**UNIVERSIDADE DE BRASÍLIA**
Instituto de Geociências
Programa de Pós-Graduação em Geologia

TESE DE DOUTORADO

**LUCAS SANTOS BATISTA TELES**

# DEPÓSITOS DE AGROMINERAIS DA FAIXA DE DOBRAMENTOS BRASÍLIA: GEOLOGIA, CARACTERIZAÇÃO E POTENCIAL

**Brasília, Novembro de 2023.**

IG | Instituto de Geociências

PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA

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# DEPÓSITOS DE AGROMINERAIS DA FAIXA DE DOBRAMENTOS BRASÍLIA: GEOLOGIA, CARACTERIZAÇÃO E POTENCIAL

TESE DE DOUTORADO APRESENTADA AO INSTITUTO DE GEOCIÊNCIAS DA UNIVERSIDADE DE BRASÍLIA PARA A OBTENÇÃO DO TÍTULO DE DOUTOR EM GEOLOGIA NA ÁREA DE CONCENTRAÇÃO DE PROSPECÇÃO E GEOLOGIA ECONÔMICA.

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*“Cansei de ser passivo na mudança*
*Quero trazer mudança enquanto ainda estou vivo*
*Não quero que nossos filhos tenham nossos medos*
*Por isso meu trabalho transmite esperança.”*

**SID**

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# RESUMO

O agronegócio é um dos principais componentes do Produto Interno Bruto brasileiro, sendo inclusive reconhecido internacionalmente por sua força e expectativa de desenvolvimento crescente. No entanto, a dependência externa de insumos, em especial dos elementos fósforo (P) e potássio (K) para a fabricação de fertilizantes, representa uma fragilidade que impõe a atual necessidade de evolução da pesquisa e exploração do setor de agrominerais. Atualmente, a produção nacional de fosfato é basicamente oriunda de complexos alcalinos carbonatíticos e o real potencial dos depósitos sedimentares permanece incerto, o que contraria a tendência mundial. Para o potássio, o cenário ainda é mais crítico, tendo em vista que todas as bacias do hemisfério sul são naturalmente empobrecidas no elemento devido a sua evolução geológica. Dentro dessa questão, surge o interesse nas rochas dos grupos Vazante e Bambuí, inseridos na Porção Externa da Faixa de Dobramentos Brasília e que hospedam depósitos conhecidos de P e K. Por mais que esses depósitos já tenham sido abordados na literatura, o número de trabalhos focados na caracterização geológica dessas áreas é bastante reduzido e carente de novos dados e modelos que fomentem a discussão e consequente evolução do conhecimento acerca dos depósitos sedimentares de agrominerais. Com o principal objetivo de preencher essa lacuna, a presente tese de doutorado propõe uma descrição detalhada das rochas, associações faciológicas, ambientes deposicionais e modelos genéticos dos depósitos sedimentares fosfáticos do Tipo Coromandel-MG, Tipo Campos Belos-GO e finalmente, para o depósito potássico de Cedro do Abaeté-MG. O depósito Tipo Coromandel-MG ocorre inserido na Formação Retiro, base do Grupo Vazante e apresenta uma intrínseca relação entre uma Unidade Rudácea, composta por diamictitos polimíticos, arenitos conglomeráticos e arcóseos finos e a Unidade Fosfatada. As fácies fosfatadas compreendem Fosforitos Laminados, Fosforitos Brechados e Siltitos Fosfatados que apresentam teores de $P_2O_5$ variando de 2% a 34%. Devido as correlações de campo e evolução da bacia Vazante, essas rochas foram interpretadas como a materialização da sedimentação ocorrida em ambiente glaciomarinho, onde as condições físico-químicas favoráveis, a precipitação fosfática, foram diretamente controladas por geleiras terminais, em um mecanismo classificado como depósitos de fosforitos de capa (“*cap phosphorites*”) em analogia e semelhança com os dolomitos glaciais já amplamente abordados. De forma semelhante, o depósito do Tipo Campos Belos-GO, enquadrado no contexto da Formação Sete Lagoas, base do Grupo Bambuí, também apresenta uma relação inerente entre a Unidade Fosfatada e os diamictitos da Formação Jequitaí. Tal unidade é subdividida nas fácies Fosforito Estratificado/Laminado, Fosforito Brechado, Fosforito Pedogenético e Siltito Fosfatado, nas quais os valores de $P_2O_5$ variam entre 4% e até mais de 30%. Por mais que os modelos genéticos entre os depósitos do Tipo Coromandel e Campos Belos possuam suas similaridades, alguns outros fatores genéticos cruciais não permitem o mesmo enquadramento. A ação do paleo relevo, incluindo paleo canais encaixados nas rochas graníticas da Suíte Aurumina ou arcóseos do topo do Grupo Araí são controles fundamentais nos depósitos e que, conjuntamente com assembléia mineral mais simples, fácies de minério e interpretações ambientais distinguem os dois modelos. O depósito potássico de Cedro do Abaeté está inserido na Formação Serra da Saudade, topo do Grupo Bambuí. O depósito é composto por pelitos exóticos de coloração esverdeada denominados de verdetes e possui relatos de teores de $P_2O_5$, em média de 8%, porém com locais pontuais com até 34%, entretanto, a importância econômica do depósito se dá pela presença de teores de 7% a 14% de $K_2O$ espacializados em um massivo volume de verdetes. A partir dos dados de magnetometria, gamaespectrometria, geoquímica e mineralogia é possível relacionar a gênese dos verdetes a intrusões alcalinas profundas do Grupo Mata da Corda e interpretar a mineralização como resultado de metassomatismo potássico dos sedimentos pelíticos primários, em razão da circulação dos fluídos oriundos dessas intrusões. Finalmente, os novos dados adicionados com as novas interpretações genéticas e seus respectivos vetores exploratórios são poderosas ferramentas para a ampliação, tanto do conhecimento, como também no âmbito de exploração e suprimento do mercado nacional de agrominerais.

