtained with experimental calibrations can be attributed to dynamic recrystallization (deformation-assisted) that occurred at temperatures close to the solidus affecting amphibole equilibrium. The Fe/(Fe + Mg) ratios of both biotite and amphibole indicate crystallization of the Ourilândia granitoids under high to intermediate oxygen fugacity conditions in general (mostly between nickel-nickel oxide (NNO+0.5 and NNO+2.8) or slightly above the quartz-fayalite-magnetite (QFM) buffer) with H₂O contents in melt from 4-7 wt%, similar to those for the Rio Maria suite from Carajás province and more oxidized members from the Baltic Shield, while Closepet-type granites and pyroxene-free sanukitoids from the Matok pluton are less oxidized. This contrasts with the reduced conditions inferred for ultra-Mg Elan-type granitoids. The differences observed in the crystallization parameters and compositions of ferromagnesian minerals in the Ourilândia granitoids reflects the distinct natures of their sources. The high-K calc-alkaline leucogranites were generated from crustal sources; sanukitoids indicate an enriched mantle source, while

the high-Ti granodiorite is related to crust-mantle interaction with extensive crustal input and trondhjemites to mafic sources with little to no contribution from enriched magma.

Keywords: Mineral Chemistry, Mesoarchean, Granitoids, Carajás province.

3.1 INTRODUCTION

Sanukitoids and potassic leucogranites, along with the notable occurrence of tonalite-trondhjemite-granodiorite (TTG) suites, constitute significant components of the Archean crust in many cratons (Shirey & Hanson 1984, Smithies & Champion 1999, Jayananda *et al.* 2000, Moyen *et al.* 2003, Halla 2005, Kovalenko *et al.* 2005, Jayananda *et al.* 2006, Lobach-Zhuchenko *et al.* 2008, Heilimo *et al.* 2010, Laurent *et al.* 2014). In the Amazonian craton, these rocks have been well documented over the last 30 years and are recognized as important components of Archean terrains commonly related to late- and postcollisional orogenic events (3.0-2.5 Ma) (Althoff *et al.* 2000, Oliveira *et al.* 2009, Almeida *et al.* 2013). The presence of large volumes of granites is commonly interpreted as evidence of crustal reworking related to the stabilization of the oldest cratons (Kröner 1981, Davis *et al.* 1994). Some of the oldest occurrences of sanukitoid associations are found in the Amazonian craton of Brazil (2.85-2.87 Ma; Pimentel & Machado 1994, Macambira & Lancelot 1996, Avelar *et al.* 1999, Oliveira *et al.* 2009, 2010, 2011, Santos & Oliveira 2016; Silva *et al.* 2018 and references therein), although in most of the other cratons they are dated ca. 2.7-2.52 Ma (Jayananda *et al.* 2000, Heilimo *et al.* 2010, Jayananda *et al.* 2018).

The geochemical constraints on sanukitoids are controversial, with enrichments in both mantle-compatible (Mg#, MgO, Ni, and Cr) and incompatible elements (Sr, Ba, light rare earth elements (LREEs), K, Ba, and P); an origin involving a metasomatized mantle source in subduction-related environment (Martin *et al.* 2009 and references therein). On the other hand, the leucogranite granitoids have a peraluminous affinity ($A/CNK \geq 1.0$) and clear potassic signature ($K_2O/Na_2O > 0.5$) and are described as products of the partial melting of older felsic crust (TTGs) (Almeida *et al.* 2011, 2013, 2017). In addition, there is a general consensus that Archean TTGs are defined geochemically as sodic granitoids poor in ferromagnesian minerals and that their formation occurs through partial melting of hydrated mafic crust at different depths (Martin & Moyen 2002, Martin *et al.* 2005, 2014, Jayananda *et al.* 2015).

Considering the importance of sanukitoid, leucogranite and sodic rocks as a significant group of granitoids with transitional Archean-Proterozoic dates, mineral chemistry is an essential method widely used for determining the composition and crystallization conditions of plutonic magma sources (Ridolfi *et al.* 2010, Mutch *et al.* 2016 and references therein).

Furthermore, these rocks commonly contain ferromagnesian mineral assemblages in equilibrium, whose aspect contributes to their use as significant objects for petrologic studies (Hammarstron & Zen 1986). Nevertheless, few studies of mineral chemistry and thermobarometry in Mesoarchean granitoids have been reported in the literature (Lobach-Zhuchenko *et al.* 2008, Oliveira *et al.* 2010, Rapopo 2010, Bhattacharya *et al.* 2014, Terentiev & Santosh 2017, 2018); previous data have contributed to estimated temperatures of crystallization and emplacement of those granitoids.

Recently, diverse Mesoarchean granitoids were reported in the Ourilândia do Norte area (southeastern Amazonian craton – Carajás Province), which formed in a syn-collisional setting at 2.92-2.88 Ga and can be distinguished as sanukitoids, potassic leucogranites, sodic granitoids and associated mafic enclaves (Santos & Oliveira 2016, Silva *et al.* 2018, Silva & Oliveira 2019, Silva *et al.* 2019). They are broadly similar to the types described for other cratons. These previous studies contributed to advancing knowledge in relation to geological mapping and petrographic, geochemical and geochronological aspects of these rocks. However, there are no mineral chemistry data and thermobarometry studies for understanding the evolution of Ourilândia magmatism. To pursue this goal, electron microprobe analyses were obtained for silicates and iron-titanium oxides to determinate the quantitative chemical compositions and classifications of the main mineral phases. The mineral chemistry data will be helpful to constrain the crystallization parameters, such as H₂O (water content), pressure (P), temperature (T) and fO_2 (oxygen fugacity), and to discuss their relations with the mineral assemblage equilibria and magnetic petrology. Some previous studies using available experimental data on similar rock types were selected for comparison (Lobach-Zhuchenko *et al.* 2008, Oliveira *et al.* 2010, Rapopo 2010, Bhattacharya *et al.* 2014, Terentiev & Santosh 2017, 2018). We intend to contribute to further understanding of the crystallization conditions of sanukitoids, leucogranites and sodic granitoids in the Carajás province, as well as determine their physicochemical conditions of formation and the relation with analogous Archean granitoids in other cratons.

3.2 GEOLOGICAL BACKGROUND

The Carajás province is recognized as a relict of the oldest and best-preserved Archean fragment of the South American platform, which has been stable since the Neoproterozoic (Almeida *et al.* 1981) (Figure 3.1a). Tassinari & Macambira (2004) proposed that the Carajás province is part of the geochronological domain of the Central Amazonian province while Santos (2003) considered it an independent tectonic segment. The province has been

subdivided into two main tectonic domains (Santos 2003, Vasquez *et al.* 2008): (i) the Rio Maria domain, exclusively Mesoarchean (3.0-2.87 Ga) and (ii) the Carajás Domain, Meso- to Neoarchean (3.0-2.76 Ga). Dall'Agnol *et al.* (2013) interpreted that the Carajás Domain represents a heterogeneous lithological crust and called its southernmost portion of Sapucaia subdomain, interpreted as similar to Rio Maria Domain, although affected by Neoarchean events; and the northernmost portion of Canaã dos Carajás subdomain, which represents the basement of the Neoarchean Carajás basin (Figure 3.1b).

The Mesoarchean Rio Maria domain, situated in the south portion of the province, is composed of greenstone belts and four main groups of Archean granitoids: (i) the TTG series represented by the Arco Verde and Mariazinha tonalites and Mogno trondhjemite; (ii) the high-Mg granitoids and associated rocks of the Rio Maria suite; (iii) the high-Ba-Sr leucogranodiorites of the Guarantã suite; and (iv) the potassic leucogranites forming the Mata Surrão granite (Oliveira *et al.* 2009, 2011, Almeida *et al.* 2011, Santos *et al.* 2013a, Almeida *et al.* 2013, Santos & Oliveira 2016, Almeida *et al.* 2017, Silva *et al.* 2018, Silva-Silva *et al.* 2020). The Sapucaia subdomain is defined by (i) Sapucaia *greenstone belts* and amphibolites; (ii) a TTG series composed of the Colorado, Água Azul do Norte and Nova Canadá trondhjemites; (iii) the high-Mg Água Azul and Água Limpa granodiorites; (iv) the high Ba-Sr Nova Canadá leucogranodiorite; (v) the potassic Xinguara and Velha Canadá granites; and (vi) the high-HFSE granitoids of the Vila Jussara suite (Santos *et al.* 2013b, Teixeira *et al.* 2013, Silva *et al.* 2014, Gabriel & Oliveira 2014, Leite-Santos & Oliveira 2016, Dall'Agnol *et al.* 2017, Santos *et al.* 2018, Silva *et al.* 2020). Finally, the Canaã dos Carajás subdomain is formed essentially by (i) the Chicrim-Cateté and Ouro Verde granulites; (ii) high-K leucogranites (Cruzadão, Serra Dourada, Boa Sorte and similar granites); (iii) restricted TTG series (Rio Verde trondhjemite) and amphibole-bearing tonalites (Campina Verde tonalitic complex); (iv) high-HFSE granitoids (Planalto and Vila União suites); and (v) charnockites (Feio *et al.* 2012, 2013, Santos *et al.* 2013a, Rodrigues *et al.* 2014, Delinardo *et al.* 2015, Tavares *et al.* 2018, Marangoanha *et al.* 2019a, b, 2020, Felix *et al.* 2020) (Figure 3.1c).

At the end of the Archean, there was the youngest magmatic event of the Carajás province (Althoff *et al.* 2000, Souza *et al.* 2001) which indicates its final phase of cratonization with remarkable tectothermal events. The clastic sedimentary rocks of the Rio Fresco Group (DOCEGEO 1988) were subsequently deposited which later were intruded by Paleoproterozoic (1.88 Ga) A-type granites of the Jamon and Serra dos Carajás suite (Dall'Agnol *et al.* 2005, Dall'Agnol & Oliveira 2007) along with distinct compositional dikes (Rivalenti *et al.* 1998, Silva Junior *et al.* 1999, Silva *et al.* 2016).

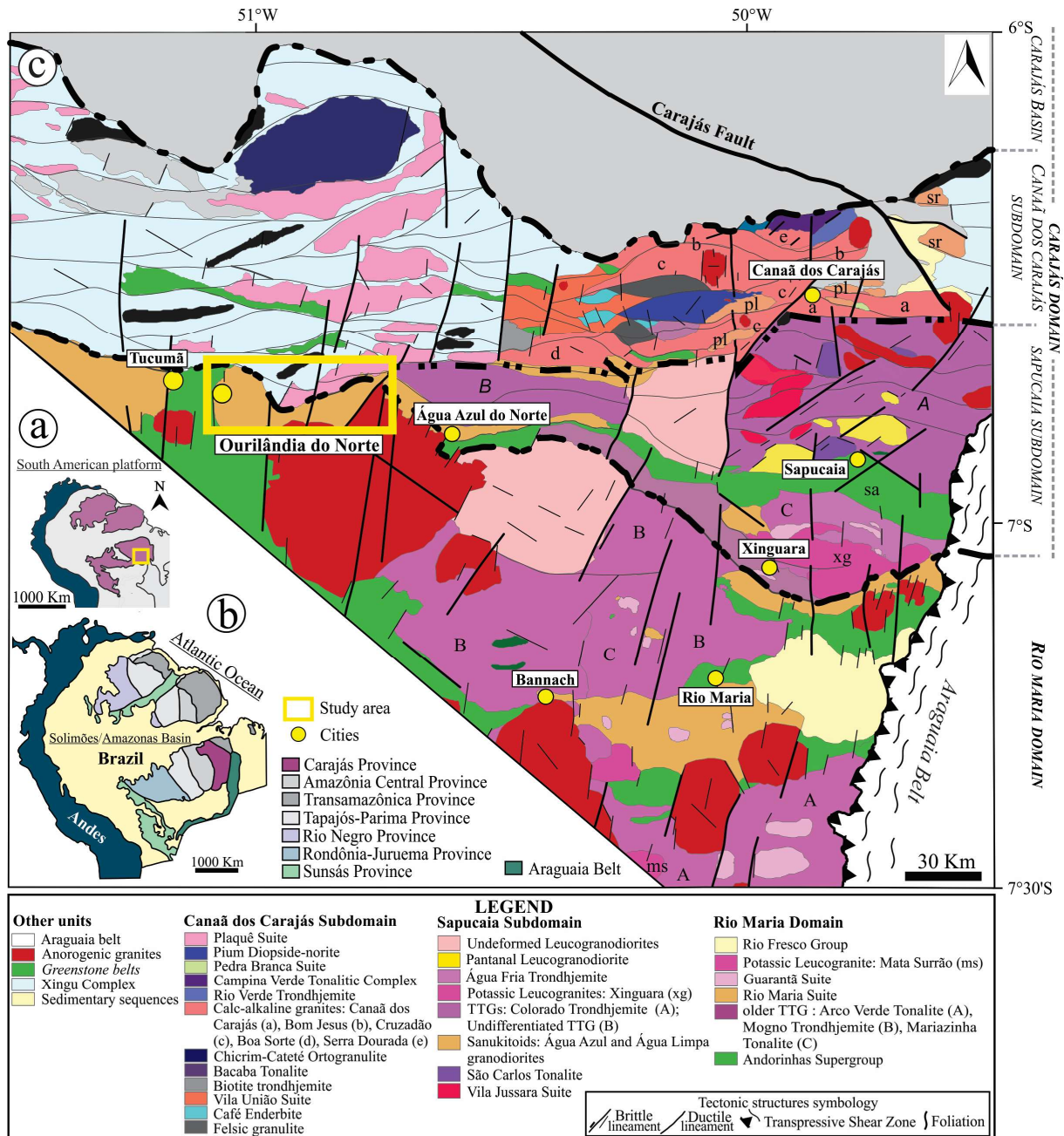


Figure 3.1 - Regional geologic context from the Carajás province: a) Amazonian cráton location in the South American platform (adapted after Santos 2003, 2006); b) Geochronological provinces from the Amazonian craton (modified after Dall'Agnol *et al.* 2013); c) Geologic map (1:100.000) from the Carajás province, highlighting the Ourilândia do Norte study area (based on Vasquez *et al.* 2008, Oliveira *et al.* 2010, Almeida *et al.* 2011, Guimarães *et al.* 2012, Santos & Oliveira 2012, Feio *et al.* 2013, Gabriel & Oliveira 2014, Marangoanha *et al.* 2019b, 2020, Silva *et al.* 2020). The tectonic configuration after Vasquez *et al.* (2008) and Dall'Agnol *et al.* (2013) is shown in the right corner.

3.3 GEOLOGY OF THE OURILÂNDIA DO NORTE AREA

The Mesoarchean leucogranites, sanukitoids, trondhjemites and associated rocks from the Ourilândia area are exposed across an area of 400 km² (Figure 3.2). Detailed mapping has revealed that these rocks occur as small plutons and batholiths whose emplacement was conditioned by transcurrent E-W shear zones (Santos & Oliveira 2016, Silva *et al.* 2018). The leucogranites and associated rocks comprise equi- to heterogranular monzogranites and

Titanium-enriched porphyritic granodiorites. The latter are characterized by small plutons or ellipsoidal lenses within the equigranular monzogranite. The equigranular granodiorite corresponds to a batholith elongated WSW-ENE, 6 to 11 km thick and greater than 40 km in length. It contains several inclusions of small lenses of sanukitoids (heterogranular granodiorite). It is crosscut by the Paleoproterozoic Seringa granite and intruded into the Água Azul trondhjemite to the southeast, Xingu complex to the north, and Sapucaia group and porphyritic granodiorite rocks to the west.

The sanukitoid batholith covers an area of 296 km² in the mid-western portion of the geologic map (Figure 3.2), and is limited to the north by the Xingu complex, to the west by the Tucumã group and to the east by the equigranular monzogranite. It has an ellipsoidal shape where the predominant variety is an equigranular light gray granodiorite ± tonalite with greenish shades due to saussuritized plagioclase. A subordinate heterogranular granodiorite has been mapped as several lens-shaped plutons (< 2 km²) within the leucogranite batholith. In the southwestern portion of the map, the porphyritic granodiorite variety crops out as a circular pluton of approximately 35 km², which is crosscut by equigranular granodiorite. Trondhjemites comprise a porphyritic granitoid that crop out in the central portion of the study area, forming small (< 2 km²) ellipsoidal plutons. It occurs associated with quartz dioritic rocks of sanukitoid affinity. The spatial arrangement of all studied granitoids follows the ENE-WSW trend of the ductile structures, which is consistent with the tectonic foliation that dips moderately to steeply towards southward. Near the shear zone, mylonitic foliation is observed in sanukitoid mafic-enriched varieties, while mafic-depleted varieties, compositional banding is predominantly affected by complex folds or sectioned by submagmatic faults (Figure 3.2). The microgranular mafic enclaves have flattened or rounded forms and display evidence of interaction with the sanukitoid rocks, while they are absent in monzogranites. These features suggest their coexistence in the magmatic stage.

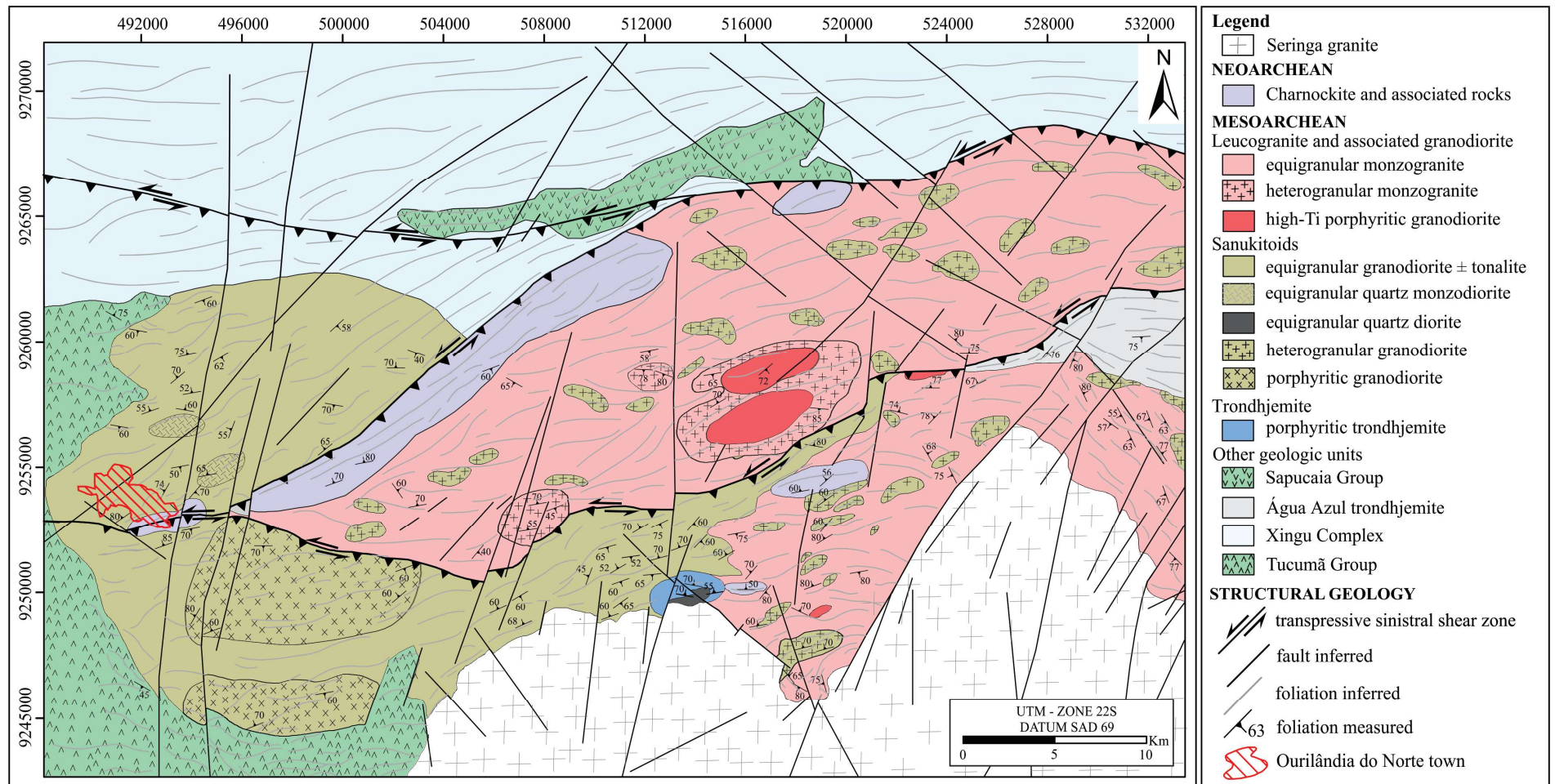


Figure 3.2 – Geologic map (scale 1:50.000) of the Ourilândia do Norte area. Modified after Silva *et al.* (2019).