# ABSTRACT

Agrobusiness is a crucial component of Brazil's Gross Domestic Product and is internationally recognized for its robustness and prospects for ongoing growth. However, the reliance on imported inputs, particularly phosphorus (P) and potassium (K) for fertilizer production, is a significant vulnerability for the economic future of Brazil. This dependence underscores the urgent need for advancements in research and development in the agromineral sector. Presently, Brazil's phosphate production primarily comes from carbonatite alkaline complexes, but the true potential of sedimentary deposits remains underexplored, diverging from global patterns. In terms of potassium, the situation is even more challenging. All basins in the southern hemisphere inherently lack this element due to their geological history. This context highlights the importance of the Vazante and Bambuí groups' rocks in the External Portion of the Brasília Fold Belt, which are known to contain significant P and K deposits. Despite existing literature on these deposits, there is a scarcity of studies focusing on their geological characterization. This gap hinders the generation of new data and models that could drive forward our understanding of sedimentary agromineral deposits.. Aiming to address this deficiency, this doctoral thesis presents a comprehensive analysis of the rocks, facies associations, depositional environments, and genetic models of sedimentary phosphate deposits of the Coromandel and Campos Belos types, as well as the potassic deposit of Cedro do Abaeté. The Coromandel Type, found within the Retiro Formation at the base of the Vazante Group, shows a unique interplay between a Rudaceous Unit, consisting of polymictic diamictites, conglomeratic sandstones, and fine arkoses, and a Phosphatic Unit. The Phosphatic Unit includes Laminated Phosphorites, Brecciated Phosphorites, and Phosphatic Siltstones, with P2O5 contents ranging from 2% to 34%. These formations, interpreted as products of glacimarine sedimentation influenced by terminal glaciers, are akin to 'cap phosphorites,' paralleling the well-known glacial dolomites (cap dolomite). Similarly, the Campos Belos Type in the Sete Lagoas Formation at the base of the Bambuí Groupalso exhibits an inherent relationship between the Phosphatic Unit and the diamictite of the Jequitaí Formation. This unit is divided into Stratified/Laminated Phosphorite, Brecciated Phosphorite, Pedogenic Phosphorite, and Phosphatic Siltstone facies, with P2O5 values ranging from 4% to 30%. Despite similarities in the genetic models of the Coromandel and Campos Belos deposits, distinct genetic factors, such as the influence of paleorelief and simpler mineral assemblages, set them apart. The potassic deposit at Cedro do Abaeté, situated within the Serra da Saudade Formation at the top of the Bambuí Group, consists of greenish-colored pelite (verdetes), with an average P2O5 contents of 8% and areas reaching up to 34%. Its economic value lies in its 7% to 14% K2O content within a substantial volume of verdetes. This mineralization is linked to deep alkaline intrusions of the Mata da Corda Group, interpreted as potassic metasomatism of primary pelitic sediments influenced by fluids from these intrusions. In conclusion, the addition of new data and genetic interpretations, along with their exploration implications, are instrumental in expanding knowledge and exploration capabilities within Brazil's domestic agromineral market.

# CAPÍTULO 1 - INTRODUÇÃO

## 1.1 Apresentação

Na última década, devido ao crescente desenvolvimento das grandes províncias agrícolas brasileiras, a necessidade por insumos básicos, utilizados na fabricação de fertilizantes a base de NPK, apresentou um crescimento exponencial. Em consequência do domínio da produção agrícola em condições climáticas tropicais, todo o território nacional, e em especial as áreas cultiváveis, são recobertas por latossolos, que em virtude dos seus aspectos genéticos apresentam-se como uma classe de solos espessos, altamente intemperizados, ácidos, ricos em óxidos, pobres em argilominerais e de baixa fertilidade natural.

Sendo assim, para que ocorra a manutenção da produção do setor, esses insumos básicos, denominados de agrominerais, se tornam de alto valor estratégico para a economia do país. Dentre esses insumos, destacam-se a importância dos elementos fósforo (P) e potássio (K), que juntamente com o nitrogênio (N), são os macronutrientes essenciais para o desenvolvimento das plantações, principalmente daquelas formadas por plantas de ciclos curtos (Malavolta *et al*., 2002) e que compõem a maioria do plantio em larga escala no Brasil. No entanto, o país ainda possui forte dependência externa desses insumos, o que representa uma das maiores fragilidades do setor de agronegócio nacional.

Para se ter uma noção da evolução do comércio e utilização desses insumos, segundo Cruz *et al*. (2017), entre os anos de 2000 e 2015, a utilização de fertilizantes no país cresceu cerca de 87%, sendo que no ano de 2015, 65% do total dos insumos empregados no setor agrícola foram provenientes de importações. Já no ano de 2022, o volume de fertilizantes absorvidos no mercado nacional foi de aproximadamente 38 milhões de toneladas, sendo 86% do total oriundo de importações, como mostram os dados da Associação Nacional para Difusão de Adubos - ANDA.

A partir desses fatos, surge a atual necessidade da evolução do conhecimento geológico e proposição de modelos genéticos robustos que auxiliem na identificação de novos alvos exploratórios, além de novas técnicas de processamento e utilização desses insumos, que atendam aos padrões modernos de crescimento sustentável e resultem no consequente aumento da produção interna. Todavia, mesmo sendo muito dependente da produção externa, o Brasil possui bom e crescente potencial exploratório para agrominerais, fato corroborado pelo Plano Nacional de Fertilizantes proposto pelo Governo Federal no ano de 2021, por meio de uma ação conjunta entre o Ministério da Agricultura, Pecuária e Abastecimento e o Ministério de Minas e Energia, que visa fomentar a produção e distribuição de insumos para a indústria de fertilizantes nacional.

Atualmente, cerca de 80% da produção brasileira de fósforo é de origem a partir de fonte magmática, associada a complexos alcalino-carbonatíticos, geralmente situados ao longo do Azimute 125º (Souza, 2001) e os depósitos sedimentares, associados às bacias proterozoicas, carecem de estudos mais específicos para avaliar a real potencialidade dessas áreas dentro do cenário nacional de produção. As ocorrências de potássio são ainda mais restritas, e os principais depósitos encontram-se associados a sequências evaporíticas das sub-bacias de Taquari-Vassouras e Santa Rosa de Lima (Cerqueira *et al.*, 1997), no estado do Sergipe, além de alguns outros depósitos situados em sequências evaporíticas paleozoicas da Bacia do Amazonas (Friedrich, 1997; Costa & Wanderley Filho, 2008).

Em adição a esses depósitos já conhecidos e explorados, o país possui outros contextos geológicos passíveis da ocorrência de agrominerais, que podem aumentar ainda mais a expectativa de crescimento desse setor de importante relevância econômica e estratégica. Dentre esses contextos, destaca-se o da Faixa de Dobramentos Brasília, com depósitos de rochas fosfáticas e potássicas hospedados nas sequências dos grupos Vazante e Bambuí.

Por um lado, os depósitos de fosfato do Grupo Vazante ocorrem diretamente associados às Formações Retiro (Dardenne, 2000) e Rocinha (Nogueira, 1993), sendo o último reconhecido como a maior acumulação de fosfato sedimentar brasileiro. Na outra vertente, encontram-se os depósitos fosfáticos do Grupo Bambuí, encaixados nas rochas das formações Sete Lagoas (Monteiro, 2009) e Serra da Saudade (Chaves *et al.*, 1971; Dardenne *et al.*, 1986 e Lima *et al.*, 2007). Uma das características de maior importância desses depósitos decorre das altas concentrações de $P_2O_5$ registrados na literatura, como é o caso de Dardenne & Schobbenhaus (2003) que citam valores de 30% a 35% para o depósito de Lagamar, inserido na sequência metarrítmica da Formação Rocinha.

Por outro lado, o depósito da Formação Serra da Saudade é o que apresenta os menores teores de $P_2O_5$ que são em média de 8%, porém em algumas porções, mais influenciadas por processos supergênicos, esses valores alcançam 25% (Lima *et al.*, 2007). No entanto, Lima *et al.* (2007) descrevem valores de $K_2O$ entre 7% e 14% para tal depósito, e tendo em vista o grande volume de áreas mineralizadas, a demanda da indústria por esse insumo, a localização geográfica no centro do Brasil e a evolução da tecnologia de beneficiamento mineral, aumenta-se o valor estratégico de tal depósito.