3.4 DATA AND METHODS

Detailed mineralogical and textural characterization of the Fe-Ti oxides were performed in 115 polished thin sections using a Zeiss microscope coupled to both transmitted and reflected light with modal compositional data compiled from previous studies (Santos & Oliveira 2016, Silva et al. 2018) considering 2000 points per section on a 0.4 mm grid using the Endeuper Hardledge software. These rocks were classified according to the Subcommission on the Systematics of Igneous Rocks of IUGS (Le Maitre *et al.* 2002). Prior to analysis by Scanning Electron Microscope (SEM) the thin sections were coated with carbon film to eliminate electrostatic charge-up on the sample surface. Back-Scattered Electron (BSE) images of the opaque minerals and major element compositions of all mounted grains were obtained from 14 polished thin sections of representative samples of each petrographic variety, using a LEO-1430 SEM coupled with an Energy Dispersive X-ray Spectrometer which operated at an accelerating voltage of 20 kV and 0.3 nA beam current at the Microanalysis Laboratory of the Geosciences Institute of the Federal University of Pará (IG-UFPA). Magnetic susceptibility (MS) measurements were obtained *in situ* on individual samples and without weather evidence using a susceptibility field meter (MS-30) supplied by ZH instruments with a sensitivity of 10^{-7} SI units at the Magnetic Petrology Laboratory (IG-UPA), with an average of three measurements in different sections of the each sample, which was considered the average of the values as representative, totaling 141 measurements of MS. The values were plotted on frequency histograms using the Minitab 18 software (free version).

3.5 PETROGRAPHY

3.5.1 Classification and textural aspects

The Mesoarchean granitoids from the Ourilândia area classify as granodiorites to monzogranites, and subordinate tonalite, trondhjemite, quartz-diorite and quartz-monzodiorite (Figure 3.3). These rocks have hypidiomorphic, inequigranular (medium- to coarse-grained) to porphyritic textures, are pinkish to greenish, and exhibit well-preserved igneous characteristics. Leucogranites classify as hololeucocratic to leucocratic whose mafic contents are in general less than 10 wt%, except for the associated high-Ti granodiorite, characterized by higher mafic proportion (up to 18 wt%). Sanukitoids are mesocratic with mafic contents ranging from 11-35 wt% and rare quartz-diorite varieties exhibit mafic proportions greater than 40 wt%. In the trondhjemite, mafic contents are less than 10.5 wt% (Figure 3.3). Biotite is the only ferromagnesian mineral present in the leucogranite and associated high-Ti

granodiorite group (Figure 3.4a-c), while amphibole, biotite and magmatic epidote are important mafic phases in the sanukitoids (Figure 3.4d-f). Petrographic observation for the sanukitoids indicates the early crystallization of amphibole (euhedral aspect, occurrence as inclusion in quartz and frequent association with plagioclase, the absent relicts of pyroxene within amphibole) (Figure 3.4f). The trondhjemite presents biotite and epidote as varietal minerals and hornblende as an important accessory phase (Figure 3.4g-i). In general, primary accessory minerals are titanite, apatite, zircon, allanite and opaque minerals (magnetite, ilmenite, sulfides and goethite). Mineralogical transformations ranging from chloritization of biotite to sericitization and saussuritization of plagioclase are related to late- to postmagmatic stages. All varieties have been subject to moderate deformation associated with mylonitic structures, resulting in undulose extinction and stretching of quartz crystals (*ribbon*) and orientation of mafic minerals along the foliation planes.

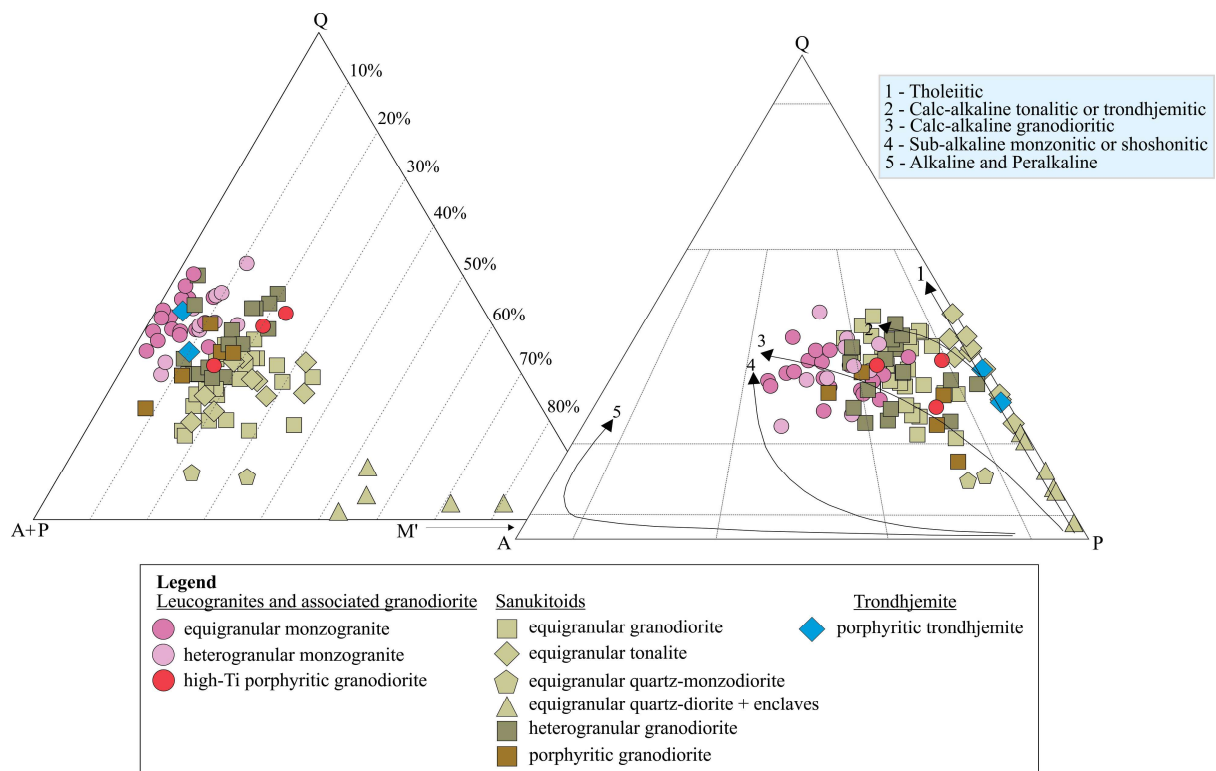


Figure 3.3 - QAP and Q-(A+P)-M' diagrams (fields of Le Maitre *et al.* 2002) and granitic series evolution trend (Bowden *et al.* 1984) for the Mesoproterozoic rocks from the Ourilândia.

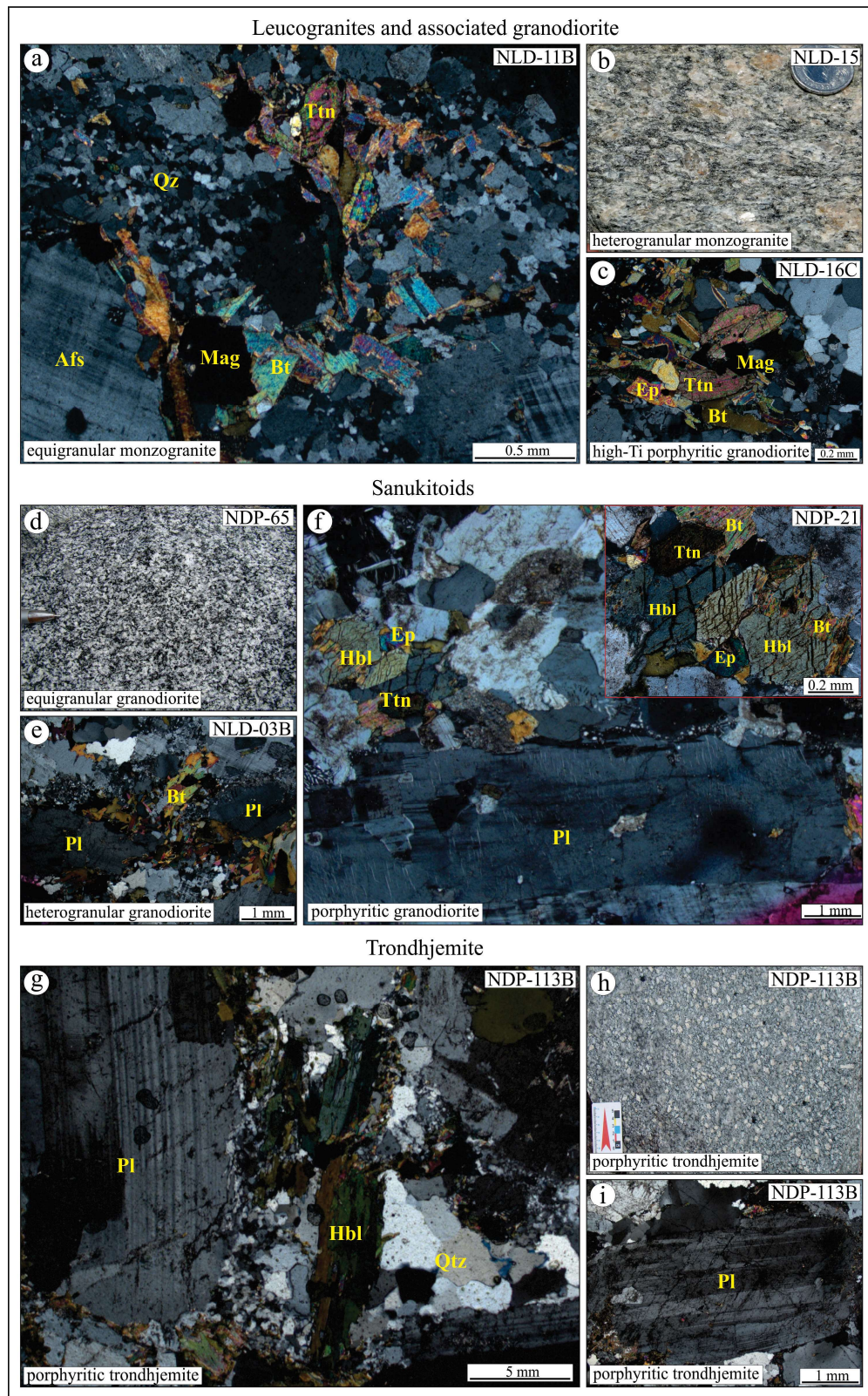


Figure 3.4 - Photomicrographs of the textural aspects of the Ourilandia granitoids: Leucogranites and high-Ti granodiorite: (a) hypidiomorphic magnetite (Mag) immersed into a fine-grained quartz-feldspar matrix associated with titanite (Ttn) and biotite (Bt); (b) alkaline feldspar (Afs) phenocrystal (ranging in size from 1 to 3.0 cm) oriented according to the mylonitic texture; (c) significative occurrence of prismatic titanite (Ttn) and opaques (Mag) associated with hypidiomorphic epidote (Ep) and biotite (Bt). Sanukitoids: (d) slightly foliated coarse-grained equigranular granodiorite; (e) saussuritized plagioclase (Pl) phenocrystal associated with biotite (Bt) and recrystallized quartz (Qtz) mantling the phenocrysts; (f) several plagioclase (Pl) phenocrysts partially saussuritized immersed into a matrix composed of biotite (Bt), hornblende (Hbl), epidote (Ep), quartz (Qtz). Trondhjemite: (g-i) porphyritic texture with 1-2 cm long plagioclase (Pl) crystals. It is common the presence of biotite replaced by chlorite and saussuritized plagioclase phenocrysts. Mineral abbreviations based on Whitney & Evans (2010).

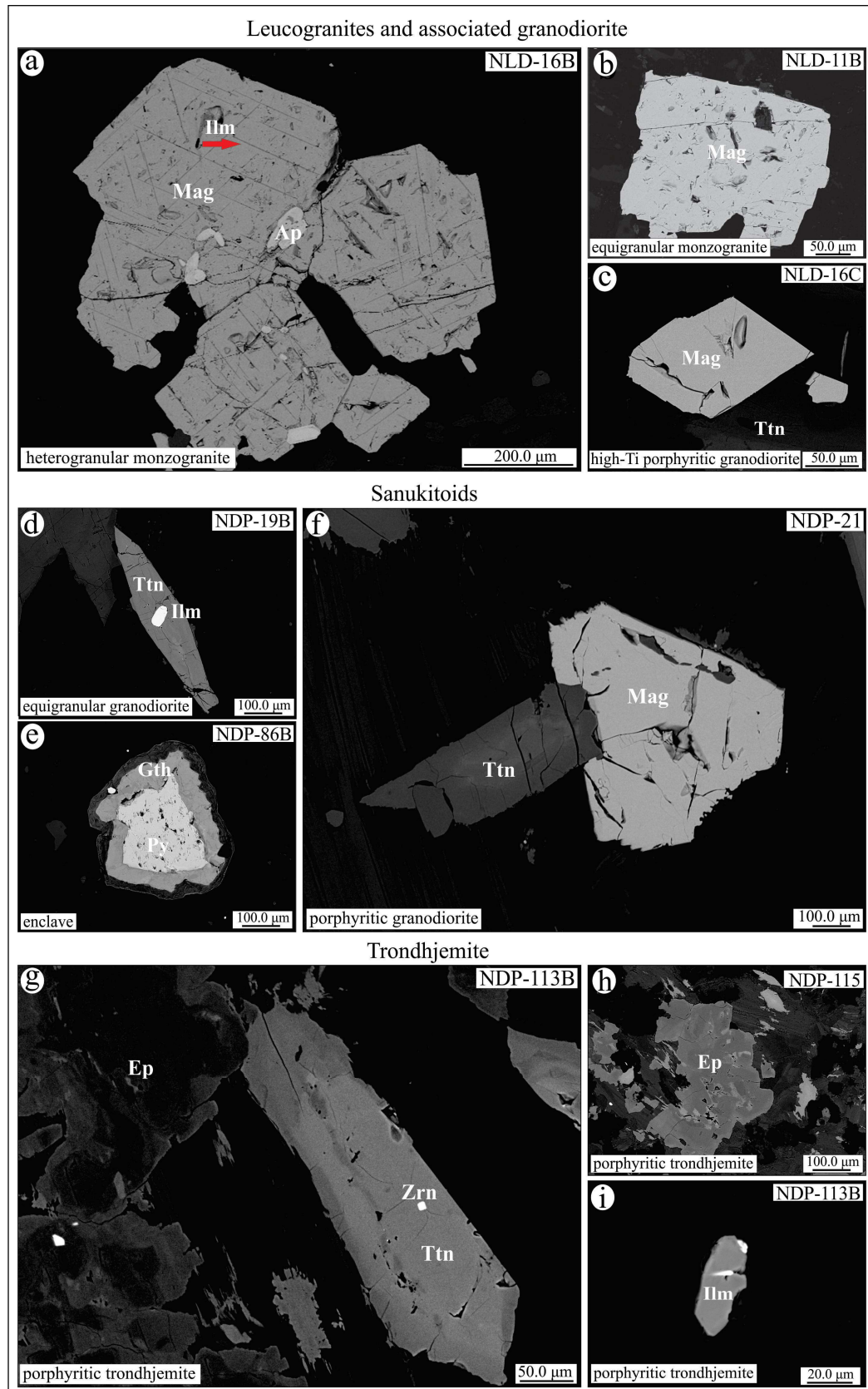


Figure 3.5 - SEM photomicrography of Fe-Ti oxide minerals and mafic minerals of the main petrographic varieties from the Ourilândia granitoids. a) thin trellis ilmenite (Ilm) lamellae in magnetite (Mag) idiomorphic host and apatite (Ap) inclusion; b) idiomorphic coarse-grained magnetite (Mag) crystal well-preserved; c) idiomorphic magnetite (Mag) in contact with titanite (Ttn); d) ilmenite enclosed by hypidiomorphic titanite; e) xenomorphic goethite (Gth) mantling pyrite (Py); f) coarse-grained magnetite (Mag) in contact with zoned titanite (Ttn); g) idiomorphic titanite (Ttn) with zircon (Zrn) inclusion in contact with epidote (Ep); h) common occurrence of xenomorphic epidote (Ep); i) rare minute ilmenite (Ilm) in the trondhjemite. Mineral abbreviations based on Whitney & Evans (2010).

3.5.2 Opaques minerals and magnetic susceptibility (MS)

Opaque minerals are composed of magnetite and ilmenite, with minor occurrence of goethite, pyrite, chalcopyrite and hematite (as martite). They occur as individual and/or aggregates crystals, either as inclusion or in contact with ferromagnesian minerals (biotite and amphibole), epidote and titanite (Figure 3.5a-i). The Fe-Ti oxide minerals have influence on MS since magnetite is the main mineral controlling the iron partition during magmatic evolution (Clark 1999, Frost 1991a,b). In the leucogranites and associated high-Ti granodiorite, magnetite is the main Fe-Ti oxide mineral, with modal contents ranging from 0.15-1 wt%, and occurs as idio- to hypidiomorphic fine- to medium-grained crystals with dimensions ranging from 1-1.5 mm (Figure 3.5a-c). Rare thin lamellae of ilmenite oxy-exsolution can occurs in equigranular monzogranite (Figure 3.5a) whereas magnetite shows straight contact with titanite in high-Ti granodiorite (Figure 3.5c). In the sanukitoids, ilmenite shows expressive modal contents (0.15-0.35 wt%) and occurs as hypidiomorphic to xenomorphic crystals, with dimensions ranging from 1-2 mm, and commonly are mantling by titanite (Figure 3.5d) in equigranular sanukitoids varieties. Rare fine-grained goethite and pyrite crystals can occur in equigranular granodiorite varieties or mafic microgranular enclaves (Figure 3.5e). Magnetite occurs as an individual crystal in porphyritic granodiorite and has high modal contents (Figure 3.5f). Opaque minerals are rare in trondhjemites (Figure 3.5g-i).

The frequent presence of primary magnetite in the leucogranites and associated high-Ti granodiorite control the MS values in frequency histograms, and indicates oxidized crystallization conditions for their magma (Figure 3.6a). Note that opaque and ferromagnesian mineral contents show a positive correlation with MS values for these varieties (Figure 3.6b-c). In contrast, the rare to absent magnetite contents in sanukitoids and trondhjemite influence their lower values of MS (Figure 3.6a; Apêndice A1) and suggests crystallization conditions slightly less oxidized than leucogranitic varieties. Note that sanukitoids and trondhjemite are distributed mostly on intermediate to low MS values in the histogram ($\log -4.26$ to -2.62 ; $< 1 \times 10^{-3}$ SI), while leucogranites and high-Ti granodiorite are distributed in the highest MS field ($\log -2.62$ to -1.77 ; $> 1 \times 10^{-3}$ SI)(Figure 3.6a). The magnetic behavior of the sanukitoids is not homogeneous, since porphyritic granodiorite stands out for its higher MS which is consistent with the high magnetite modal content (> 0.25 wt%). On the other hand, mafic minerals and epidote do not control MS values, indicating a negative correlation with the MS values (Figure 3.6c-d). The existing compositional differences among leucogranites,

sanukitoids and trondhjemites result from the contrasts in their sources, which are reproduced in their distinct MS values and opaque mineral contents.