Finalmente, mesmo que o entendimento geológico acerca da Faixa Brasília e seus depósitos de agrominerais tenha apresentado grande evolução nos últimos anos, várias lacunas de conhecimento persistem. Sendo assim, surge a necessidade da aquisição de novos dados petrográficos, geoquímicos e cartográficos que permitam ampliar o conhecimento, o enquadramento estratigráfico e a caracterização dessas ocorrências, sendo que dessa forma, certamente se abrirão novas perspectivas exploratórias e oportunidades de mercado.

## 1.2 Justificativa

Em consulta ao acervo bibliográfico relativo aos depósitos (depósitos fosfáticos dos grupos Vazante e Bambuí e depósito potássico do Grupo Bambuí) fica claro o pequeno volume de trabalhos focados na descrição geológica e proposição de modelos genéticos que enquadrem ambas as acumulações anômalas e sua evolução ao longo do tempo geológico.

Dentro desse panorama e baseado nos novos dados coletados em campo e processados ao longo do desenvolvimento deste trabalho, a tese se justifica ao apresentar interpretações e modelos genéticos com o intuito de enriquecer e abrir novas portas para a evolução do conhecimento dos depósitos. A quebra de paradigmas de processos genéticos já estabelecidos pode inclusive auxiliar no desenvolvimento de novas rotas para tratamento e recuperação destas substâncias pela indústria de processamento e produção de insumos.

Para o caso do depósito fosfático da base do Grupo Vazante, localizado nas proximidades da cidade de Coromandel-MG, os trabalhos existentes são basicamente os de Barbosa *et al*. (1970) e Dardenne (2000), sendo esse último o primeiro registro da existência de níveis fosfáticos na porção basal do Grupo Vazante. Recentemente, Sousa Marques *et al*., (2021) propuseram um modelo de sedimentação em condições sin- a pós-glaciais para a Formação Retiro e associam a precipitação fosfática à uma expressiva transgressão marinha. Da mesma forma que o trabalho mais atual, a presente tese também converge para interpretações de ambientes sedimentares similares aos descritos pelos autores. No entanto, ainda acrescenta uma possibilidade de fosfogênese mais adequada para o desenvolvimento do depósito em ambiente glaciogênico com paleogeografia coerente com as condições sedimentares.

O depósito fosfático da base do Grupo Bambuí, situado entre as cidades de Campos Belos-GO e Arraias-TO (em outras localidades), da mesma forma que o depósito do Grupo Vazante anteriormente citado, foi inicialmente estudado por Dardenne (2000) e posteriormente mais bem detalhado por Monteiro (2009). Entretanto, os resultados culminaram em uma dissertação de mestrado bem difundida entre os pesquisadores do tema, porém não abarcada por publicação em periódico. Levando em consideração a quantidade e qualidade dos dados existentes e as novas observações das características de fosfogênese, tornou-se possível a elaboração de um artigo com capacidades significativas de acréscimo de informação geológica ao depósito.

Finalmente, no caso do depósito potássico da Formação Serra da Saudade, localizado nas adjacências da cidade de Cedro do Abaeté-MG, a utilização de dados de aerogeofísica, formas regionais de ocorrência, presença de minerais hidrotermais e evidências químicas de metassomatismo potássico possibilitaram uma nova interpretação que inclui a participação de magmatismo alcalino como processo ativo na gênese do depósito.

## 1.3 Objetivos

A tese de doutorado tem dois grandes objetivos principais: avaliar a metalogênese e o potencial dos depósitos (no âmbito da Geologia Econômica) e subsidiariamente contribuir com o enquadramento geológico dos depósitos (contexto da Geologia Regional).

Para se atingir esses objetivos principais, foram estabelecidas metas específicas que podem ser listadas da seguinte forma:

- Apresentar as características geológicas gerais do depósito de fosfato da Formação Retiro (Base do Grupo Vazante);
- Descrever em detalhe as principais rochas da Formação Retiro e propor seu enquadramento faciológico;
- Propor um modelo fosfogenético para o depósito de Coromandel-MG sustentado pelos ambientes deposicionais e baseado em dados de campo, mineralógicos e geoquímicos;
- Apresentar as características geológicas gerais do depósito de fosfato da Formação Sete Lagoas (Base do Grupo Bambuí);
- Descrever em detalhe as principais rochas fosfatadas da Formação Sete Lagoas e propor seu enquadramento faciológico;
- Propor um modelo metalogenético para o depósito de Campos Belos-GO/Arraias-TO sustentado pelos ambientes deposicionais e baseado em dados de campo, mineralógicos e geoquímicos;
- Apresentar as características geológicas gerais do depósito de potássio da Formação Serra da Saudade (Topo do Grupo Bambuí);
- Expor os dados de aerogeofísica, mineralogia e de geoquímica do depósito da Formação Serra da Saudade;
- Propor um modelo metalogenético para a mineralização potássica com base nos novos dados observados;
- Comparar e inserir os depósitos na evolução geológica e temporal da Faixa de Dobramentos Brasília e
- Marcar e identificar os vetores exploratórios que indiquem áreas favoráveis a ocorrência de ambos os tipos de depósitos.

## 1.4 Materiais e Métodos

Para se atingir os objetivos propostos, a metodologia de trabalho foi dividida nas seguintes etapas, incluindo distintas análises e avaliações:

- Revisão bibliográfica com enfoque aos trabalhos clássicos voltados aos principais depósitos de fosfato e potássio, além dos artigos relativos à evolução das bacias proterozoicas do Brasil Central;
- Campanhas de campo para coleta de amostras, observação das relações estratigráficas e refinamento da cartografia dos principais depósitos de agrominerais presentes na Faixa Brasília. Destaque para os depósitos sedimentares de fosfato dos grupos Bambuí e Vazante e de argilas enriquecidas em $K_2O$ do topo do Grupo Bambuí;
- Confecção e descrição de lâminas petrográficas, análises geoquímicas (óxidos de elementos maiores), microscopia eletrônica de varredura (em argilominerais simples e interestratificados) e difratometria de Raios-X em amostras selecionadas de todos os depósitos em discussão;
- Comparação qualitativa e quantitativa entre os modelos metalogenéticos dos depósitos de fosfato e potássio da Faixa Brasília, com destaque para os depósitos da base e topo do Grupo Bambuí e os depósitos tipo Rocinha - Lagamar e tipo Coromandel;
- Avaliação da fisiografia das bacias Vazante e Bambuí, incluindo aspectos sobre os processos de transporte, os ambientes deposicionais e suas respectivas influências nos modelos de mineralização propostos. Esta etapa do trabalho deverá ser desenvolvida a partir da reconstrução de fácies e ambientes, particularmente das fácies mais específicas como glaciogênicas, plataforma carbonática rasa, pelitos de águas profundas etc.;
- Avaliação da solubilidade natural dos diferentes tipos petrográficos enquadrados como fonte de agrominerais ou que sejam potenciais remineralizadores de solos. Neste contexto, é fundamental entender em que fase mineral os elementos de interesse estão associados;
- Publicação de 3 artigos em periódicos relevantes para a área de concentração pretendida.

Ao todo foram realizados 38 dias de campo, divididos em 5 campanhas, sendo que a divisão das atividades foi definida com base na complexidade e tamanho areal de cada depósito. Para a redação dos 3 artigos propostos, foram coletadas inúmeras amostras entre rochas encaixantes, fosfatadas e verdetes, entretanto, um total de 126 acabaram selecionadas devido a sua importância representativa dos ambientes deposicionais. De acordo com o tipo litológico e sua função dentro do contexto, essas amostras selecionadas foram laminadas e analisadas quantativamente. As análises de Fluorescência de Raios X e de Difração de Raio-X ocorreram conforme a rotina sistemática dos Laboratórios de Raio-X e de Estudos Geodinâmicos da Universidade de Brasília. Em adição, os dados químicos relativos aos verdetes, foram adquiridos conforme a rotina de análise de ICP-AES do Laboratório ACME, no Canadá.

### 1.5 Organização da Tese

A presente tese de doutorado está organizada na forma de artigos sucessivos e concatenados, visando demonstrar claramente os objetivos propostos e os resultados atingidos.

O capítulo 1 é referente a Introdução, incluindo a contextualização das áreas estudadas, objetivos principais e específicos, justificativas, materiais e métodos e demais aspectos necessários para enquadramento do tema e entendimento das questões centrais da pesquisa.

Os capítulos 2, 3 e 4 são apresentados na forma de artigos publicados ou submetidos. O capítulo 2 é dedicado às questões geológicas e genéticas do depósito de fosfato da Formação Retiro, base do Grupo Vazante (Depósito do tipo Coromandel-MG). O capítulo 3 é referente ao depósito de fosfato da Formação Sete Lagoas, base do Grupo Bambuí (Depósito do tipo Campos Belos-GO). O capítulo 4 é focado nas características geológicas gerais e principais controles do depósito de potássio da Formação Serra da Saudade, base do Grupo Bambuí.

O capítulo 5 é dedicado as discussões integradas sobre todos os resultados obtidos ao longo do trabalho. Nesse capítulo são apresentadas as principais ocorrências agrominerais da Faixa Brasília, seguidas da indicação dos principais vetores exploratórios, da síntese dos principais controles das mineralizações e indicação da potencialidade a novas descobertas dentro do cenário atual de conhecimento.