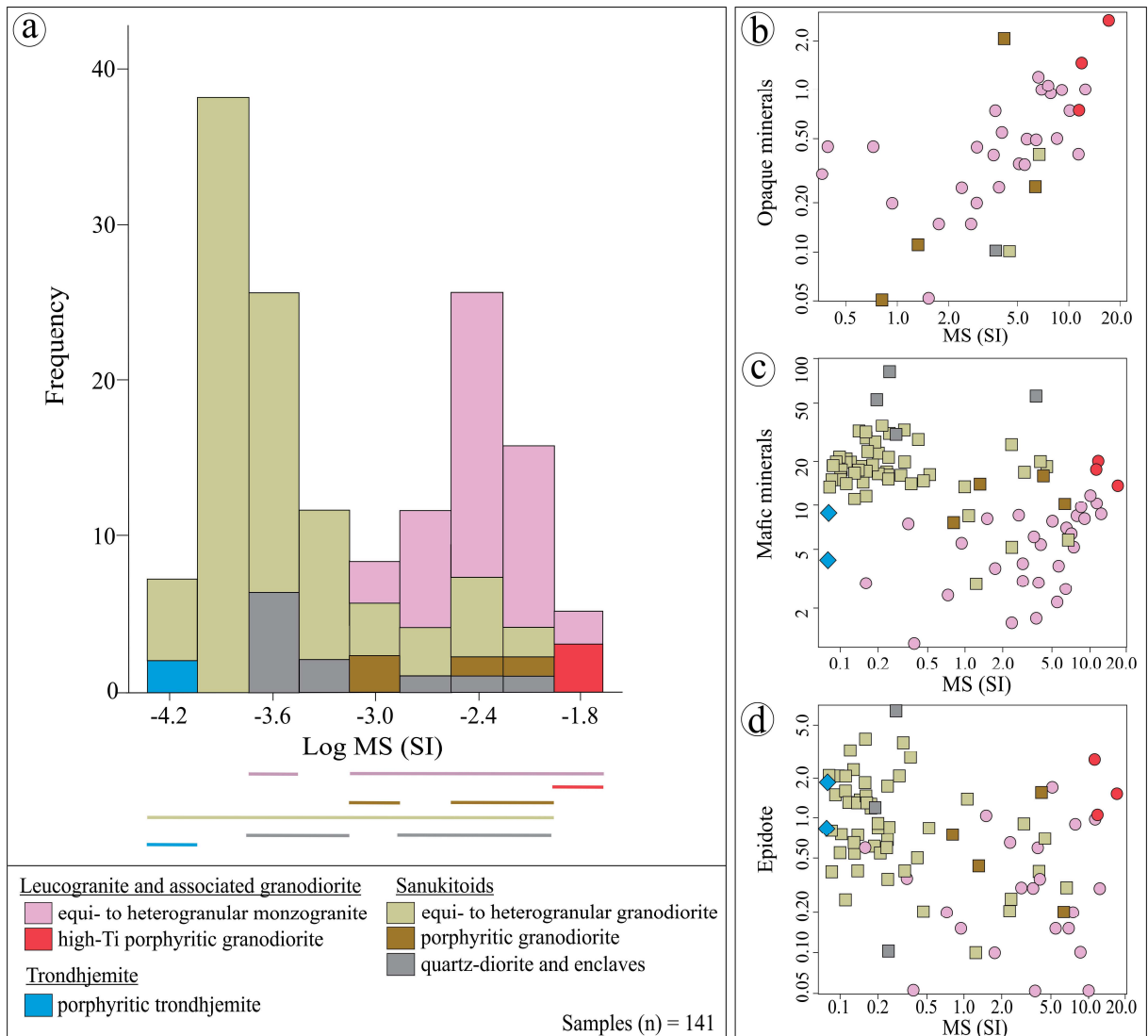


Figure 3.6 – MS frequency histogram and comparative modal diagram: a) MS histogram showing the distributions of 141 magnetic susceptibility measurements realized in representative samples from the Ourilândia granitoids; b) binary diagram of magnetic susceptibility (SI) versus mafic minerals (wt %); c) binary diagram of magnetic susceptibility (SI) versus opaques minerals (wt %). Note that trondhjemite and sanukitoids show lower opaques mineral contents which most of the samples can not be visualized in the diagram; d) binary diagram of MS (SI) versus epidote contents (wt %).

3.6 MINERAL CHEMISTRY

3.6.1 Analytical Method

Mineral chemical data were acquired using a JEOL JXA-8230 electron microprobe equipped with five wavelength dispersive spectrometers (WDS) and complementary mineral compositions of opaque minerals were obtained using an LEO 1430 scanning electron microscope (SEM) equipped with one energy dispersive spectrometer (EDS) at the Microanalysis Laboratory of the Federal University of Pará (UFPA). Fourteen polished thin

sections of representative samples from the Ourilândia area were first carbon-coated and then analysed. Quantitative WDS microanalyses were done in preselected crystals of silicates (biotite, amphibole, epidote, titanite and plagioclase) and Fe-Ti oxides (magnetite and ilmenite). All samples used for mineral chemistry had available whole-rock chemical compositions compiled from previous studies in the Ourilândia area (Santos & Oliveira 2016, Silva *et al.* 2018). The analytical operating conditions of EDS analyses were 20 kV for the column acceleration voltage, while WDS analyses were performed under the following operating conditions: a column accelerating voltage of 15 kV, a current of 20 nA, analysis times of 20 s for major elements and 40 s for minor and trace elements, with beam diameters of 10 microns for feldspars and 1 micron for all other minerals. The analytical precisions were $\pm 1\%$ and $\pm 10\%$ for major and minor elements, respectively. The method followed the standards matrix corrections: lithium fluoride (LiFH) for V, Mn, Fe, Ni and Ba; pentaerythritol (PETJ) for K, Ca, Ti and Sr; thallium acid phthalate (TAP) for Na, Si, Al and Mg; and layered dispersion element (LDE1) for F. Standards were andradite (Si and Ca), microcline (Al and K), hematite (Fe), olivine (Mg), albite (Na), pyrophanite (Ti and Mn), vanadinite (V and Cl), topaz (F).

3.6.2 Amphibole

Amphibole classification follows the nomenclature proposed by Leake *et al.* (1997) and Hawthorne *et al.* (2012), with structural formulas based on 23 oxygen atoms (H₂O-free content), cations reported with a set of 13 cations minus Ca, Na, and K (13-CNK) and ferric-ferrous iron partition calculated according to the charge balancing method of Schumacher (1997). The analyzed crystals found in sanukitoids and trondhjemites are calcic [$_{\text{B}}\text{Ca} > 1.7$; $(\text{Na}+\text{K})_{\text{A}} < 0.50$; $_{\text{B}}\text{Ca}/(\text{Ca}+\text{Na}) = 0.81\text{--}0.96$], classified mainly as magnesiohornblende, with subordinate ferropargasite, actinolite hornblende and tschermakite compositions (Figure 3.7a-b). Amphibole compositions are characterized by significantly high MgO and relatively low FeO contents in equigranular sanukitoids, while the opposite trend is observed in porphyritic granodiorite (sanukitoid), and the FeO contents in trondhjemites samples are moderate. In addition, the $\text{Mg}/(\text{Mg} + \text{Fe}^{+2})$ ratio range from 0.53 to 0.80, Al contents fall between 0.52 and 3.10, and $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio (Fe-number) vary from 0.24 to 0.43 in the sanukitoids reach 0.50 in trondhjemites (Apêndice A2). The volatile components (OH and F) are higher than the Cl contents. There is evidence of simple substitutions of Mg^{+2} by Fe^{+2} in the [C] site, tschermak-type ($\text{Al}^{\text{VI}}\text{Al}^{\text{IV}}\text{Mg}_{-1}\text{Si}_{-1}$) coupled substitution between the [T] and [C] sites, and plagioclase ($\text{NaSi Ca}_{-1}\text{Al}^{\text{IV}}_{-1}$) exchange, with the introduction of Si in the [T] and Ca in the [B]. There is not evidence of edenite-type substitution. Al-tschermak-type substitution is related to

pressure variations (Hollister *et al.* 1987, Schimidt 1992) while plagioclase-type and edenite-type substitutions occur due to changes in temperatures (Blundy & Holland 1990).

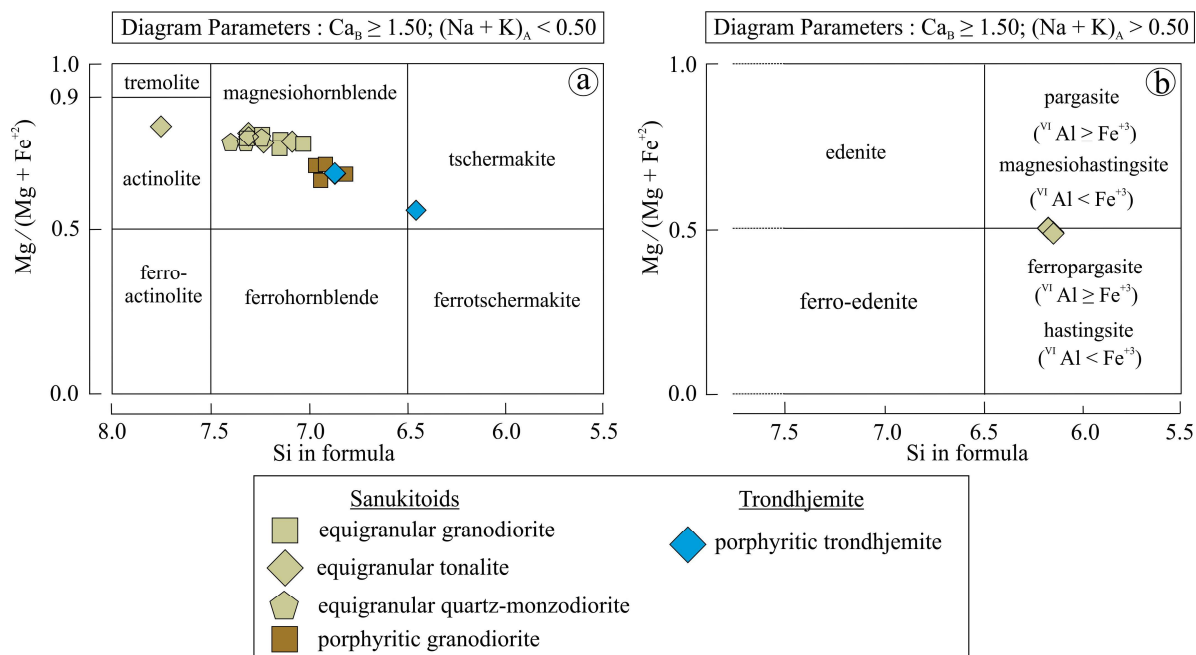


Figure 3.7- Classification diagram (Leake *et al.* 1997) for amphibole of the sanukitoids and trondhjemite granitoids from the Ourilândia area.

3.6.3 Biotite

The biotite structural formula follows the method based on 22 oxygen atoms (anhydrous basis) and assumes that all iron is in the Fe⁺² cationic state (Apêndice A3). According to the classification criteria of the International Mineralogical Association (IMA – Rieder 1998), the biotite from the Ourilândia granitoids plot in the Fe/ (Fe+Mg) ratio varying from 0.3 to 0.5 and Al^{IV} from 2.3 to 2.5 in general, except for equigranular monzogranite samples that are located close to the more ferrous field and equigranular tonalite of sanukitoid affinity which has lower Al^{IV} content (Figure 3.9a). As shown in the total Al vs. Mg diagram (Figure 3.9b), all biotite analyses plot in the calc-alkaline domain. They are characterized by high MgO (> 10 wt %) and low TiO₂ (< 2 wt %), and Al₂O₃ (~ 15 to 16 wt %), with no significant variations between the cores and rims.

The Fe/(Fe + Mg) ratio in biotite range from 0.3 to 0.5 in all Ourilândia granitoids and are consistent with their magnesian compositions in the binary diagram [Si versus Fe/(Fe + Mg) ratio], except for some biotites from the equigranular granodiorite which plot in phlogopite composition field (Deer *et al.* 2013, Figure 3.9c]. The majority of samples analyzed display chemical compositions akin to hydrothermally re-equilibrated biotites, with few analyses close to the primary magmatic field (Figure 3.9d – Nachit *et al.* 2005). There is evidence of MgFe₁ (phlogopite-annite) and M^{2+VI}Al^{IV}₂□^{VI}Si₂ (annite-phlogopite) cationic substitutions, which are considered common in calc-alkaline magmas (Stussi & Cuney 1996).

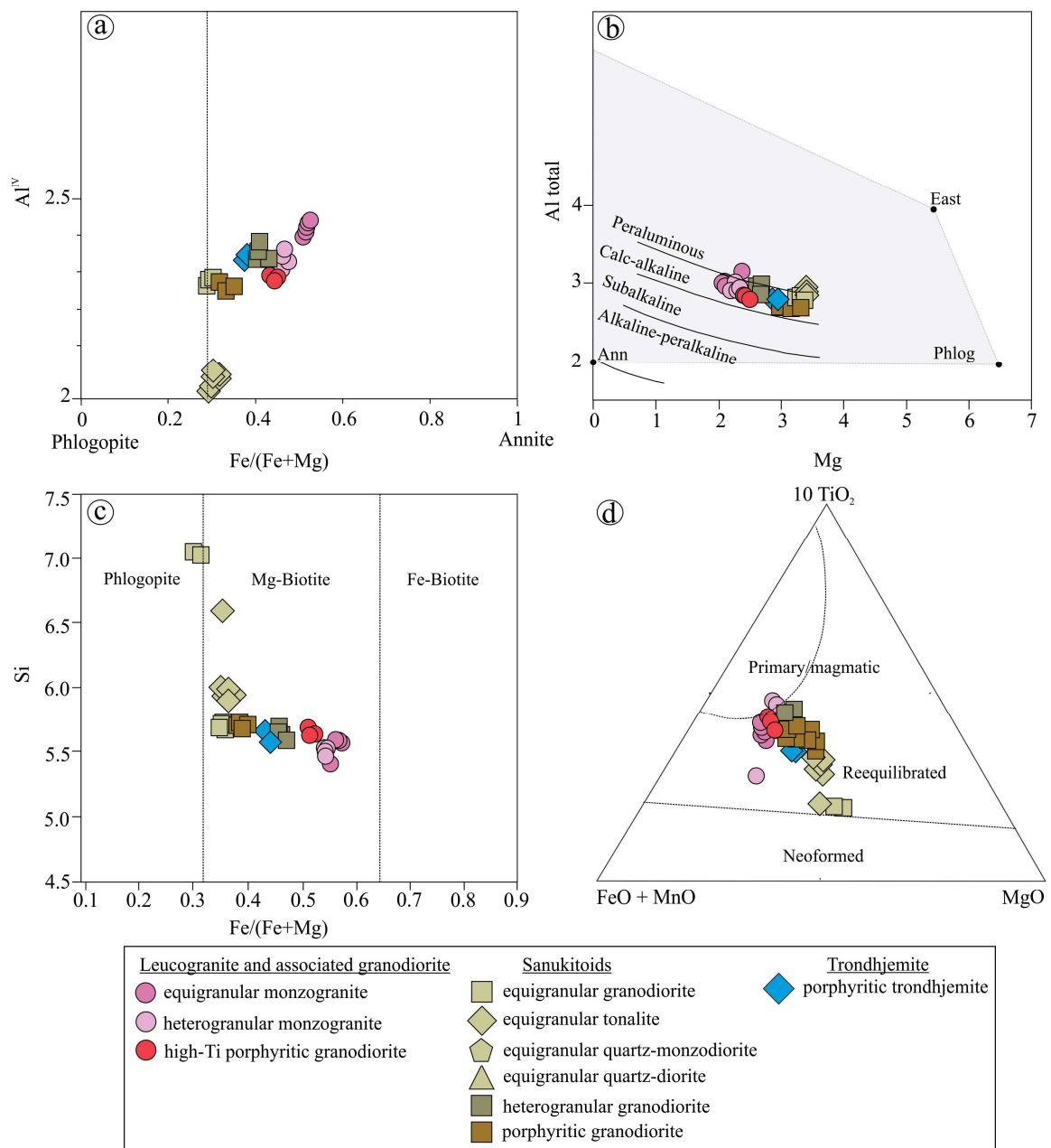


Figure 3.8 - Compositional variation of biotites from the Ourilândia area: (a) $IVAl$ vs $Fe/(Fe + Mg)$ diagram (Deer *et al.* 2013); (b) total Al vs Mg diagram (Nachit *et al.* 1985); (c) Binary diagram Si per formula in biotite vs $Fe/(Fe + Mg)$ ratio (Rieder 1998, Deer *et al.* 2013); (d) Ternary diagram $10*TiO_2$, $FeO+MnO$, MgO in wt % (Nachit *et al.* 2005). Abbreviations: East - eastonite; Phlog - phlogopite; Ann – annite.

3.6.4 Plagioclase

Plagioclase chemical analyses realized in unaltered phenocrysts of all studied granitoids show significant contrasts in their compositions. Plagioclase crystals in the sanukitoids are more calcic than those in the leucogranites and trondhjemites, except for quartz-diorite variety. They correspond mainly to andesine and oligoclase in equigranular and heterogranular sanukitoids varieties with rare analyses plotting in the albite field in quartz-diorite variety (Apêndice A4; Figure 3.9a). In turn, plagioclases found on leucogranites group are more sodic than those analysed in the high-Ti porphyritic granodiorite. Trondhjemite has

saussuritized medium-grained plagioclase phenocrysts whose compositions plot in the transition range between albite and oligoclase. There is not significant contrast in terms of chemical compositions between phenocrysts and matrix grains.

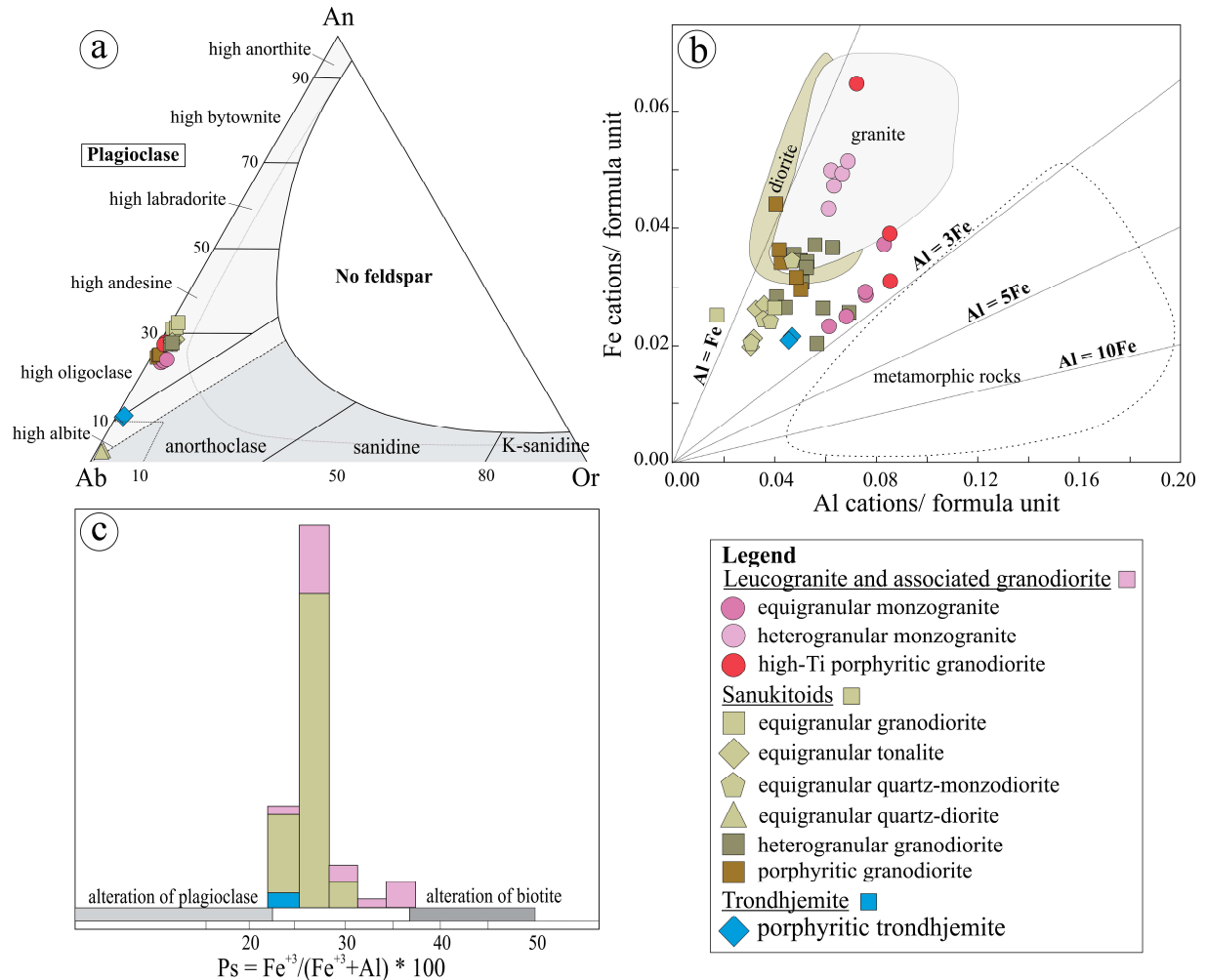


Figure 3.9 - Plagioclase, titanite and epidote classifications: a) Ab-An-Or ternary diagram plot for plagioclase compositions from the Ourilândia granitoids (Deer *et al.* 2013); b) Titanite diagram based on Fe vs. Al cations per formula unit (after Aleinikoff *et al.* 2002) with fields of magmatic and metamorphic titanite origins from Kowallis *et al.* (1997); c) Histogram for magmatic epidotes from the Ourilândia granitoids in mole per cent (mol %) of pistacite (Ps) with compositional plagioclase and biotite alterations field from Tulloch (1979).

3.6.5 Titanite

Titanite is an accessory mineral in both igneous and metamorphic rocks, and because of its capacity for element substitution, it has great potential as a petrogenetic indicator (Hayden & Watson 2008). Previous studies in the Ourilândia area described four distinct textural types in titanite (Silva *et al.* 2018); however, in the present paper, two main types were investigated: (a) medium-grained idiomorphic titanite and (b) fine-grained hypidiomorphic titanite, which commonly occurs in association with ilmenite. The idiomorphic ilmenite textural type is attributed to a magmatic origin, while the latter has a postmagmatic origin. Frost *et al.* (1991a,b) reported that during the cooling of plutonic rocks,

titanite can be formed by two distinct processes: (1) during peritectic reactions involving replacement of pyroxene by hornblende and hydration in the magmatic stages or during *subsolidus* cooling and (2) oxidation during postmagmatic re-equilibration in calc-alkaline rocks following a cooling trend under reduced conditions, which contribute to ilmenite formation. The majority of the analyzed titanite crystals plot in the igneous domain (Figure 3.9b). They are characterized by low Al_2O_3 (0.7 – 2.2 wt %) and high CaO (20 - 26 wt%) and TiO_2 (37 – 40 wt%) contents. The Fe/Al ratios range between 0.6-0.9, with rare samples higher than 2.0 (Apêndice A5). This mineral is commonly found in rocks formed from oxidized magma (Wones 1989, Frost & Lindsley 1991, Frost 1991a,b), and along with magnetite and other accessory minerals can be associated to peritectic reactions during the magmatic stage in calc-alkaline granitoids (Oliveira *et al.* 2010).

3.6.6 Fe-Ti Oxides

Magnetite is the predominant Fe-Ti oxide mineral in the leucogranites and associated high-Ti granodiorite, with minor occurrence in sanukitoids and trondhjemites. It occurs as individual crystals and aggregates of small grains, both as inclusions or in contact with ferromagnesian phases. Its chemical composition has nearly end-member content (Fe_2O_3) with low TiO_2 contents (< 0.02 wt%), and other trace components Al_2O_3 , CaO, MnO, MgO, Cr_2O_3 , and V_2O_5 are less than 0.3 wt % (Apêndice A7). The $\text{Fe}^{+3}/(\text{Fe}^{+3} + \text{Fe}^{+2})$ ratios range up to 0.89. In turn, ilmenite coexists with magnetite in three textural types: *trellis* ilmenite (**T-Ilm**), individual crystals (**I-Ilm**) and composite ilmenite (**C-Ilm**). The **T-Ilm** results from oxy-exsolution process from Ti-rich magnetite forming lamellae of ilmenite under *subsolidus* conditions (Buddington & Lindsley 1964, Haggerty 1991). **I-Ilm** and **C-Ilm** are early crystallized phases without important chemical variations. Analyses of ilmenite rims and cores show chemical compositions with low SiO_2 , Al_2O_3 , and MgO, and no Cr_2O_3 and V_2O_5 , while TiO_2 (~ 43 to 51 wt%), FeO (~ 36 to 44 wt%) and Fe_2O_3 (3.5 to 5.2 wt %) contents are high

3.7 DISCUSSION

3.7.1 Physical-chemical estimates for crystallization of the Ourilândia granitoids

The mineralogy and chemical compositions of igneous rocks are closely related to the variations in physical-chemical parameters such as temperature, pressure, oxygen fugacity and volatiles during magma evolution (Erdmann *et al.* 2014). For this reason, several thermodynamic equations based on the chemistry of amphibole, feldspars, micas, titanite, Fe-

Ti oxides, and other accessory minerals have been used for the Ourilândia granitoids as effective indicators to discuss their petrological evolution.

3.7.1.1 Temperature

Experimental studies established by Watson & Harrison (1983) and Harrison & Watson (1984), and re-evaluated by Boehnke *et al.* (2013), validated that zircon and apatite solubilities depends on temperature and SiO₂ contents in crustal melts, providing a powerful tool for determining the peak temperatures of magmatic systems considering pressure independence over a range of H₂O between 0 and 10 wt%. Gervasoni *et al.* (2016) proposed a new zircon saturation model based on temperature and melt compositions extending this model for intermediate to felsic rocks. To this effect, the authors created a new compositional parameter called G which contributes to describe the zircon saturation patterns in a wide range of rock compositions (peraluminous, metaluminous to peralkaline melts). The G parameter involves important chemical components such as FeO and MgO which were not considered in previous models. The temperature is calculated in degrees Celsius (1σ errors) using the following reaction:

$$\ln [\text{Zr}] = [(4.29 \pm 0.34) - (1.35 \pm 0.10) \cdot \ln G + (0.0056 \pm 0.0002) \cdot T (\text{°C})] \quad (1)$$

where [Zr] represents Zirconium concentrations in melt (μg/g), $G = [(3 \cdot \text{Al}_2\text{O}_3 + \text{SiO}_2)/(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO} + \text{FeO})]$ in molar proportions and T is the temperature in degree Celsius.

Studies on the Ourilândia rocks estimate a zircon saturation temperature in an average of 841 – 990 °C for leucogranites and associated high-Ti granodiorite, 826 – 981 °C for sanukitoids and 853 - 977 °C for trondhjemites, while apatite saturation estimates yields slightly similar values corresponding to 884 – 979 °C, 826 – 894 °C and 909 °C, respectively (Table 3.1). Thus, as reported from the textural aspects, zircon and apatite are early-crystallizing minerals, and the saturation temperatures obtained are interpreted as valid to represent the near-*liquidus* temperatures.

Ridolfi *et al.* (2010) and Ridolfi & Renzulli (2012) proposed refined equations for estimating temperature based on magnesian amphibole compositions from calc-alkaline to alkaline magmas, that crystallized at mantle and lower- to upper-crustal pressures, under near-*liquidus* to near-*solidus* temperatures, and broad redox and H₂O conditions. Amphibole acts as an important rock-forming mineral in granitoid rocks, and its ubiquitous occurrence makes it a potential indicator for the evolution of crystallization (Blundy & Holland 1990). The geothermometer of Ridolfi *et al.* (2010) provides temperatures for the sanukitoids between

738 °C and 770 °C and relatively higher values for the porphyritic variety (799-811 °C) and trondhjemites (799-892 °C), as listed in Table 7. Using the Putirka (2016) calibrations, temperature yields values ranging from 761–794 °C for the sanukitoids and 772-796 °C for the trondhjemites, which agree from those obtained by the previous geothermometers.

Table 3.1 - Physico-chemical crystallization conditions of the representative samples from Ourilândia do Norte granitoids.

Geological group	Leucogranites and associated granodiorite			Xenolith	Sanukitoids				Trondhjemite
	eMzG	hMzG	pGrd		eGrd	eTnl	eQzDrt	pGrd	pTrdh
Facies	NLD-30A	NLD-16B	NLD-16C	NLD-31B	NDP-50A	NDP-65	BRM-49	NDP-21	NDP-115
Samples									
Zr (ppm) (Silva <i>et al.</i> 2018)	123.3	346.0	340.5	182.8	107.6	125.1	157.5	135.9	114.8
P ₂ O ₅ (wt%) (Silva <i>et al.</i> 2018)	0.10	0.17	0.28	0.13	0.10	0.11	0.2	0.14	0.08
M (Watson & Harrison 1983, Boehnke <i>et al.</i> 2013)	1.42	1.48	1.58	1.45	1.72	1.78	2.24	1.69	1.47
G (Gervasoni <i>et al.</i> 2016)	8.0	7.7	6.5	4.0	4.2	4.1	4.1	4.3	4.6
Temperature (°C)									
Zircon (Watson & Harrison 1983, Boehnke <i>et al.</i> 2013)	863	851	841	894	831	838	826	851	853
Zircon (Gervasoni <i>et al.</i> 2016)	990	967	925	981	958	964	945	972	977
Apatite (Harrison & Watson 1984)	884	952	979	944	864	858	886	909	909
Amphibole (Ridolfi <i>et al.</i> 2010)	-	-	-	-	760-770	765-770	738-747	779-811	779-892
Amphibole (Putirka 2016)	-	-	-	-	764-794	765-772	761-770	770-794	772-796
Pressure (MPa) - Amphibole									
Hammarstron & Zen (1986)	-	-	-	-	124-188	157-168	~ 100	226-244	216-230
Hollister <i>et al.</i> (1987)	-	-	-	-	114-174	139-152	~ 100	216-237	220-250
Johnson & Rutherford (1989)	-	-	-	-	100-142	115-125	~ 100	173-189	200-260
Schmidt (1992)	-	-	-	-	188-205	218-229	133-170	283-297	312
Anderson & Smith (1995)	-	-	-	-	~ 100	100-118	~ 100	157-172	200
Ridolfi <i>et al.</i> (2010)	-	-	-	-	~ 100	~ 100	~ 100	112-140	~ 200
Mutch <i>et al.</i> (2016)	-	-	-	-	189-210	204-210	160-175	240-251	200-258
Oxygen fugacity									
log <i>f</i> O ₂ (Ridolfi <i>et al.</i> 2010)	-	-	-	-	-12.9	-12.9	-12.9	-13.2	-14.12 to -13.17
melt H ₂ O (wt.%) (Ridolfi <i>et al.</i> 2010)	-	-	-	-	5.2-5.6	5.4	5.2-5.4	5.7	4.0

Abbreviations: MzG = monzogranite, Grd = granodiorite, Tnl = tonalite, QzDrt = quartz-diorite, Trdh = trondhjemite, e = equigranular, h = heterogranular, p = porphyritic; Anderson & Smith (1995): $P (\pm 0.6 \text{ Kbar}) = 4.76\text{Al} - 3.01 - \{[T (\text{°C}) - 675]/85\} * \{0.530\text{Al} + 0.005294 [T (\text{°C}) - 675]\}$; Gervasoni *et al.* (2016): see text; Hammarstron & Zen (1986): $P (\pm 3 \text{ Kbar}) = -3.92 + 5.03\text{Al}$; Harrison & Watson (1984) = $\ln D_{\text{apatite/melt}} = [(8400 + ((\text{SiO}_2 - 0.5)2.64 \times 10^4)/T) - [3.1 + (12.4(\text{SiO}_2 - 0.5))]$; Hollister *et al.* (1987): $P (\pm 3 \text{ Kbar}) = (5.64 * \text{Al total}) - 4.76$; Johnson & Rutherford (1989): $P (\pm 0.5 \text{ Kbar}) = 4.23 \text{Al}_t - 3.46$; Mutch *et al.* (2016): $P (\pm 0.5 \text{ Kbar}) = 0.5 + 0.331(8) * \text{Al}_t + 0.995(4) * (\text{Al}_t)^2$; Putirka (2016): $T (\text{°C}) = 1201.4 - 97.93[\text{Si}_{\text{Amp}}] + 201.82[\text{Ti}_{\text{Amp}}] + 72.85[\text{Mg}_{\text{Amp}}] + 88.9[\text{Na}_{\text{Amp}}] + 40.65[P(\text{GPa})]$; where $P (\text{kbar}) = (5.03 * \text{Al total}) - 3.53$ was converted to GPa (Blundy & Holland, 1990); Ridolfi *et al.* (2010): $T (\text{°C}) = -151.487\text{Si}^* + 2041$, where $\text{Si}^* = \text{Si} + (\frac{\text{Al}^{\text{IV}}}{15}) + (2\text{Ti}^{\text{IV}}) - (\frac{\text{Al VI}}{2}) - (\frac{\text{Ti VI}}{1.8}) + (\frac{\text{Fe}^{+3}}{9}) + (\frac{\text{Fe}^{+2}}{3.3}) + (\frac{\text{Mg}}{26}) + (\frac{\text{Ca B}}{5}) + (\frac{\text{Na B}}{1.3}) - (\frac{\text{Na A}}{15}) + (\frac{\square \text{A}}{2.3})$; Schmidt (1992): $P (\pm 0.6 \text{ Kbar}) = 4.76 \text{Al}_t - 3.01$; Watson & Harrison (1983): $\ln D_{\text{Zr, zircon/melt}} = \{-3.8 - [0.85 (M - 1)]\} + 12.900/T$; onde $\ln D_{\text{Zr, zircon/melt}} = \text{Zr content in melt (ppm)}$; $M = (\text{Na} + \text{K} + 2\text{Ca})/(\text{Al.Si})$ = compositional parameter related to zircon solubility in SiO₂ and melt; Zr_{melt} whole-rock zirconium concentration and temperature (Kelvin).

Constraints on temperature can also be obtained by comparing amphibole compositions from Ourilândia sanukitoids, high-Mg granodiorites from the Rio Maria suite (Carajás province) and similar compositional rocks from the Pinatubo dacite based on experimental studies (Proteau & Scaillet 2003). The temperatures estimated by this method reach 750 °C considering the plot of Ti vs. Na + K, which is sensitive to temperature variations (Figure 3.10a). The porphyritic sanukitoid and trondhjemite varieties show a larger interval of temperature (700 to 790 °C). For leucogranites and associated high-Ti granodiorite, calculating the temperature based on aforementioned geothermometers is not possible due to the absence of amphibole.

Microstructural observations indicate that amphibole is formed at an early stage of magmatic crystallization, which leads to higher temperatures for this process, close to those

obtained by zircon and apatite saturations ($> 900\text{ }^{\circ}\text{C}$). However, the temperatures obtained by geothermometers are generally lower ($< 800\text{ }^{\circ}\text{C}$).

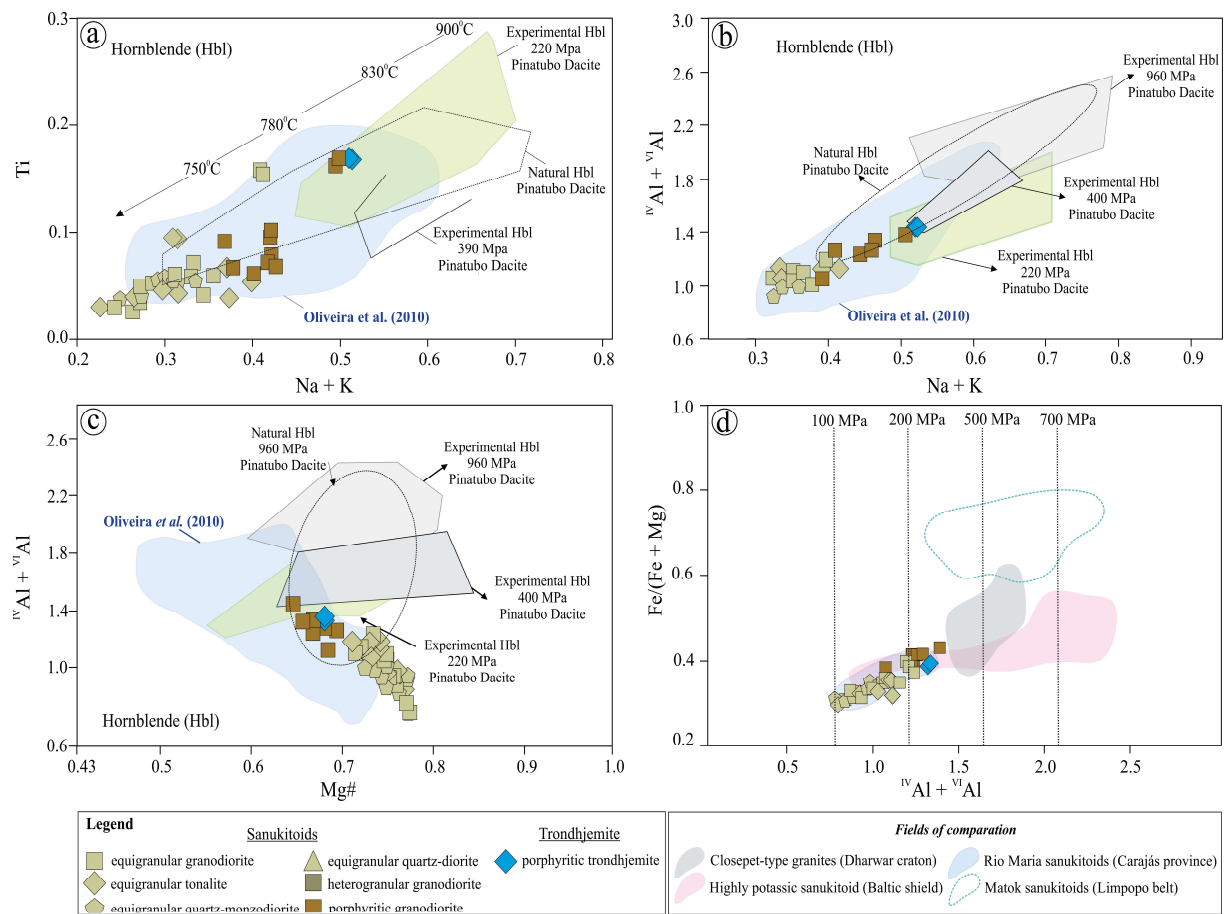


Figure 3.10 – Comparative diagrams based on hornblende compositions: a) Ti vs. Na + K diagram; b) $IVAl + VIAl$ vs. Na + K diagram; c) $IVAl + VIAl$ vs. Mg# diagram; d) $Fe/(Fe+Mg)$ ratio vs. $IVAl + VIAl$ diagram (isobars from Anderson & Smith, 1995). Note that the temperatures and pressures are based on experimental studies of natural hornblende produced in the Pinatubo dacite system which are characterized by similar geochemical signatures in comparison with Ourilândia sanukitoids (Scaillet & Evans, 1999, Proteau & Scaillet 2003). Fields of comparison: Closepet-type granites (Bhattacharya *et al.* 2014), Highly potassic Late Archean sanukitoids from the Baltic Shield (Lobach-Zhuchenko *et al.* 2008), Rio Maria sanukitoids from the Carajás province (Oliveira *et al.* 2010), free-pyroxene Matok granodiorites of sanukitoid affinity from the Limpopo Belt (Rapopo 2010).

These lower values can be understood as a result of the compositional reequilibration process in some amphibole crystals; and let us assume two main hypotheses for mineral re-equilibration: (i) it was related to retrograde metamorphism in the upper amphibolite facies; or (ii) it was associated with recrystallization and alteration during the deformation-assisted late-to postmagmatic cooling process. The first assumption is unlikely since the concept of retrograde metamorphism does not apply to an originally igneous rock (Best 2003). On the other hand, the second premise is consistent with geologic and microstructural observations in the Ourilândia granitoids, such as the presence of microfractures in feldspars filled by residual minerals, indicating that dynamic recrystallization processes (Best 2003) or submagmatic

deformation (Blenkinsop 2000) can have occurred at temperatures close to the *solidus* and confirming a syntectonic nature for the studied granitoids, as pointed out by Silva *et al.* (2018). This interpretation is in line with amphibole deformation experiments, which indicate that recrystallization processes are activated at temperatures above 650-700 °C (Imon *et al.* 2004), similar to the temperature obtained using geothermometers for the Ourilândia granitoids.

3.7.1.2 Pressure

Several empirical and experimental studies have demonstrated that the Al-in-amphibole geobarometer is an effective indirect means for determining the pressure of calc-alkaline granitoids, especially when they are buffered by quartz, plagioclase, alkali feldspar, biotite, hornblende, titanite and Fe-Ti oxides (Hammarstrom & Zen 1986, Hollister *et al.* 1987; Johnson & Rutherford 1989, Schmidt 1992, Anderson & Smith, 1995, Ridolfi *et al.* 2010; Mutch *et al.* 2016 and references therein). Experimental results indicate that the calculated pressure may reflect the level of hornblende crystallization rather than the direct pressure of magma consolidation (Hollister 1987). The mineral assemblage described in the Ourilândia granitoids is suitable for the application of the Al-in-amphibole geobarometer. Therefore, applying the equation proposed by Johnson & Rutherford (1989) yields pressure values between 100 and 189 MPa for sanukitoids and between 200 and 260 MPa for trondhjemites; a similar value is also computed with the Anderson & Smith (1995) and Hollister *et al.* (1987) calibrations (Table 7). In turn, the Schmidt (1992) geobarometer yields pressure ranging from 133-229 MPa for equigranular sanukitoids and slightly higher values for porphyritic sanukitoids (283-297 MPa) and trondhjemite (312 MPa). Using Ridolfi *et al.* (2010) and Ridolfi & Zenzulli (2012) geobarometers, pressures vary of 100 to 140 MPa for sanukitoids and 200 MPa for trondhjemite. Erdmann *et al.* (2014) have reported that the Ridolfi *et al.* (2010) and Ridolfi & Zenzulli (2012) calibrations yield reasonably reliable temperature estimates, but their use as a potential geobarometer is limited for determining crystallization pressures over a large depth range. These geobarometers did not show significative discrepancies in the Ourilândia granitoids pressures in comparison to other geobarometers.