O capítulo 6 encerra o trabalho com as conclusões e recomendações pertinentes e necessárias para o contínuo avanço do conhecimento, tanto dos aspectos característicos de cada depósito, como também para o entendimento de suas contextualizações dentro da evolução geológica da Faixa de Dobramentos Brasília.

Finalmente, o capítulo 7 apresenta a lista dos trabalhos citados no corpo da tese e que não fazem parte da seção de resultados, uma vez que cada um dos artigos apresentam as referências bibliográficas consultadas e citadas, na sua parte final.

# CAPÍTULO 2 - ARTIGO 1

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## SEDIMENTOLOGY, STRATIGRAPHY AND GLACIAL GENETIC MODEL OF THE COROMANDEL PHOSPHATE DEPOSIT, VAZANTE GROUP, CENTRAL MINAS GERAIS STATE, BRAZIL

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**Abstract -** The Coromandel phosphate deposit is placed at the external zone of the Brasília Fold Belt and occurs within Vazante Group rocks, more specifically at the Retiro Formation, the lower group unit. This formation is characterized by a glaciogenic facies association that comprises polymictic diamictite, conglomeratic sandstone, fine whitish arcosean, massive and laminated siltstone, besides phosphated facies, including phosphated siltstone, laminated phosphorite and brecciated phosphorite. Field observations show that the phosphatic facies occur in straight relation to the glaciogenic sediments and not rarely directly over diamictite, wich matrix can be phosphated as well. These rocks $P_2O_5$ contents range from 2% to 34% and the succession suggest an establishment of a glaciotransitional environment responsible to constrain favorable alkalinity, temperature and oxirreduction conditions to directly chemical precipitation of fluorapatite in a mechanism analogue as the cap dolomites, supporting an idea of "cap phosphorites". The phosphate source is related to the glacial sedimentary supply of continental origin (granite, carbonatite and other alkaline bearing rocks). In addition, the input of cold water, as result of ice melting episodes, became a limiting development factor for phosphorus metabolizing organism which improves the $P_2O_5$ system enrichment. For the unique genetic conditions, this phosphatic deposit has been called as the Coromandel Deposit Type.

**Keywords** - Sedimentary phosphate, Retiro Formation, Vazante Group, Coromandel Deposit Type, Cap Phosphorites, Glacio related phosphogenesis.

### 1. Introduction

Among the known Brazilian sedimentary deposits, those of the Vazante Group stands out. In the literature, two distinct phosphate levels are described. The first one is related to the Retiro Formation and the second one to the Rocinha Formation, both located at the basal portion of the Vazante Group. In one hand, the Rocinha Formation deposit, which represents the largest accumulation of Brazilian sedimentary phosphate, was initially described by Dardenne et al. (1986) and studied by a series of classic researchers such as Rocha Araújo et al. (1992), Nogueira

(1993), Dardenne et al. (1997), Oliveira (2011), Sanches (2012), Sousa Marques et al. (2015) and Sanches et al. (2016). On the other hand, the Retiro Formation deposit was first described by Barbosa et al. (1970) and only studied by Dardenne (2000) and most recently Sousa Marques et al. (2021).

Based on the previous works and general characteristics, the Rocinha deposit fits well in the proterozoic phosphogenic model, widely discussed by Papineau (2010) and Nelson et al (2010), which suggest that the $P_2O_5$ sources, as well as of Fe, would be the weathering exposed post glacial continental areas where $PO_4^{2-}$ is taken to the sea, forming Fe oxyhydroxides complexes with $PO_4$. In stratified seas, as potentially occurred in the Proterozoic, when reaching the suboxic and anoxic transition zones, due to the movement generated by ascending marine currents, these complexes would be reduced by microorganisms action, releasing P that binds with F and $CO_2$ of the sea water to form carbonate-fluorapatite that precipitates in marine sediments. However, the intrinsically association with glacial facies, mineralogy, distribution of ore ratios and occurrence form suggests that the lower deposit of the Retiro Formation is genetically different from the Rocinha Formation.

Taking account the work scarcity and current need for these inputs, the present paper aims to contribute with new stratigraphic data, faciological description, sedimentary environments proposition and finally introduce a plausible phosphogenetic model for the Retiro Formation geological context. In Brazil, especially on the last decade, the search for new exploratory targets and alternative methods of soil remineralization were driven by the country's high external dependence and increase in phosphate ore prices (Fonseca & Silva, 2014). Unlikely to the world scenario, about 80% of the phosphate explored in the country are of igneous origin, associated with alkaline carbonatitic complexes (Souza, 2001) and sedimentary deposits have always been underestimated at the productive scenario.