More recently, Mutch *et al.* (2016) revised the pioneering model of Hammarstrom & Zen (1986) and expanded their application to granitic rocks with diverse bulk compositions at near-*solidus* temperatures and pressures of 80-1000 MPa, considering amphiboles analyses from the rims of grains displaying plausible textural equilibrium with plagioclase and other mineral assemblages. Both geobarometers give overlapping values for equigranular

sanukitoids from 100 to 210 MPa, 226 to 251 MPa for porphyritic sanukitoid, while trondhjemite have average values of 200 to 258 MPa. Based on experimental studies using amphibole compositions in sanukitoids from the Rio Maria suite (Carajás province – Figure 3.10b-c). Oliveira *et al.* (2010) suggested two intervals of pressure: a first high-pressure phase related to magma crystallization (600-900 MPa) and a second low-pressure stage corresponding to the final emplacement of the Rio Maria magma at approximately 100-200 MPa in the shallow crust. The results for sanukitoids from the Ourilândia area are more akin to the final emplacement pressure obtained in the region (Figure 3.10b-c). The aforementioned integrated dataset is represented on the Fe/(Fe+Mg) vs. total Al ($Al^{IV} + Al^{VI}$) diagram showing that amphibole from equigranular sanukitoids has a broad range of pressure from approximately 100-257 MPa, and that porphyritic granodiorites with sanukitoid affinity display pressures varying from 108 to 288 MPa, which overlap strictly with those of the Mesoarchean Rio Maria suite from the Carajás province. However, in comparison with the fields for Closepet-type granitoids, Archean sanukitoids from the Baltic Shield and the Limpopo belt (Matok-type high-Mg granodiorites), they indicate low pressures for amphibole crystallization or re-equilibration. Similarly, trondhjemites from Ourilândia have pressure values ranging from 200-260 MPa (Figure 3.10d; Anderson & Smith, 1995 modified).

Sial *et al.* (2008) suggested that the magmatic epidote compositions (Ps 27-29) can be an indicator of pressures in calc-alkaline and high-K calc-alkaline granitoids. This mineral is stable at high pressures (600 to 800 MPa); however, at low pressures (~ 200 MPa), it tends to become unstable. Sial *et al.* (1999, 2008) indicated that this mineral is preserved at low pressure (down to 3 – 5 kbar) only under oxidizing conditions (near the hematite-magnetite buffer or nickel-nickel oxide buffer) and is favored by rapid ascent of the magma. Therefore, the widespread occurrence of magmatic epidote in the Ourilândia granitoids could suggest that it was a stable phase at high pressure and that during final magmatic emplacement; it had fast ascent rates inhibiting its re-equilibration at lower pressure. Due to the absence of proper mineral assemblages, no barometric estimates can be applied in leucogranites and associated high-Ti granodiorite.

3.7.1.3 Oxygen fugacity (fO_2)

The fO_2 is a thermodynamic parameter used in geological systems to indicate the oxidation state of iron at a fixed temperature. It is measured in units of pressure and can be indirectly deduced from the equilibrium of mineral assemblages considered buffers (Clark 1999). These buffers are experimental determinations of multivariate silicate and Fe-Ti oxide balance arising from reactions that occur during rock formation and are insensitive to the

addition of other mineral phases in equilibrium. Haggerty (1991) reported the difficulty of estimating the initial fO_2 from primary magma due to natural re-equilibration under *subsolidus* conditions where magnetite usually becomes Ti-free during slow magmatic cooling and ilmenite undergoes multiple stages of oxidation and exsolution. For this effect, the ferromagnesian silicate compositions, especially the Fe/(Fe+Mg) ratios in amphibole (Figure 3.11a) and biotite (Figure 3.11b), are important to estimate the redox state of the magmas, since these minerals become richer in magnesium according to the increasing fO_2 (Anderson & Smith 1995, Bogaerts *et al.* 2006, Anderson *et al.* 2008).

In the Ourilândia granitoids, the whole-rock FeOt/(FeOt + MgO) ratios, Fe# = Fe/(Fe + Mg) values in amphibole and biotite are consistent with the oxidized nature of the magma (Figure 3.11a-b). This premise is supported by the presence of an equilibrium mineral indicative of high fO_2 titanite + magnetite + quartz in mineral paragenesis (Wones 1989). Ridolfi *et al.* (2010) formulated an equation based on amphibole compositions to estimate the fO_2 in granitic rocks by the following expression:

$$\Delta NNO = 1.644Mg^* - 4.01 \quad (2)$$

$$\text{where } Mg^* = Mg + \frac{Si}{47} - \frac{[6]Al}{9} - 1.3 [6]Ti + \frac{Fe+3}{3.7} + \frac{Fe+2}{5.2} - \frac{BCa}{20} - \frac{ANa}{2.8} + \frac{Al}{9.5} \quad (\text{accuracy of } 0.4 \text{ log units})$$

The results show that log fO_2 ranges from log -12.9 to -13.2 for equigranular sanukitoids and log -14.12 to -13.17 for trondhjemite (Table 3.1; Figure 3.11c-d). However, fO_2 is slightly higher for the porphyritic sanukitoids (log -13.22) than for other sanukitoids. These values agree with the results of petrographic study of Fe-Ti oxide minerals, where porphyritic sanukitoids have high magnetite contents reflecting their high MS values compared with the other sanukitoid varieties and trondhjemites.

Further inferences about fO_2 can also be done on the basis of magmatic epidote compositions of granitic rocks (Liou 1973). Previous studies have shown a direct relation between the thermal stability of magmatic epidote and fO_2 (Schmidt & Poli 2004, Sial *et al.*, 2008). In the Ourilândia granitoids, the pistacite molecule {Ps = [Fe³⁺ / (Fe³⁺ + Al)] * 100} in the leucogranites and associated high-Ti granodiorite, the sanukitoids and the trondhjemites range from 25 to 29 %, 20 to 29 % and 20 to 26 %, respectively. Liou (1973) reported that these values are generally achieved between the hematite-magnetite (HM) and nickel-nickel oxide (NNO) buffers, supporting the current interpretation of the estimated fO_2 for the Ourilândia granitoids. Although calculating fO_2 using the Ridolfi *et al.* (2010) method for leucogranites and associated high-Ti granodiorite is not possible, due to the absence of

amphibole in their mineral assemblages, high fO_2 is assumed for these rocks considering their highest magnetite contents and MS measurements in comparison to the sanukitoids and trondhjemites.

Thus, the moderate values of whole-rock Fe# (< 0.9) and Fe/(Fe+Mg) ratios (< 0.6) in biotite are consistent with their more oxidized crustal source that can crystallize magnetite in the high- fO_2 domain (probably near the Δ_{NNO}). On the other hand, sanukitoids and trondhjemites are related to less oxidized conditions, whose source has a mantle contribution associated with crustal assimilation (Silva *et al.* 2018). The lower magnetite contents and MS values support crystallization conditions between the Δ_{QFM} and Δ_{NNO} buffers indicating moderate oxidized conditions for the sanukitoids, but still in the magnetite stability domain, and low fO_2 conditions for the trondhjemites. Porphyritic sanukitoid has a distinct nature (high magnetite and ferromagnesian contents), and was probably derived from a source different from that of the other sanukitoids.

3.7.1.4 Water contents (H_2O_{melt})

Water is considered the major volatile component dissolved into aluminosilicate melts, and its concentration strongly influences mineral stability (Holtz *et al.* 2001). The presence of hydrated magmatic phases, such as sericitized plagioclase, amphibole, biotite and secondary minerals chlorite, muscovite, chalcopyrite and pyrite, in granitoid rocks permits an estimation of the water content dissolved in the magma (Best 2003). In this sense, the experimental calibration method of Ridolfi *et al.* (2010) recognized that the Al^{VI} content in amphibole is sensitive to the water content in the melt, considering an accuracy of 0.4 wt% for magnesiohornblende compositions. The results yield H_2O values ranging from 5.2 wt% to 5.7 wt% for sanukitoids and 4.0 wt% for trondhjemite (Table 3.1). Caution should be taken to interpret melt H_2O values only using the Ridolfi *et al.* (2010) calibration, without considering independent and meaningful parameters such as whole-rock compositions, source, mineralogy and textural aspects of granitic rocks.

Erdmann *et al.* (2014) reported that the melt H_2O model can be under- to overestimated and do not reliably calculate melt H_2O contents. For this reason, the melt H_2O values were combined with mineralogical and textural characteristics to be further interpreted. It is assumed that melt H_2O content values calculated are in conformity with the typical values for calc-alkaline magmas and are considered the minimum values to stabilize calcic amphibole at magmatic temperatures and prevent pyroxene crystallization (4 wt% to 9 wt% H_2O) (Naney 1983, Dall'Agnol *et al.* 1999, Bogaerts *et al.* 2006, Oliveira *et al.* 2010).

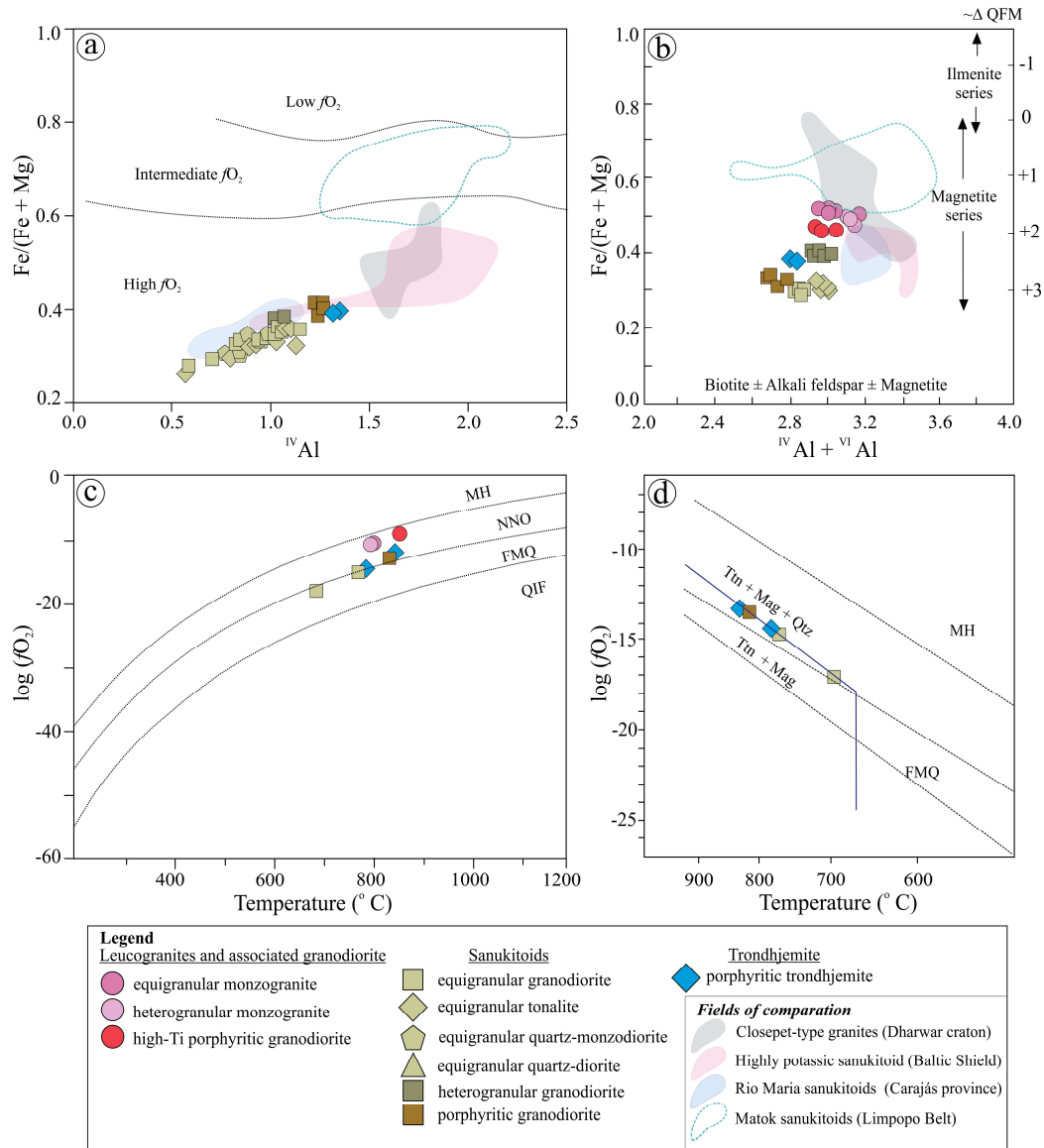


Figure 3.11– The fO_2 diagrams of the Mesoarchean granitoids from the Ourilândia and similar rocks: a) $Fe/(Fe+Mg)$ vs ^{IV}Al in amphibole (based on Anderson & Smith 1995); b) $Fe/(Fe+Mg)$ vs $^{IV}Al + ^{VI}Al$ in biotite (Anderson *et al.* 2008); c) fO_2 buffer diagram based on Clark (1999) modified considering $\log fO_2$ vs Temperature ($^{\circ}C$); d) fO_2 buffer diagram based on Wones (1989) modified considering $\log fO_2$ vs Temperature ($^{\circ}C$). Note that for leucogranites and high-Ti granodiorite the fO_2 was estimated based on mineralogy, whole-rock chemistry and $Fe/Fe + Mg$ ratio < 0.6 in biotite. Fields of comparison: Closepet-type granites from the Dharwar craton (Bhattacharya *et al.* 2014), Late Archean sanukitoids from the Karelian craton (Lobach-Zhuchenko *et al.* 2008), Mesoarchean Rio Maria sanukitoids from the Amazonian craton (Oliveira *et al.* 2010), free-pyroxene Matok granodiorites of sanukitoid affinity from the Limpopo belt (Rapopo 2010). Experimental buffer (Buddington & Lindsley 1964): MH = magnetite-hematite, NNO = nickel-nickel oxide, QFM = quartz-fayalite-magnetite, QIF = quartz-ilmenite-fayalite, F – Fayalite, Qtz – Quartz, Ttn – Titanite, Mag – Magnetite.

Considering that amphibole is an accessory mineral in the trondhjemite and is absent in the leucogranites and associated high-Ti granodiorite, lower water contents (< 5 wt% H_2O_{melt}) are assumed to have been attained during their magmatic evolution than during that of granitoids with sanukitoid affinity. Accounting for these assumptions, the sanukitoid magmas are concluded to have had higher H_2O contents than trondhjemite and leucogranite magmas and to have contained at least 4 wt% H_2O and possibly more than 7 wt% H_2O , as indicated by their mineralogy and textural aspects.

3.7.2 Comparison with analogous granitoids

3.7.2.1 Carajás province

The Mesoarchean sanukitoids from the Rio Maria suite occur in the southeastern part of the Carajás province, covering large areas of the Rio Maria domain. The granitoids exposed to the east of the Bannach area are composed of four main groups: granodiorites, intermediate rocks, layered rocks and mafic enclaves (Oliveira *et al.* 2010). These rocks are akin to the Ourilândia sanukitoids, except for the cumulate layered varieties (Santos & Oliveira 2016). Thus, the mineralogical and textural aspects of both Bannach and Ourilândia rocks are correlated by the absence of pyroxene, and presence of saussuritized plagioclase, Mg-hornblende, Mg-biotite and magmatic epidote, representing their main mafic minerals. Temperatures and pressures estimated for the Ourilândia granitoids obtained through geothermometers and barometers are consistent with those predicted by Oliveira *et al.* (2010) and supported by the experimental studies of Scaillet & Evans (1999) and Bogaerts *et al.* (2006). Temperatures attributed to the Ourilândia granitoids range from 738 – 794 °C in equigranular sanukitoids and 770 – 811 °C for porphyritic sanukitoids, while for the Bannach granitoids, *solidus* temperatures vary between 730 and 780 °C. Oliveira *et al.* (2010) noted that the lowest temperature reflects re-equilibration towards the cooling path. A similar statement can be made for the Ourilândia granitoids; however, in this case, it is probably related to recrystallization and alteration during the deformation-assisted late- to postmagmatic cooling process. This interpretation is consistent with more recent studies that have revealed a syntectonic nature of these plutons (Santos & Oliveira 2016, Silva *et al.* 2018). Zircon (T_{Zr}) and apatite (T_{Ap}) saturation temperatures yield values higher than 800 °C and probably represent crystallization conditions close to the *liquidus* temperature for the Ourilândia granitoids. In sanukitoids from both the Ourilândia and Bannach areas, the estimated pressure varies from 100 to 300 MPa, except for the cumulate layered rocks of the Bannach area, which formed under pressures up to 900 MPa. The high pressure (> 900 MPa) of these rocks has controversial significance because the cumulate amphibole crystals are not in equilibrium with the other mineral phases as reported by Oliveira *et al.* (2010).

Magnetic petrology study obtained from the granitoids of the Rio Maria suite (Bannach area) indicate that primary magnetite is rare or absent in sanukitoids, reflected by their low bulk MS ($< 1 \times 10^{-3}$ SI; Dias *et al.* 2006). On the other hand, the Ourilândia sanukitoids show ambiguous behavior, because the porphyritic granodiorite variety has high magnetite contents and high MS values. The equigranular sanukitoids, along with showing textural affinities with those of the Bannach area, have magnetite very scarce and low values

of MS (down log - 4.26), which make it more akin to reduced granitoids (ilmenite-series). However, based on independent thermobarometric constraints, the sanukitoid magmatism of the Ourilândia and Banach areas is proposed to have evolved under relatively oxidizing conditions, above the NNO buffer (NNO+0.5 to NNO+1.0). Thus, the frequent presence and high contents of magnetite in the porphyritic granodiorite as well as its higher bulk MS (up to log -2.0) also reveal a more oxidized nature for the magmatic sanukitoids from Ourilândia than for other sanukitoids. Epidote compositions (Ps of 20 to 30 mol %) provide further support for high fO_2 because these values are achieved between the HM and NNO buffers (Liou 1973). This contrast suggests differences in the compositions of their sources in relation to those of other sanukitoids in the Carajás province. Trondhjemites show aspects of magnetic petrology similar to those of the equigranular sanukitoids in these areas. Experimental studies have demonstrated that at least 5 wt% H₂O is required to have amphibole as the *liquidus* silicate phase and to inhibit the formation of pyroxene (Naney 1983, Proteau & Scaillet 2003). Therefore, the high contents of amphibole in the sanukitoids from the Ourilândia area indicate that their precursor magmas had minimum dissolved H₂O contents higher than 5 wt%. For comparison, the parental magmas of the Rio Maria suite are shown to have been water-rich, with more than 7 wt% dissolved H₂O (Oliveira *et al.* 2010).

3.7.2.2 Other province

Mesoarchean granitoids from Ourilândia reveal compositional affinities to those observed in distinct Archean to Proterozoic terrains such as the Neoarchean high-Mg granodiorites from the Limpopo belt (Matok Pluton – Rapopo 2010), late Archean sanukitoids from the Karelian craton (Kovalenko *et al.* 2005, Lobach-Zhuckenko *et al.* 2008), Closepet granites from the Dhawar craton (Bhattacharya *et al.* 2014) and Paleoproterozoic high-Mg granitoids from the East Sarmatian orogen (Terentiev & Santosh 2017, 2018). All of these rocks have available thermobarometry data that can be used to compare their petrological constraints with those for the rocks from Ourilândia.

The Neoarchean Matok pluton, emplaced in the Pietersburg block, northern Kaapvaal Craton (South Africa), is formed by pyroxene-bearing and free-pyroxene granodiorites related to a late to postcollisional tectonic setting (Rapopo 2010). The main bulk mineralogy of the pyroxene-free granodiorites is similar to that of the Ourilândia granodiorites of sanukitoid affinity, and their geothermobarometric calculations indicate that these granitoids crystallized between 680 and 757 °C and was emplaced somewhere between 860 MPa and 330 MPa. These results are consistent with the crystallization temperatures of the Ourilândia granitoids (690 – 811 °C), despite of some samples with amphibole re-equilibration, along with similar

oxidizing fO_2 crystallization conditions ($\Delta_{\text{NNO}}+1$) in water-rich magma ($H_2O > 5\text{wt}\%$; Laurent *et al.* 2014); however, the higher pressures emplacement estimated for the free-pyroxene granodiorites ($> 400 \text{ MPa}$) are significantly distinct from those obtained in this study ($100 - 300 \text{ MPa}$).

The late Archean granitoids from the Karelian craton (Baltic Shield) are characterized by high-Mg and high-K intrusions, varying from diorite to granites of sanukitoid affinity (Kovalenko *et al.* 2005, Lobach-Zhuckenko *et al.* 2008). The analysis of primary amphiboles (Mg-hornblende and edenite) indicate crystallization temperatures between $1150 \text{ }^\circ\text{C}$ and $1230 \text{ }^\circ\text{C}$ and an estimated emplacement pressure of $160 \pm 60 \text{ MPa}$ (Kovalenko *et al.* 2005). Geological features and geochemical signatures suggest that these rocks formed in a context analogous to those determined for the Ourilândia granitoids (subduction); however, their crystallization temperatures were higher. Another group of late Archean granitoids with compositional affinities to the Ourilândia rocks are the Closepet-type granites exposed in the eastern Dharwar craton of southern India (Moyen *et al.* 2003, Jayananda *et al.* 2018). Strictly, these granitoids reveal geochemical and mineralogical characteristics akin to the high-Ti granodiorite (leucogranites group) from Ourilândia (Silva *et al.* 2018). Geothermobarometric calculations for the Closepet-type granites indicate temperatures ranging from 600 to $750 \text{ }^\circ\text{C}$ and emplacement pressures between 410 and 480 MPa (Bhattacharya *et al.* 2014). In addition, analysis of biotite implies that the Closepet-type magmas crystallized under high fO_2 conditions (above FMQ buffer) with no variation in the late-stage magmatic fluid. The estimated temperature is consistent with that obtained for the high-Ti granodiorite from Ourilândia; however, its pressure is lower than that proposed for the Closepet granites. They also differ in terms of fO_2 , where the Ourilândia granitoids have the highest fO_2 (mostly above the Δ_{NNO} buffer).

Terentiev & Santosh (2017) studied postcollisional granitoids from the Paleoproterozoic East Sarmatian (East European craton) which are recognized to show some sanukitoid affinities along with intermediate rocks. They are high-Mg to low-Mg and medium- to high-K granitoids whose magnesian compositions of amphibole [magnesiohornblende; $(\text{Mg}/(\text{Mg}+\text{Fe}^{+2}) = 0.50 - 0.66)$ and biotite $[\text{Fe}/(\text{Fe}+\text{Mg}) = 0.49-0.58]$ of these rocks are similar to those attributed to the Ourilândia granitoids. Geobarometric data indicate crystallization at upper-crustal depths ($170-240 \text{ MPa}$), approaching 491 MPa in some granitoids; and crystallization temperatures ranging from $700-902 \text{ }^\circ\text{C}$ in intermediate rocks and high-Mg granitoids. In terms of fO_2 , high fO_2 was assumed for the East Sarmatian granitoids (at least $\text{NNO}+0.5$ to $+2.5$), although this interpretation is not consistent with the

general absence of magnetite and the abundance of ilmenite, where the latter feature is indicative of ilmenite-series granitoids crystallized at low fO_2 (Ishihara 2004). Thus, the estimated water contents range of 2.8-5.35 wt% (using the Ridolfi *et al.* 2010 method) is not significantly distinct from the values obtained for the Ourilândia magmatism (4-5.7 wt%). Neoproterozoic high-K calc-alkaline granites from the southern Brasília Orogen present geochemical features akin to those of the Ourilândia leucogranites (Salazar-Naranjo & Vlach 2018) and show similar Fe-Ti oxides contents. Although the thermometric data indicate zircon saturation temperatures of approximately 609-820 °C (at 510 ± 60 MPa), which are lower than those attributed to the Ourilândia leucogranites (884-979 °C), they share similarities in terms of crystallization conditions that are compatible with oxidizing conditions ($0 \leq \Delta_{NNO} \leq +1$).

Terentiev & Santosh (2018) used the Mg-number vs. Si in a formula diagram for magmatic amphibole to show the compositional variation of Fe-K to Mg-K suites related to late- and postcollisional settings from distinct Precambrian cratons (Figure 3.12a). In this case, amphibole is the main mineral phase controlling the Mg/Fe ratio. The Elan-type granites have singular characteristics because of their highest MgO, Cr and Ni and lowest TiO₂ and FeOt/(FeOt+MgO) contents in relation to the other high-Mg granitoids worldwide (Terentiev & Santosh 2018). Although the fO_2 increases from reduced ferroan granites towards oxidized ferroan and magnesian granitoids, the Elan-type granites are magnetite-free and ilmenite predominates as an index of fO_2 . Similarly, in the Ourilândia granitoids, the equigranular sanukitoids have lower magnetite contents than the porphyritic varieties. The absence of magnetite in the Mg-rich rocks can be theoretically explained in two ways: (a) reaction involving Ilmenite + FeO in amphibole = Ulvöspinel + Quartz, which assume that as Mg increases in the magmatic system, the equilibrium moves to higher fO_2 , or (b) replacement of magnetite by epidote during magmatic crystallization (Oliveira *et al.* 2010). In addition, Terentiev & Santosh (2018) reported that ilmenite completely disappears in high-Mg rocks when crustal contamination occurs and/or the mantle source was previously metasomatized by crustal components, whereas ilmenite is abundant when the source is a hybrid of crustal and mantle magmas. This information suggests that crustal input could change the overall fO_2 of the magma. Assuming these premises and based on the mineralogical and textural aspects of the Ourilândia granitoids, Figure 3.12a shows that the equigranular sanukitoids are in the transitional domain between magnetite instability (magnetite out) and ilmenite formation (ilmenite in) with Si in the amphibole formula between 7.7 to 7.9 wt% and Mg# of 0.75 to 0.80. On the other hand, the porphyritic sanukitoids plot in the more stable domain of the magnetite realm, which supports its higher magnetite contents in relation to the equigranular

counterparts. Therefore, magnetite seems to be a stable mineral phase only for specific compositions, generally with Mg# and Si in the amphibole formula up to 0.75 and 7.8, respectively. In the distinct compositional range of Mg# and Si in the amphibole formula, the magnetite becomes an unstable mineral phase (magnetite out) and ilmenite is predominant (ilmenite in).

Amphibole and biotite chemistry can be used to distinguish magma source compositions based on TiO_2 wt% vs. Al_2O_3 wt% in amphibole (Figure 3.12b) and $\text{FeO}_{\text{total}}/(\text{FeO}_{\text{total}} + \text{MgO})$ vs. MgO wt% contents for biotite (Figure 3.12c). The equigranular sanukitoids are characterized by Al_2O_3 contents in amphibole between 1.0 and 5.2 wt% and TiO_2 from 0.2-1.5 wt%, plotting in the transition between the domains of crustal components and crust-mantle mixed sources; meanwhile, the porphyritic granodiorite has more aluminous amphibole compositions (Al_2O_3 5.2-8 wt%) with slightly higher TiO_2 than the other sanukitoids varieties (TiO_2 1-1.9 wt%) and plots in the crust-mantle mixed source field.

These results are similar to those for the less aluminous members of the Rio Maria suite, Matok-type sanukitoids and high-K granitoids from the Baltic Shield (Figure 3.12b). Thus, biotite compositions of the leucogranites show FeO# ($= \text{FeO}t/\text{FeO}t + \text{MgO}$) between 0.35-0.51 wt% along with low MgO (4.0-8.5 wt%) contents, plotting in the crustal source field, whereas high-Ti granodiorites plot in the crust-mantle mixed source field which is consistent with their more magnesian nature than the leucogranites (MgO 9.0-10.5 wt% and Fe# 0.38-0.45 wt%) (Figure 3.12c). The contrasts observed in the crystallization parameters and compositions of the ferromagnesian minerals of the Ourilândia granitoids reflects their distinct sources. The high-K calc-alkaline leucogranite was generated from crustal source, sanukitoids point towards an enriched mantle source, while the high-Ti granodiorite is related to crust-mantle interaction with expressive crustal input and the trondhjemite to a mafic source with little to no contribution from enriched magma (Figure 3.12c).

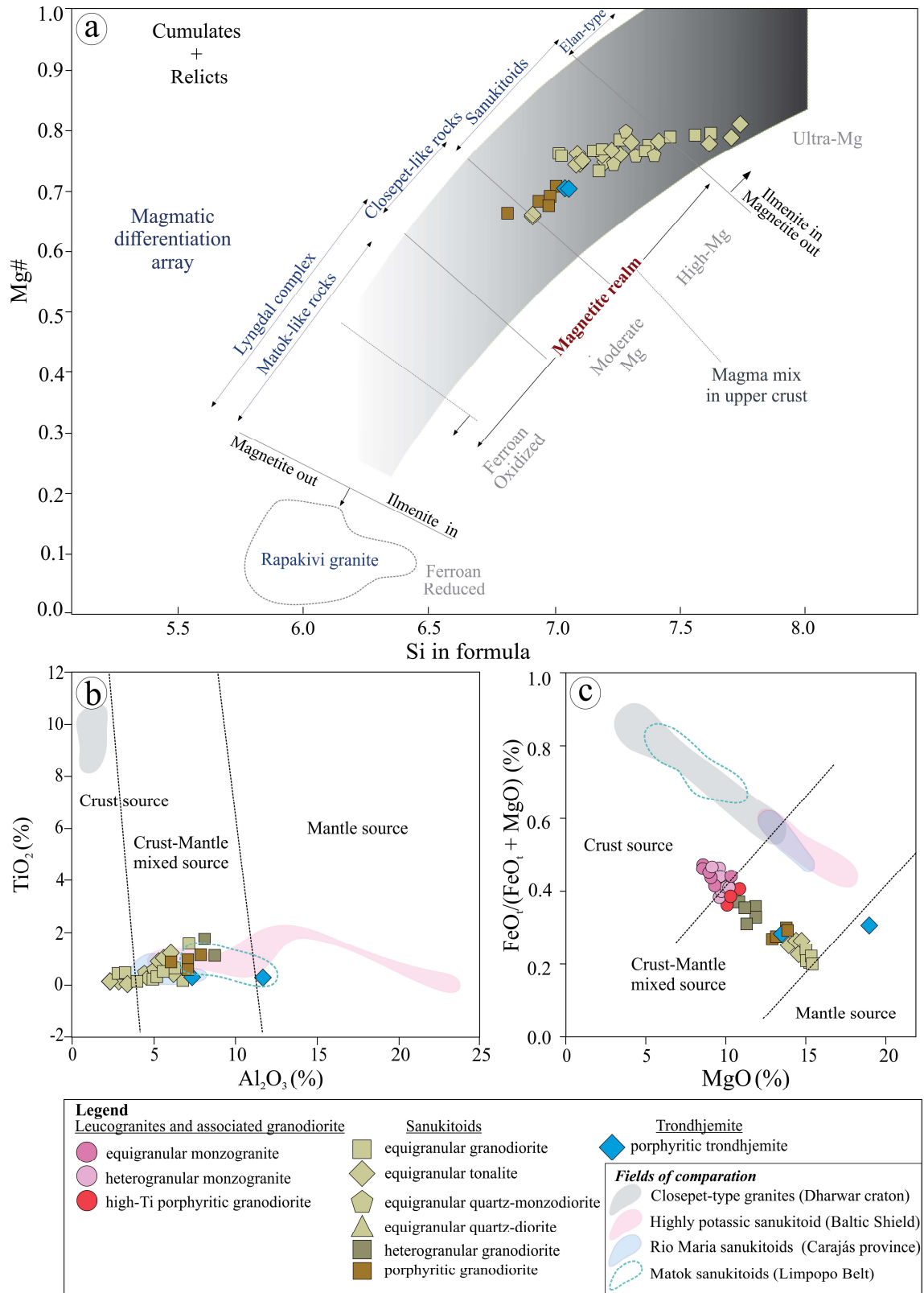


Figure 3.12 - Mineral chemistry diagrams: a) Mg-number vs. Si in the amphiboles formula diagram for the magmatic amphiboles of the Ourilândia granitoids using dataset from compositional variations of the hornblende biotite metaluminous granitoids of the Terentiev & Santosh (2018) modified; b) Plot TiO₂ wt% vs. Al₂O₃ wt% for primary hornblende (after Jiang & An 1984); c) plot of FeO_{total}/(FeO_{total} + MgO) vs. MgO wt% for biotite (after Zhou 1986, Zhao *et al.* 2012); FeO_{total} indicates total iron. Fields of comparisons: Closepet-type granites from the Dharwar craton (Bhattacharya *et al.* 2014), Highly potassic sanukitoids from the Karelian craton, Baltic Shield (Lobach-Zhuchenko *et al.* 2008), Rio Maria sanukitoids from the Carajás province, Amazonian craton (Oliveira *et al.* 2010), free-pyroxene Matok granodiorites of sanukitoid affinity from the Limpopo Belt (Rapopo 2010).

3.8 CONCLUSIONS

In the Ourilândia area occurs a Mesoarchean magmatism of distinct nature which is composed of leucogranites and associated high-Ti granodiorite, sanukitoids, and minor occurrence of trondhjemites. These granitoids display similarities in terms of mineralogy; however, differ on geochemical grounds, crystallization constraints and source. Magnetite predominates in the leucogranites and porphyritic sanukitoid variety reflecting their higher magnetic susceptibility ($MS > 1 \times 10^{-3}$ SI) whereas low to absent magnetite content was reported for equigranular sanukitoids and trondjemite. Application of the geothermometers and barometers based on the amphibole compositions in sanukitoids and trondhjemite yield temperatures ranging from 738 to 892 °C and emplacement pressure between 100 and 312 MPa. Temperature estimates down to 800 °C was attributed to the compositional amphiboles re-equilibration associated with recrystallization during deformation-assisted late- to postmagmatic cooling process. In this regard, a range of crystallization conditions was assumed derived from the comparasion between experimental studies carried out on similar magmatic geochemical grounds, mineralogy, mineral proportions and compositions, combined to the Fe/(Fe + Mg) ratios in biotite and amphibole. An additional constraint on crystallization temperatures was given by estimates of zircon and apatite saturation solubility models, especially in leucogranites and high-Ti granodiorite without amphibole. These parameters indicate that the precursor magmas that originated porphyritic sanukitoids and leucogranites were oxidized ($fO_2 = \Delta_{NNO} + 1.5$) which is consistent with their higher MS values, large amount of magnetite, magnesian biotite and amphibole, and Fe/(Fe + Mg) ratios in biotite and amphibole (when present) down to 0.5. Intermediate oxidizing conditions are assumed to the equigranular sanukitoids and low fO_2 is attributed to the trondhjemites ($fO_2 = \Delta_{NNO} + 0.5$ or slightly near to the QFM buffer, respectively). Sanukitoid magmas have the highest H₂O contents than trondhjemite and leucogranites (H₂O ~ 5 wt%), at least 4 wt% H₂O and possibly more than 7 % H₂O, as indicated by their mineralogy (e.g. high modal content of amphiboles) and textural aspects (e.g. saussuritization of plagioclase). Relative to other Archean sanukitoids, Ourilândia sanukitoids crystallization constraints agree with the fO_2 interval proposed for the Rio Maria sanukitoids and for the more oxidized members from the Baltic Shield; meanwhile, the Closepet-type granites and free-pyroxene sanukitoids from the Matok pluton are slightly less oxidized reaching the interface to the intermediate fO_2 field. These results contrast with the low fO_2 conditions inferred for the ultra-Mg granitoids from the East Sarmatian orogen.

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CAPÍTULO 4 – CONSIDERAÇÕES FINAIS

Na área de Ourilândia do Norte (PA) afloram três principais grupos de granitoides mesoarqueanos (2,92-2,88 Ga): (i) *leucogranitos e granodiorito alto-Ti associado* – compreendem monzogranitos equi- a heterogranular e granodiorito porfirítico enriquecido em titanita; (ii) *sanukitoides* – constituídos predominantemente por granodioritos (equigranular, heterogranular e porfirítico), com tonalito, quartzo monzodiorito e quartzo diorito subordinados; e (iii) *trondhjemito porfirítico* – caracterizado pela pouca deformação e freqüente presença de enclaves. Baseado em estudos de suscetibilidade magnética (SM) e de caracterização dos óxidos de Fe-Ti, foi possível a distinção de três principais populações magnéticas: (a) *baixos valores de SM* (A; SM varia de $0,05 \times 10^{-3}$ a $0,57 \times 10^{-3}$ SI) – É representada por raras fases opacas, há predominância de sanukitoides e os trondhjemitos ocorrem exclusivamente nesta população; (b) *intermediários valores de SM* (B; SM entre $0,59 \times 10^{-3}$ a $2,35 \times 10^{-3}$ SI) – o conteúdo modal de ilmenita prevalece sobre o de magnetita, há variáveis proporções de sanukitoides e leucogranitos; e (c) *altos valores de SM* (C; SM $2,35 \times 10^{-3}$ a $17,0 \times 10^{-3}$ SI) – caracterizado por variedades com alto conteúdo de magnetita, e a ilmenita ocorre subordinada, como os tipos texturais em treliça e composta. Os leucogranitos e granodiorito associado predominam sobre os sanukitoides. É notório o acréscimo dos valores de SM no sentido das variedades mais evoluídas (trondhjemito e sanukitoides → leucogranitos e granodiorito alto-Ti), associado com a correlação positiva entre SM e os conteúdos modais de opacos e FeO, e negativa com o de epidoto, minerais máficos e MgO. O estudo de química mineral dos principais minerais formadores destes granitoides mostrou os seguintes resultados: (i) Os anfibólios descritos nos sanukitoides foram classificados como magnesio-hornblenda, de afinidade cálcica, razão $Mg/(Mg+Fe^{+2}) \geq 0,70$, com subordinada ocorrência de ferropargasita e actinolita-hornblenda. No trondhjemito, o anfibólio ocorre como mineral acessório e foi classificado como magnesio-hornblenda e tschermakita; (ii) A biotita apresenta razão $Fe^{+2}/(Mg + Fe^{+2})$ de até 0,6 nos leucogranitos e granodiorito alto-Ti, e $\leq 0,4$ nos sanukitoides e trondhjemito; (iii) O plagioclásio é predominantemente oligoclásio, sem significativa variação composicional entre fenocristais e matriz, comumente é encontrado intensamente a moderadamente saussuritizado; (iv) O conteúdo de pistacita no epidoto e $TiO_2 \leq 0,137$ indica origem primária, apesar de também de ter sido encontrado epidoto secundário com faces hipidiomórficas; (v) A titanita plota no campo de origem ígnea em diagramas de classificação; (vi) Magnetita e ilmenita são os principais minerais óxidos de Fe-Ti encontrados. Baseado em calibrações experimentais, temperaturas de saturação de zircão (T_{Zr}) e apatita (T_{Ap}) variam entre T_{Zr} 884-990 °C e T_{Ap} 884-979 °C (leucogranitos e granodiorito

alto-Ti), T_{Zr} 826-964 °C e T_{Ap} 864-886 °C (sanukitoides) e T_{Zr} 853-977 °C e T_{Ap} 909 °C (trondhjemitos). Geotermômetros e barômetros baseados no conteúdo de Alumínio no anfibólio indicam temperaturas entre 738-811 °C (sanukitoides) e 779-892 °C (trondhjemitos), e pressão no geral entre 100 a 280 MPa, representando condições de crosta superior. A ausência de anfibólio nos leucogranitos e granodiorito associado impossibilitou a precisa estimativa de temperatura. As condições de cristalização mais baixas obtidas com as calibrações experimentais podem indicar condições de abertura do sistema magmático relacionado à deformação, reafirmando a natureza sintectônica destas rochas, com recristalização dinâmica ocorrendo próximo a temperatura do *solidus*. Apesar dos leucogranitos e granodiorito alto-Ti associado apresentarem relativo enriquecimento de #Fe em rocha total, o que poderia sugerir condição reduzida de formação, os mesmos são rochas de afinidade cálcico-alcálica, com baixo HFSE, magnetita indicativa de ser primária, e elevada SM, o que indica que as mesmas foram formadas em condições oxidantes (provavelmente no domínio do tampão Δ_{NNO}). O sanukitoides e o trondjemitos apresentam $FeOt/(FeOt + MgO)$ em rocha total e em anfibólio e biotita, indicativa de formação em condição oxidante ($\Delta_{NNO}+1,0$). Admite-se que estas rochas se formaram em tais condições, porém para as variedades equigranulares estimam-se condições ligeiramente acima a do tampão FMQ ($\Delta_{FMQ}+0,5$) devido o seu baixo conteúdo de fases opacas. Conclui-se que o magma precursor dos sanukitoides era hidratado ($H_2O > 4-7$ wt%), enquanto $H_2O < 4-7$ wt% foram admitidos para os leucogranitos e granodiorito alto-Ti associado, e trondhjemitos, como indicado pela ausência de anfibólio na paragéneses dos primeiros e baixo conteúdo de anfibólio no segundo. Estes resultados são comparados aqueles estimados para rochas cálcico-alcálicas da Suíte Rio Maria na Província Carajás e membros oxidados de outros terrenos Arqueanos a Paleoproterozóicos do Cinturão Báltico, orógeno Sarmatiano (Europa Ocidental), granitos tipo *Closepet* e granodioritos sem piroxênio do plúton Matok.

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APÊNDICE A1 - MAGNETIC SUSCEPTIBILITY MEASUREMENTS (MS).