## 2. Study Area and Geological Setting

The study area is located at the Coromandel County, State of Minas Gerais, in the Triângulo Mineiro/Alto Paranaíba mesoregion, around 430 km from Brasília, more precisely between the metric coordinates UTM 284.653N to 295.011N and 7.963.329E to 7.984.435E (WGS 84 Horizontal Datum, Zone 23S). Taking the city of Brasília-DF as a reference point, the main access roads are the BR-040 up to the city of Paracatu, Minas Gerais State, from where must follow path along the MG-188 (Alírio Herval Highway) to the city of Coromandel - MG, which the area entrance is finally carried out by BR-352 (Gustavo Capanema Highway) and vicinal farm roads (Fig. 1).

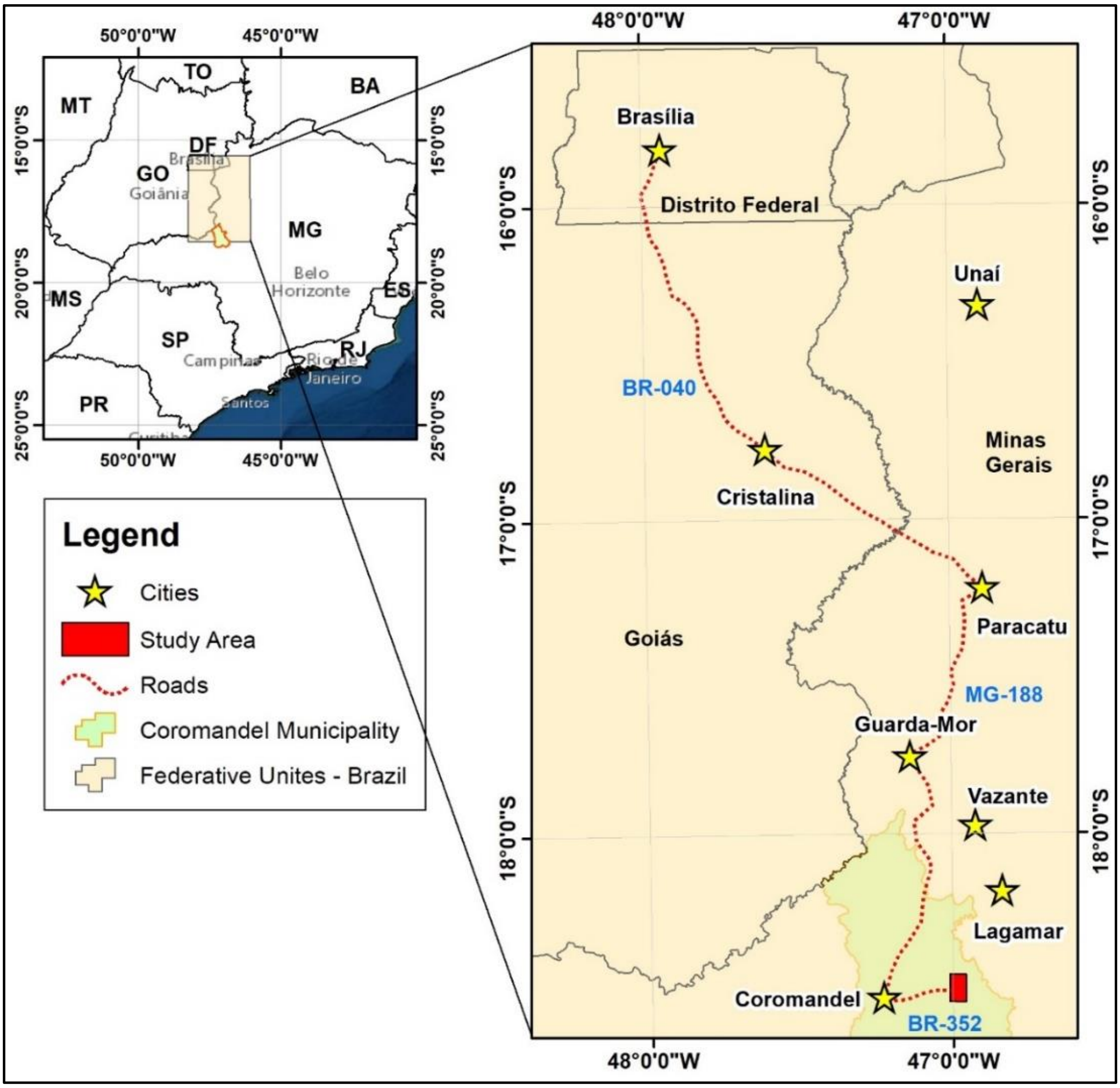



**Fig. 1 -** Map of localization, and main roads of access to the study area.

At the study area outcrops metasedimentary rocks of low metamorphic grade whose chronostratigraphic positioning is still controversial. At least, in part of the successions with rocks related to tectonic contacts. Three rock sets with a wide distribution in the Brasília Fold Belt are potentially present in the regional framework, including the Canastra, Vazante and Bambuí Groups (Fig. 2).