Pop.	N°	Sample	K (SI)	Log K (SI)	Facies	Unit	Pop.	N°	Sample	K (SI)	Log K (SI)	Facies	Unit	Pop.	N°	Sample	K (SI)	Log K	Facies	Unit
A	1	NDP-115	0.05x10 ⁻³	-4.262	pTrd	Trondhjemite	A	49	NDP-39C	0.20x10 ⁻³	-3.697	eQzDrt	Enclave	C	97	NLD-30B	2.55x10 ⁻³	-2.593	eMzG	Leucogranite
	2	NDP-113B	0.06x10 ⁻³	-4.218	pTrd	Trondhjemite		50	NDP-108	0.21x10 ⁻³	-3.669	eTnl	Sanukitoid		98	NLD-06B	2.67x10 ⁻³	-2.573	eMzG	Leucogranite
	3	NDP-126	0.07x10 ⁻³	-4.119	hGrd	Sanukitoid		51	NDP-28A	0.21x10 ⁻³	-3.669	eGrd	Sanukitoid		99	NLD-19	2.69x10 ⁻³	-2.570	eMzG	Leucogranite
	4	NDP-124	0.07x10 ⁻³	-4.119	hGrd	Sanukitoid		52	NDP-89A	0.23x10 ⁻³	-3.638	eGrd	Sanukitoid		100	NLD-17B	2.90x10 ⁻³	-2.537	eMzG	Leucogranite
	5	NDP-98A	0.07x10 ⁻³	-4.113	eTnl	Sanukitoid		53	NLD-26ANT	0.23x10 ⁻³	-3.628	hMzG	Sanukitoid		101	NLD-10A	2.92x10 ⁻³	-2.534	eMzG	Leucogranite
	6	NLD-24C	0.08x10 ⁻³	-4.094	eGrd	Sanukitoid		54	NDP-38A	0.24x10 ⁻³	-3.627	eTnl	Sanukitoid		102	NDP-127	2.93x10 ⁻³	-2.533	eMzG	Leucogranite
	7	NDP-128	0.08x10 ⁻³	-4.086	hGrd	Sanukitoid		55	BRM-82A	0.24x10 ⁻³	-3.619	eGrd	Sanukitoid		103	NDP-62	3.01x10 ⁻³	-2.521	eTnl	Sanukitoid
	8	NDP-88A	0.09x10 ⁻³	-4.036	eGrd	Sanukitoid		56	BRM-66	0.24x10 ⁻³	-3.619	eGrd	Sanukitoid		104	NLD-20B	3.04x10 ⁻³	-2.517	eMzG	Leucogranite
	9	NDP-47	0.09x10 ⁻³	-4.013	eGrd	Sanukitoid		57	NDP-130	0.24x10 ⁻³	-3.614	hGrd	Sanukitoid		105	NLD-11A	3.37x10 ⁻³	-2.472	hGrd	Sanukitoid
	10	NLD-26B	0.09x10 ⁻³	-4.009	hGrd	Sanukitoid		58	NDP-121	0.25x10 ⁻³	-3.603	eGrd	Sanukitoid		106	NLD-04B2	3.45x10 ⁻³	-2.462	eMzG	Leucogranite
	11	NDP-122	0.09x10 ⁻³	-4.004	eGrd	Sanukitoid		59	BRM-38B	0.25x10 ⁻³	-3.602	Enclave	Enclave		107	NLD-24B	3.70x10 ⁻³	-2.431	eMzG	Leucogranite
	12	NDP-120	0.10x10 ⁻³	-4.000	eGrd	Sanukitoid		60	BRM-11B	0.27x10 ⁻³	-3.568	eGrd	Sanukitoid		108	NDP-112A	3.72x10 ⁻³	-2.429	Enclave	Enclave
	13	BRM-10A	0.10x10 ⁻³	-4.000	eGrd	Sanukitoid		61	BRM-116B	0.28x10 ⁻³	-3.552	Enclave	Enclave		109	NLD-17C	3.72x10 ⁻³	-2.429	eMzG	Leucogranite
	14	NDP-105	0.10x10 ⁻³	-3.991	eGrd	Sanukitoid		62	BRM-112	0.30x10 ⁻³	-3.522	eGrd	Sanukitoid		110	NLD-27	3.89x10 ⁻³	-2.410	eMzG	Leucogranite
	15	BRM-44	0.11x10 ⁻³	-3.958	eGrd	Sanukitoid		63	NDP-39B	0.30x10 ⁻³	-3.519	Enclave	Enclave		111	NDP-15B	4.00x10 ⁻³	-2.398	eTnl	Sanukitoid
	16	BRM-13	0.11x10 ⁻³	-3.958	eGrd	Sanukitoid		64	NDP 19A	0.31x10 ⁻³	-3.504	eGrd	Sanukitoid		112	NLD-03A2	4.02x10 ⁻³	-2.396	eMzG	Leucogranite
	17	NLD-04A1	0.11x10 ⁻³	-3.955	hGrd	Sanukitoid		65	NDP-26	0.31x10 ⁻³	-3.501	eGrd	Sanukitoid		113	NDP-117A	4.06x10 ⁻³	-2.391	hMzG	Leucogranite
	18	NDP-101	0.11x10 ⁻³	-3.947	hGrd	Sanukitoid		66	NDP-15C	0.32x10 ⁻³	-3.492	Enclave	Enclave		114	NDP-23	4.23x10 ⁻³	-2.374	pGrd	Sanukitoid
	19	NDP-20	0.12x10 ⁻³	-3.924	eGrd	Sanukitoid		67	NDP-104	0.33x10 ⁻³	-3.486	eTnl	Sanukitoid		115	NDP-42	4.28x10 ⁻³	-2.368	eMzG	Leucogranite
	20	BRM-31	0.12x10 ⁻³	-3.920	eGrd	Sanukitoid		68	NDP-15A	0.33x10 ⁻³	-3.481	eTnl	Sanukitoid		116	NDP-106	4.52x10 ⁻³	-2.345	eTnl	Sanukitoid
	21	NDP-01	0.12x10 ⁻³	-3.913	eGrd	Sanukitoid		69	NDP-08	0.35x10 ⁻³	-3.459	eTnl	Sanukitoid		117	NLD-21	4.84x10 ⁻³	-2.315	eMzG	Leucogranite
	22	NDP-125	0.12x10 ⁻³	-3.910	hGrd	Sanukitoid		70	NLD-06A	0.37x10 ⁻³	-3.435	hGrd	Sanukitoid		118	NDP-91	5.11x10 ⁻³	-2.291	hMzG	Leucogranite
	23	NLD-03B	0.13x10 ⁻³	-3.889	hGrd	Sanukitoid		71	NDP-55	0.37x10 ⁻³	-3.423	eTnl	Sanukitoid		119	NLD-18	5.44x10 ⁻³	-2.264	eMzG	Leucogranite
	24	NDP-51A	0.13x10 ⁻³	-3.882	eGrd	Sanukitoid		72	NLD-22	0.40x10 ⁻³	-3.394	eGrd	Sanukitoid		120	NLD-08	5.62x10 ⁻³	-2.250	eMzG	Leucogranite
	25	NLD-12	0.14x10 ⁻³	-3.863	hGrd	Sanukitoid		73	NDP-30A	0.42x10 ⁻³	-3.372	eGrd	Sanukitoid		121	NDP-89B	5.83x10 ⁻³	-2.234	eMzG	Leucogranite
	26	NDP-100	0.14x10 ⁻³	-3.854	hGrd	Sanukitoid		74	NDP-57B	0.42x10 ⁻³	-3.371	Enclave	Enclave		122	NDP-43A	6.15x10 ⁻³	-2.211	eMzG	Leucogranite
	27	NDP-81A	0.14x10 ⁻³	-3.854	eGrd	Sanukitoid		75	NDP-103	0.44x10 ⁻³	-3.353	Enclave	Enclave		123	NDP-86B	6.21x10 ⁻³	-2.207	Enclave	Enclave
	28	NDP-71	0.14x10 ⁻³	-3.847	hGrd	Sanukitoid		76	NLD-07A	0.46x10 ⁻³	-3.331	hGrd	Sanukitoid		124	NDP-25A	6.33x10 ⁻³	-2.198	pGrd	Sanukitoid
	29	NDP-49	0.14x10 ⁻³	-3.842	eGrd	Sanukitoid		77	NLD-02A	0.51x10 ⁻³	-3.286	hGrd	Sanukitoid		125	NLD-11B	6.45x10 ⁻³	-2.190	eMzG	Leucogranite
	30	NDP-45	0.14x10 ⁻³	-3.838	eGrd	Sanukitoid		78	NDP-57A	0.57x10 ⁻³	-3.240	eTnl	Sanukitoid		126	NDP-93	6.65x10 ⁻³	-2.177	hMzG	Leucogranite
	31	NDP-29	0.14x10 ⁻³	-3.835	eGrd	Sanukitoid	B	79	BRM-63	0.59x10 ⁻³	-3.229	eGrd	Sanukitoid		127	NDP-112B	6.74x10 ⁻³	-2.171	hGrd	Sanukitoid
	32	NDP-125	0.15x10 ⁻³	-3.829	hGrd	Sanukitoid		80	NDP-48	0.70x10 ⁻³	-3.156	eGrd	Sanukitoid		128	NDP-92B	6.93x10 ⁻³	-2.159	hMzG	Leucogranite
	33	NDP-32	0.15x10 ⁻³	-3.818	eGrd	Sanukitoid		81	NDP-118A	0.72x10 ⁻³	-3.139	eMzG	Leucogranite		129	NLD-07B	7.50x10 ⁻³	-2.125	eMzG	Leucogranite
	34	NDP-50A	0.16x10 ⁻³	-3.798	eGrd	Sanukitoid		82	NDP-58	0.77x10 ⁻³	-3.115	eGrd	Sanukitoid		130	NLD-16B	7.80x10 ⁻³	-2.108	hMzG	Leucogranite
	35	BRM-49	0.16x10 ⁻³	-3.795	eQzMzD	Sanukitoid		83	NDP-84A	0.81x10 ⁻³	-3.089	pGrd	Sanukitoid		131	NDP-95A	7.84x10 ⁻³	-2.105	hMzG	Leucogranite
	36	BRM-15	0.16x10 ⁻³	-3.795	eQzMzD	Sanukitoid		84	NLD-29	0.94x10 ⁻³	-3.028	eMzG	Leucogranite		132	NLD-14	8.53x10 ⁻³	-2.069	hMzG	Leucogranite
	37	NDP-68A	0.16x10 ⁻³	-3.795	eGrd	Sanukitoid		85	NLD-10B	0.99x10 ⁻³	-3.004	hGrd	Sanukitoid		133	NLD-28	8.91x10 ⁻³	-2.050	eTnl	Sanukitoid
	38	NLD-24A	0.16x10 ⁻³	-3.790	eGrd	Sanukitoid		86	NDP-70	1.07x10 ⁻³	-2.970	hGrd	Sanukitoid		134	NLD-11C	9.11x10 ⁻³	-2.040	hMzG	Leucogranite
	39	NDP-65	0.16x10 ⁻³	-3.782	eTnl	Sanukitoid		87	NLD-26A*	1.24x10 ⁻³	-2.906	eMzG	Leucogranite		135	NLD-04B1	10.00x10 ⁻³	-2.000	eMzG	Leucogranite
	40	NDP-53	0.17x10 ⁻³	-3.767	eGrd	Sanukitoid		88	NDP-21	1.33x10 ⁻³	-2.876	pGrd	Sanukitoid		136	NLD-16C	11.30x10 ⁻³	-1.947	pGrd	Leucogranite
	41	NDP-82A	0.17x10 ⁻³	-3.761	eQzMzD	Sanukitoid		89	NLD-25	1.52x10 ⁻³	-2.818	eMzG	Leucogranite		137	NLD-03A	11.40x10 ⁻³	-1.943	hMzG	Leucogranite
	42	NDP-37	0.17x10 ⁻³	-3.752	eGrd	Sanukitoid		90	NDP-86A	1.69x10 ⁻³	-2.772	eGrd	Sanukitoid		138	NLD-15B	11.80x10 ⁻³	-1.928	pGrd	Leucogranite
	43	BRM-14	0.18x10 ⁻³	-3.744	eTnl	Sanukitoid		91	NLD-30A	1.74x10 ⁻³	-2.759	eMzG	Leucogranite		139	NLD-20A	12.30x10 ⁻³	-1.910	hMzG	Leucogranite
	44	NDP-56	0.19x10 ⁻³	-3.725	eGrd	Sanukitoid		92	NDP-19B	1.84x10 ⁻³	-2.735	eGrd	Sanukitoid		140	NDP-54	13.10x10 ⁻³	-1.883	eMzG	Leucogranite
	45	NDP-39A	0.19x10 ⁻³	-3.709	eQzDrt	Enclave		93	NLD-16A*	1.90x10 ⁻³	-2.721	eMzG	Leucogranite		141	NLD-17A	17.00x10 ⁻³	-1.769	pGrd	Leucogranite
	46	NDP-44A	0.20x10 ⁻³	-3.703	eGrd	Sanukitoid		94	NLD-31B	2.35x10 ⁻³	-2.628	Enclave	Enclave							
	47	BRM-68A	0.20x10 ⁻³	-3.698	eGrd	Sanukitoid	C	95	NDP-116	2.35x10 ⁻³	-2.628	eGrd	Sanukitoid							
	48	NDP-31	0.20x10 ⁻³	-3.698	eGrd	Sanukitoid		96	NLD-23*	2.38x10 ⁻³	-2.623	eMzG	Leucogranite							

Abbreviations: pTrd = porphyritic trondhjemite; hGrd = heterogranular granodiorite; eTnl = equigranular tonalite; eGrd = equigranular granodiorite; eQzDrt = equigranular quartz-diorite; pGrd = porphyritic granodiorite; eMzG = equigranular monzogranite; hMzG = heterogranular monzogranite.

APÊNDICE A2 - AMPHIBOLE WDS ANALYSES.

Unit	Sanukitoids												Trondhjemite		
Facies	eGrd			eTnl			eQzMzD			pGrd			pTrd		
Samples	NDP-50A			NDP-65			BRM-49			NDP-21			NDP-115		
Analyses	C1 1.1	C1 1.2	C3 2.2	C5 1.2	C5 1.1	C2 2.1	C1 1.2	C1 1.1	C2 1.2	C2 1.2	C2 1.1	C2 1.3	C5 1.2	C5 1.1	C5 1.3
Type	rim	core	rim	rim	core	rim	rim	core	rim	rim	core	rim	rim	core	rim
SiO ₂ (wt%)	49.03	49.20	49.56	48.55	48.80	49.61	50.01	50.31	50.65	47.44	47.23	48.00	48.12	42.61	41.88
TiO ₂	0.50	0.60	0.34	0.58	0.46	0.37	0.46	0.49	0.47	0.68	0.66	0.56	0.25	0.42	0.31
Al ₂ O ₃	6.18	6.00	6.17	6.33	6.39	6.52	5.69	5.44	5.38	7.07	7.22	7.16	7.46	11.15	11.91
FeO*	13.14	13.03	13.28	13.58	13.55	12.12	12.86	12.67	12.17	15.56	15.32	14.53	14.66	18.63	19.40
MnO	0.35	0.37	0.31	0.34	0.33	0.33	0.34	0.32	0.33	0.38	0.37	0.33	0.15	0.19	0.15
MgO	14.18	14.48	14.35	13.97	14.23	14.60	14.65	14.97	15.09	12.49	12.57	12.97	12.92	9.41	8.75
CaO	11.68	11.54	11.52	11.58	11.40	11.69	11.56	11.62	11.48	11.34	11.38	11.60	11.57	11.40	11.25
Na ₂ O	0.83	0.81	0.90	0.96	1.07	0.79	0.83	0.81	0.84	1.01	0.99	0.83	1.02	1.38	1.44
K ₂ O	0.47	0.52	0.44	0.49	0.48	0.45	0.40	0.36	0.36	0.67	0.70	0.70	0.41	1.04	1.23
F	0.0	0.01	0.0	0.08	0.01	0.0	0.0	0.0	0.0	0.15	0.10	0.09	0.00	0.05	0.0
Cl	0.02	0.05	0.00	0.06	0.05	0.03	0.05	0.06	0.03	0.02	0.03	0.05	0.22	0.73	0.90
(O=F-Cl)	1.11	3.34	2.99	3.42	3.07	3.38	2.98	2.76	3.06	2.99	3.46	2.87	3.09	3.13	2.86
Total	97.49	99.95	99.88	99.94	99.86	99.91	99.84	99.81	99.88	99.80	100.03	99.72	99.89	100.16	100.08
Structural formulas on the bases of twenty three oxygen atoms															
Si	7.152	7.145	7.169	7.098	7.087	7.185	7.228	7.244	7.291	6.988	6.968	7.041	7.048	6.453	6.364
^{IV} Al	0.848	0.855	0.830	0.902	0.913	0.814	0.771	0.755	0.709	1.011	1.031	0.959	0.951	1.546	1.635
[T] site	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Ti	0.054	0.065	0.036	0.063	0.050	0.040	0.049	0.053	0.051	0.075	0.072	0.062	0.028	0.047	0.035
^{VI} Al	0.214	0.171	0.222	0.188	0.181	0.298	0.197	0.168	0.204	0.216	0.224	0.278	0.336	0.442	0.497
Fe ³⁺	0.553	0.634	0.625	0.595	0.694	0.499	0.590	0.606	0.559	0.649	0.648	0.542	0.562	0.703	0.740
Fe ²⁺	1.050	0.948	0.980	1.065	0.952	0.968	0.964	0.919	0.906	1.267	1.242	1.240	1.233	1.655	1.725
Mn	0.043	0.045	0.038	0.043	0.041	0.039	0.041	0.039	0.041	0.047	0.046	0.041	0.019	0.025	0.020
Mg	3.084	3.134	3.096	3.045	3.082	3.153	3.157	3.214	3.240	2.744	2.765	2.836	2.820	2.125	1.982
[C] site	4.946	4.934	4.963	4.936	4.949	4.959	4.950	4.947	4.949	4.924	4.927	4.938	4.972	4.952	4.964
Ca	1.824	1.796	1.786	1.814	1.773	1.814	1.789	1.791	1.770	1.790	1.799	1.820	1.815	1.849	1.831
Na	0.175	0.203	0.213	0.186	0.227	0.185	0.210	0.208	0.229	0.209	0.201	0.176	0.185	0.150	0.168
[B] site	1.999	2.000	1.999	1.999	1.999	1.999	1.999	1.999	1.999	1.999	1.999	1.996	1.999	1.999	1.999
Na	0.087	0.096	0.039	0.086	0.074	0.038	0.021	0.017	0.006	0.079	0.081	0.059	0.105	0.255	0.255
K	0.146	0.120	0.082	0.091	0.089	0.084	0.073	0.066	0.067	0.125	0.132	0.131	0.076	0.200	0.238
[A] site	0.233	0.217	0.122	0.177	0.163	0.121	0.095	0.083	0.073	0.205	0.214	0.191	0.182	0.455	0.494
Cations	15.178	15.151	15.085	15.114	15.112	15.080	15.044	15.029	15.021	15.13	15.140	15.12	15.154	15.406	15.457
Al _{IV} ^{IV} _{Al^{VI}}	1.062	1.026	1.053	1.090	1.094	1.113	0.968	0.924	0.912	1.227	1.255	1.237	1.287	1.989	2.133
Fe _T /(Fe _T +Mg)	0.342	0.335	0.342	0.353	0.348	0.317	0.329	0.322	0.311	0.411	0.406	0.386	0.389	0.526	0.554

Abbreviations: pTrd = porphyritic trondhjemite; eTnl = equigranular tonalite; eGrd = equigranular granodiorite; eQzMzD = equigranular quartz-monzodiorite; pGrd= porphyritic granodiorite.

APÊNDICE A3 – BIOTITE WDS ANALYSES.

Unit	Leucogranites and associated granodiorite				Sanukitoids								Trondhjemite			
Facies	eMzG		pGrd		eGrd		eTnl		hGrd		pGrd		pTrd			
Samples	NLD-30A		NLD-16C		NDP-50A		NDP-65		NLD-03B		NDP-21		NDP-113B		NDP-115	
Analyses	C2 1.2	C2 1.1	C1 1.4	C1 1.3	C1 1.1	C1 1.2	C6 1.3	C6 1.2	C6 2.2	C6 2.1	C2 1.2	C1 1.1	C1 1.2	C1 1.1	C2 1.2	C2 1.1
Type	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core
SiO ₂ (wt%)	34.76	36.18	37.54	36.82	38.30	38.05	38.19	38.70	37.31	37.19	38.03	38.23	37.33	37.51	36.82	37.02
TiO ₂	1.27	1.92	2.19	2.17	1.36	1.36	1.33	1.35	2.04	2.07	1.60	1.96	1.87	1.76	1.79	1.72
Al ₂ O ₃	17.22	16.56	16.50	16.13	16.25	16.08	16.32	16.16	16.39	16.44	15.36	15.66	15.72	15.77	15.35	15.30
FeO	22.50	21.55	19.25	19.39	14.85	14.77	13.99	13.90	18.18	18.32	15.61	15.54	18.56	18.02	17.42	17.17
MnO	0.35	0.36	0.35	0.35	0.25	0.25	0.24	0.20	0.17	0.19	0.22	0.20	0.10	0.05	0.13	0.10
MgO	10.22	9.31	10.31	10.21	14.35	14.46	14.47	14.74	11.77	11.69	14.63	13.66	12.43	12.48	13.03	13.00
CaO	0.10	0.04	0.00	0.00	0.12	0.09	0.01	0.00	0.00	0.02	0.00	0.00	0.06	0.03	0.08	0.01
Na ₂ O	0.05	0.08	0.09	0.09	0.12	0.11	0.06	0.07	0.15	0.15	0.09	0.05	0.02	0.11	0.07	0.07
K ₂ O	7.36	9.10	9.25	9.16	8.90	8.10	0.01	0.00	9.30	9.19	9.01	9.15	9.20	9.12	8.97	9.29
F	0.19	0.17	0.37	0.48	0.13	0.14	0.11	0.11	0.27	0.32	0.53	0.53	0.25	0.19	0.24	0.16
Cl	0.02	0.03	0.11	0.13	0.10	0.09	0.03	0.03	0.16	0.16	0.10	0.07	0.41	0.43	0.48	0.51
H ₂ O	5.99	4.73	3.90	4.85	5.20	5.22	5.50	4.90	4.33	4.26	4.85	4.70	4.03	4.42	5.66	5.53
Subtotal	100.04	100.03	99.88	99.80	99.82	99.65	90.26	90.17	100.07	100.02	100.05	99.76	99.96	99.90	100.06	99.92
(O=F-Cl)	0.09	0.08	0.18	0.23	0.08	0.08	0.05	0.06	0.15	0.17	0.25	0.24	0.20	0.18	0.21	0.18
Total	99.95	99.95	99.70	99.57	99.74	99.57	90.21	90.11	99.92	99.85	99.80	99.52	99.76	99.72	99.85	99.74
Structural formulas on the bases of twenty two oxygen atoms, considering all iron as Fe ²⁺																
Si	5.408	5.565	5.668	5.644	5.708	5.694	5.966	6.001	5.620	5.607	5.694	5.723	5.636	5.667	5.632	5.659
^{IV} Al	2.591	2.434	2.331	2.356	2.291	2.306	2.033	1.999	2.379	2.393	2.306	2.276	2.364	2.332	2.367	2.340
[T] site	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Ti	0.149	0.222	0.248	0.250	0.152	0.154	0.156	0.158	0.231	0.235	0.180	0.221	0.212	0.200	0.206	0.198
^{VI} Al	0.566	0.567	0.604	0.558	0.563	0.530	0.971	0.955	0.530	0.529	0.405	0.487	0.432	0.477	0.400	0.417
Fe ²⁺	2.927	2.773	2.431	2.486	1.850	1.848	1.828	1.802	2.290	2.310	1.954	1.946	2.343	2.277	2.228	2.196
Mn	0.046	0.046	0.045	0.046	0.032	0.032	0.032	0.026	0.022	0.024	0.028	0.026	0.012	0.006	0.017	0.013
Mg	2.371	2.135	2.320	2.333	3.188	3.227	3.370	3.407	2.643	2.627	3.265	3.049	2.797	2.810	2.971	2.963
[M] site	6.061	5.744	5.650	5.674	5.787	5.791	6.358	6.348	5.718	5.726	5.832	5.728	5.798	5.771	5.822	5.787
Ca	0.017	0.006	0.000	0.000	0.019	0.014	0.002	0.000	0.000	0.003	0.001	0.000	0.009	0.004	0.014	0.002
Na	0.014	0.024	0.026	0.026	0.033	0.032	0.019	0.023	0.043	0.045	0.026	0.016	0.006	0.034	0.019	0.022
K	1.461	1.786	1.781	1.793	1.673	1.717	0.002	0.000	1.788	1.767	1.721	1.747	1.772	1.757	1.749	1.813
[I] site	1.493	1.817	1.808	1.819	1.725	1.764	0.023	0.023	1.831	1.815	1.747	1.763	1.788	1.796	1.783	1.837
F	0.096	0.082	0.176	0.236	0.060	0.069	0.053	0.056	0.128	0.152	0.252	0.252	0.119	0.091	0.116	0.078
OH	6.218	4.856	3.936	4.959	5.170	5.215	5.736	5.068	4.353	4.285	4.843	4.689	4.056	4.455	5.778	5.641
Cl	0.006	0.006	0.029	0.033	0.025	0.023	0.008	0.009	0.041	0.042	0.025	0.017	0.105	0.111	0.125	0.132
Al total	3.158	3.001	2.935	2.914	2.854	2.836	3.005	2.954	2.909	2.922	2.711	2.763	2.796	2.809	2.767	2.758
Fe/(Fe+Mg)	0.553	0.565	0.511	0.516	0.367	0.364	0.352	0.346	0.464	0.468	0.374	0.390	0.456	0.448	0.428	0.426

APÊNDICE A4 – PLAGIOCLASE WDS ANALYSES.

Unit	Leucogranites and associated granodiorite				Sanukitoids								Trondhjemite					
Facies	eMzG		pGrd		eGrd		eTnl		eQzMzd		hGrd		pGrd		pTrd			
Samples	NLD-30A		NLD-16C		NDP-50A		NDP-65		BRM-49		NLD-03B		NDP-21		NDP-113B		NDP-115	
Analyses	C3_1.2	C3_1.1	C6_1.2	C6_1.1	C1_1.1	C1_1.2	C5_1.1	C5_1.2	C3_1.1	C3_1.2	C4_1.1	C4_1.2	C1_1.1	C1_1.2	C3_1.1	C3_1.2	C2_2.3	C2_2.2
Type	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core
SiO ₂ (wt%)	63.40	63.39	62.18	61.74	59.39	57.61	59.81	60.06	67.69	67.91	61.21	61.34	62.45	62.36	64.42	64.24	64.36	64.17
Al ₂ O ₃	21.79	21.95	22.73	22.96	23.87	25.04	23.44	23.44	18.76	19.19	23.71	23.48	22.57	22.49	21.14	21.16	21.00	21.32
FeO	0.00	0.02	0.02	0.05	0.02	0.02	0.05	0.00	0.05	0.02	0.04	0.03	0.04	0.02	0.04	0.03	0.04	0.05
CaO	3.42	3.61	4.51	4.76	6.10	7.51	5.66	5.59	0.06	0.08	5.54	5.19	4.21	4.22	2.51	2.60	2.66	3.04
Na ₂ O	9.87	9.69	9.03	8.94	8.06	7.21	8.28	8.36	11.76	11.74	8.64	8.66	9.23	9.23	10.35	10.27	10.21	10.07
K ₂ O	0.12	0.11	0.14	0.13	0.11	0.09	0.13	0.17	0.10	0.09	0.13	0.19	0.14	0.15	0.15	0.21	0.10	0.14
SrO	0.24	0.08	0.19	0.21	0.04	0.28	0.13	0.32	0.00	0.07	0.18	0.20	0.15	0.12	0.14	0.21	0.36	0.25
BaO	0.00	0.05	0.20	0.00	0.34	0.09	0.07	0.00	0.00	0.00	0.00	0.02	0.13	0.20	0.00	0.06	0.20	0.00
Total	98.86	98.90	99.03	98.80	97.73	97.87	97.59	97.94	98.42	99.00	99.44	99.08	98.80	98.78	98.76	98.78	98.95	99.03
Structural formulas on the bases of eight oxygen atoms																		
Si	2.837	2.833	2.787	2.773	2.707	2.636	2.728	2.731	3.006	2.999	2.737	2.750	2.798	2.799	2.876	2.872	2.876	2.863
Al	1.149	1.156	1.201	1.215	1.283	1.350	1.260	1.256	0.982	0.994	1.249	1.241	1.192	1.190	1.113	1.115	1.106	1.121
Fe	0.000	0.000	0.001	0.002	0.001	0.001	0.002	0.000	0.002	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.002
Ca	0.164	0.173	0.217	0.229	0.298	0.368	0.277	0.272	0.003	0.003	0.265	0.249	0.202	0.203	0.119	0.124	0.127	0.145
Na	0.856	0.840	0.785	0.778	0.713	0.639	0.732	0.737	1.013	1.005	0.749	0.753	0.802	0.803	0.896	0.890	0.885	0.871
K	0.006	0.006	0.008	0.007	0.006	0.005	0.007	0.010	0.006	0.005	0.007	0.011	0.008	0.008	0.009	0.012	0.006	0.008
Sr	0.006	0.002	0.005	0.005	0.001	0.007	0.003	0.008	0.000	0.002	0.005	0.005	0.004	0.003	0.004	0.005	0.009	0.006
Ba	0.000	0.001	0.003	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.000	0.001	0.003	0.000
Cations	5.020	5.012	5.008	5.012	5.011	5.010	5.012	5.014	5.012	5.009	5.016	5.011	5.011	5.011	5.020	5.022	5.016	5.016
Ab	83.391	82.418	77.717	76.677	70.078	63.095	72.033	72.334	99.162	99.167	73.286	74.340	79.237	79.159	87.440	86.725	86.900	85.061
An	15.958	16.977	21.461	22.577	29.276	36.357	27.234	26.709	0.261	0.355	25.971	24.603	19.961	19.999	11.704	12.114	12.529	14.172
Or	0.650	0.604	0.820	0.745	0.646	0.547	0.732	0.956	0.577	0.478	0.743	1.056	0.802	0.841	0.856	1.161	0.571	0.767

APÊNDICE A5 – TITANITE WDS ANALYSES.

Unit	Leucogranites and associated granodiorite				Sanukitoids						Trondhjemite					
Facies	hMzG		pGrd		eTnl		eQzMzD		hGrd		pGrd		pTrd			
Samples	NLD-16B		NLD-16C		NDP-65		BRM-49		NLD-03B		NDP-21		NDP-113B		NDP-115	
Analyses	C1 3.2	C1 3.3	C1 1.2	C1 1.1	C3 1.2	C3 1.1	C3 1.1	C3 1.2	C4 1.4	C4 1.3	C7 1.2	C7 1.1	C2 1.2	C2 1.1	C3 3.4	C3 3.3
Type	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core
SiO ₂ (wt%)	30.44	30.15	30.33	29.49	30.50	30.28	30.59	30.43	30.80	30.68	30.32	30.15	30.66	30.65	30.09	30.17
TiO ₂	37.24	36.84	37.46	37.18	39.14	38.73	38.51	38.99	38.62	38.81	38.66	37.87	39.50	37.89	38.94	38.28
Al ₂ O ₃	1.70	1.56	1.53	1.53	0.82	0.92	1.21	0.81	1.38	1.05	1.08	1.13	1.18	1.23	1.09	1.24
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.16	1.40	0.04	0.06	0.01	0.00	0.00	0.16	0.01	0.00	0.00	0.02
FeO*	1.76	1.75	1.37	2.11	0.77	0.97	1.24	0.73	1.25	1.02	1.22	1.57	0.79	1.55	1.41	1.56
MnO	0.15	0.16	0.11	0.05	0.06	0.03	0.01	0.09	0.05	0.09	0.07	0.09	0.00	0.08	0.05	0.09
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	26.18	25.57	26.53	25.04	26.77	25.97	26.87	27.17	26.62	26.54	26.22	26.30	27.12	26.37	26.16	26.52
Na ₂ O	0.01	0.02	0.02	0.03	0.01	0.02	0.00	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.05
K ₂ O	0.02	0.02	0.02	0.03	0.03	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.03
Total	97.49	96.06	97.37	95.45	98.25	98.34	98.46	98.31	98.74	98.23	97.59	97.30	99.29	97.80	97.77	97.96
Structural formulas on the bases of five oxygen atoms																
Si	1.017	1.022	1.014	1.007	1.009	1.003	1.011	1.008	1.014	1.015	1.010	1.011	1.004	1.020	1.002	1.005
Ti	0.936	0.939	0.942	0.955	0.975	0.966	0.958	0.972	0.957	0.966	0.969	0.955	0.974	0.948	0.976	0.959
Al	0.067	0.062	0.060	0.061	0.032	0.036	0.047	0.031	0.053	0.041	0.042	0.045	0.046	0.048	0.042	0.048
Cr	0.000	0.000	0.000	0.000	0.004	0.037	0.001	0.001	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000
Fe	0.049	0.049	0.038	0.060	0.021	0.027	0.034	0.020	0.034	0.028	0.034	0.044	0.022	0.043	0.039	0.044
Mn	0.004	0.004	0.003	0.001	0.002	0.000	0.000	0.002	0.001	0.002	0.002	0.003	0.000	0.002	0.001	0.003
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.937	0.928	0.950	0.916	0.949	0.922	0.952	0.964	0.939	0.941	0.936	0.945	0.952	0.940	0.934	0.947
Na	0.000	0.001	0.001	0.002	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.001	0.001	0.001	0.003
K	0.001	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.000	0.001
Fe/Al	0.735	0.795	0.638	0.977	0.670	0.746	0.725	0.645	0.645	0.691	0.000	0.985	0.000	0.894	0.914	0.897

Total iron reported as FeO*

APÊNDICE A6 - EPIDOTE WDS ANALYSES.

Unit	Leucogranites and associated granodiorite						Sanukitoids								Trondhjemite					
Facies	eMzG		hMzG		pGrd		eTnl		eGrd		eMzDrt		hGrd		pGrd		pTrd			
Samples	NLD-30A		NLD-16B		NLD-16C		NDP-65		NDP-50A		BRM-49		NLD-03B		NDP-21		NDP-113B		NDP-115	
Analyses	C1 1.2	C1 1.1	C1 1.3	C1 1.1	C1 1.2	C1 1.1	C1 1.1	C1 1.2	C3 1.2	C3 1.1	C3 2.2	C3 2.1	C6 3.4	C6 3.2	C3 1.1	C3 1.2	C2 1.1	C2 1.3	C3 2.1	C3 2.3
Type	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core
SiO ₂ (wt%)	37.64	37.40	37.86	37.52	37.44	37.38	37.20	37.27	37.49	37.46	37.40	37.04	36.97	31.39	37.58	37.53	37.18	37.16	37.12	36.88
TiO ₂	0.14	0.49	0.11	0.08	0.06	0.07	0.01	0.14	0.11	0.01	0.09	0.15	0.17	30.17	0.00	0.03	0.60	0.28	0.01	0.06
Al ₂ O ₃	22.86	22.05	23.10	19.63	23.36	23.15	22.18	21.91	21.87	21.18	22.98	21.74	20.59	5.43	23.19	22.61	21.16	21.52	23.50	21.61
Fe ₂ O ₃	8.86	15.02	13.43	18.03	12.74	13.05	9.28	14.41	14.91	10.16	13.39	9.66	10.58	2.79	12.95	13.62	9.63	9.65	10.98	10.45
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.06
MnO	0.30	0.22	0.50	0.07	0.39	0.28	0.22	0.14	0.15	0.14	0.17	0.13	0.13	0.07	0.20	0.26	0.08	0.14	0.09	0.12
CaO	22.82	22.70	22.71	22.62	22.73	22.92	22.45	22.98	22.48	22.38	22.88	22.43	22.44	27.15	22.86	22.63	22.60	22.21	21.94	20.66
Na ₂ O	0.00	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.06	0.01	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.06	0.17
K ₂ O	0.02	0.02	0.02	0.03	0.01	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.03	0.01	0.01	0.02	0.03	0.05	0.01	0.03
Total	92.62	97.87	97.70	97.96	96.70	96.85	91.34	96.86	97.02	91.41	96.90	91.15	90.88	97.00	96.78	96.68	91.24	90.97	93.66	89.83
Structural formulas on the bases of thirteen oxygen atoms																				
Si	3.249	3.243	3.254	3.312	3.240	3.238	3.259	3.259	3.274	3.290	3.243	3.258	3.275	2.719	3.252	3.265	3.268	3.272	3.273	3.373
Ti	0.009	0.032	0.007	0.005	0.004	0.005	0.001	0.009	0.007	0.001	0.006	0.010	0.011	1.966	0.000	0.002	0.039	0.018	0.001	0.004
Al	2.325	2.253	2.340	2.043	2.383	2.363	2.290	2.258	2.251	2.192	2.348	2.254	2.150	0.554	2.365	2.318	2.192	2.233	2.442	2.329
Fe ³⁺	0.863	0.945	0.837	1.155	0.800	0.820	0.918	0.914	0.945	1.007	0.842	0.959	1.058	0.273	0.813	0.860	0.955	0.959	0.702	0.693
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Mn	0.021	0.016	0.036	0.005	0.028	0.021	0.017	0.010	0.011	0.010	0.012	0.010	0.010	0.005	0.015	0.019	0.005	0.011	0.007	0.009
Ca	2.110	2.109	2.092	2.139	2.107	2.127	2.108	2.152	2.103	2.106	2.125	2.113	2.130	2.519	2.120	2.109	2.128	2.095	2.072	2.024
Na	0.000	0.001	0.000	0.000	0.003	0.001	0.000	0.001	0.000	0.011	0.002	0.000	0.000	0.003	0.000	0.000	0.003	0.000	0.010	0.029
K	0.002	0.003	0.002	0.003	0.001	0.001	0.000	0.000	0.000	0.002	0.000	0.001	0.004	0.001	0.001	0.002	0.004	0.005	0.001	0.003
Ps%	27.065	29.550	26.354	36.119	25.142	25.769	28.611	28.828	29.572	31.477	26.397	29.855	32.977	33.000	25.583	27.058	30.348	30.044	22.343	22.944

Note: Ps % = Ps = [Fe³⁺ / (Fe³⁺ + Al)] * 100.

APÊNDICE A7 – FE-TI OXIDES WDS ANALYSES.

Unit	Leucogranites and associated granodiorite						Sanukitoids		Leucogranites and associated granodiorite			
Facies	eMzG		hMzG		pGrd		pGrd		eMzG		hMzG	
Mineral	Magnetite						Ilmenite					
Samples	NLD-30A		NLD-16B		NLD-16C		NDP-21		NLD-30A		NLD-16B	
Analyses	Op_1.2	Op_1.1	C1_1.2	C1_1.1	C1_1.2	C1_1.1	C1_1.2	C1_1.1	C4_1.2	C4_1.1	C3_1.1	C3_1.2
Type	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core
SiO ₂ (wt%)	0.01	0.03	0.03	0.04	4.27	0.01	0.03	0.04	0.04	0.03	17.38	0.05
TiO ₂	0.02	0.11	0.03	0.03	4.94	0.43	0.08	0.00	50.50	49.50	43.49	50.17
Al ₂ O ₃	0.02	0.11	0.03	0.05	0.46	0.01	0.01	0.01	0.00	0.02	0.87	0.04
Fe ₂ O ₃	69.00	69.00	69.5	69.22	49.10	68.70	69.10	69.30	3.50	5.20	0.00	3.80
FeO	31.20	31.40	31.3	31.20	36.60	31.40	31.30	31.40	39.90	39.30	36.90	37.30
MnO	0.032	0.08	0.05	0.06	0.02	0.02	0.03	0.04	5.18	5.06	2.89	7.18
MgO	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.05	0.05	0.00	0.03
CaO	0.00	0.00	0.02	0.00	3.61	0.23	0.03	0.00	0.21	0.05	15.70	0.44
Cr ₂ O ₃	0.18	0.17	0.00	0.00	0.00	0.00	0.03	0.26	0.00	0.00	0.00	0.00
V ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.27	100.74	100.96	100.60	99.12	100.81	100.57	100.80	99.39	99.21	117.23	99.03
Magnetite: Structural formulas on the bases of four oxygen atoms								Ilmenite: Structural formulas on the bases of three oxygen atoms				
Si	0.000	0.001	0.001	0.001	0.159	0.000	0.001	0.001	0.001	0.001	0.343	0.001
Ti	0.000	0.003	0.001	0.001	0.139	0.012	0.002	0.000	0.965	0.949	0.646	0.961
Al	0.001	0.005	0.001	0.002	0.020	0.001	0.000	0.001	0.000	0.001	0.020	0.001
Fe ₃ ⁺	1.991	1.981	1.995	1.994	1.382	1.974	1.991	1.988	0.067	0.100	0.000	0.073
Fe ₂ ⁺	1.001	1.002	0.998	0.999	1.145	1.002	1.002	1.001	0.848	0.838	0.610	0.795
Mn	0.001	0.003	0.000	0.002	0.000	0.000	0.001	0.001	0.111	0.109	0.048	0.155
Mg	0.000	0.000	0.001	0.000	0.007	0.000	0.000	0.000	0.002	0.002	0.000	0.001
Ca	0.000	0.000	0.001	0.000	0.145	0.010	0.001	0.000	0.006	0.001	0.332	0.012
Cr	0.005	0.005	0.000	0.000	0.000	0.000	0.001	0.008	0.000	0.000	0.000	0.000
V	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	2.000	2.000	2.000	1.999
% Usp	0.05	0.33	0.09	0.08	15.6	1.25	0.23					

Note: Ratio of FeO e Fe₂O₃ calculated according to Carmichael (1967); Ulvöspinel (% Usp) calculated according to Lindsley & Spencer (1982).