The Canastra Group has a higher metamorphic grade, at low greenschit facies, in the chlorite zone, and contains characteristic rocks such as carbonaceous phyllites and are quartz boudins rich. In this way, its presence in the region is considered by different authors, however the Vazante and Bambuí Groups contain metasedimentary rocks, mostly pelitic, which are often confused and are considered by several authors either present or absent at the studied area. Therefore, in the item referring to the regional geological setting, will be presented the stratigraphy of these three lithostratigraphic sets.

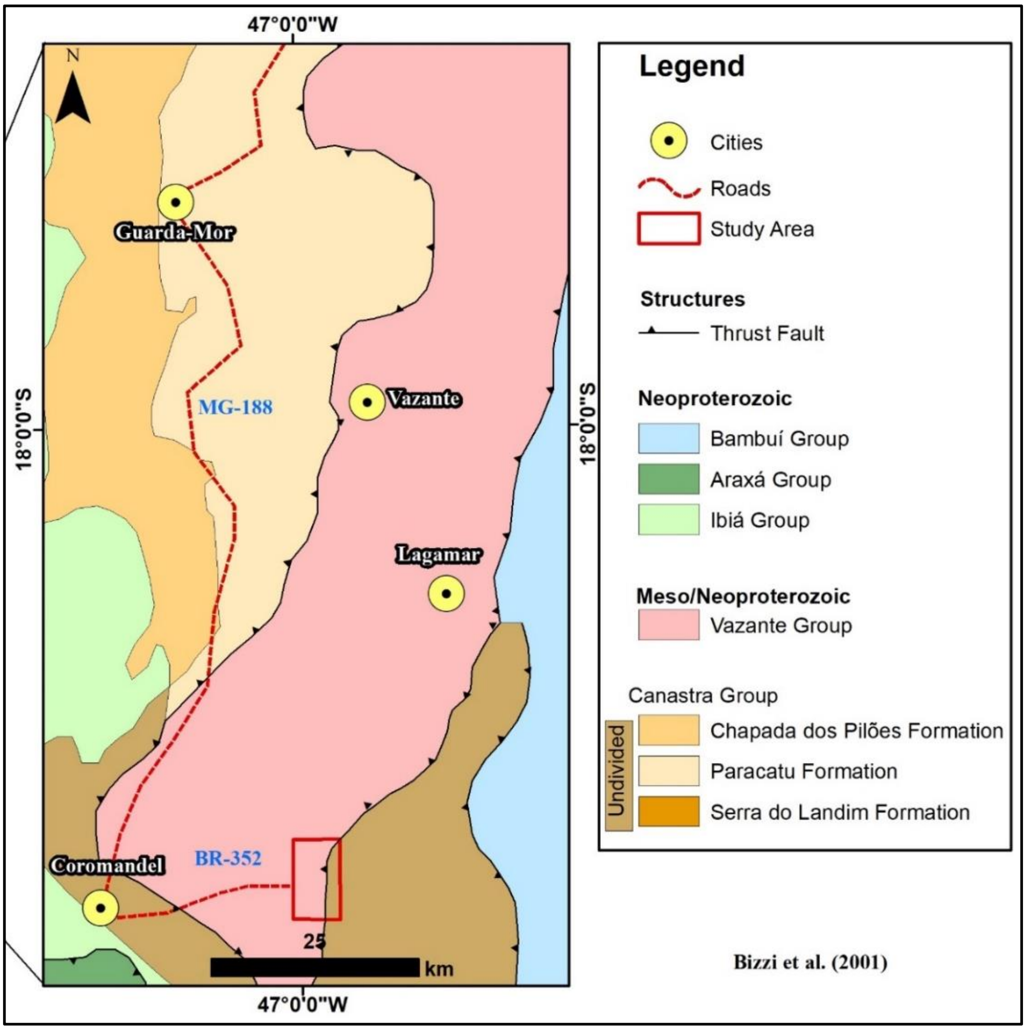



**Fig. 2 -** Regional geologic map (Bizzi et al., 2001) and principal access to the studied area. Original scale 1:650.000.

## 2.1 The Canastra Group

The Canastra Gruop is mostly distributed at the western region of the Minas Gerais State, but the characteristic rocks of the group still outcrop in restricted portions of Goiás and Distrito Federal. It consists of a thick package of pelitic to psamitic metasedimentary rocks with carbonate level associations, deposited on a regressive megacycle (Dardenne, 2000). In metamorphic terms, these rocks present metamorphic degrees that vary from greenschist facies to punctual portions at amphibolite facies, as observed in Tapira region (Silva, 2003).

Freitas Silva & Dardenne (1994) initially divided the Canastra Group stratigraphy into Serra do Landim, Paracatu and Chapada dos Pilões Formations, with Paracatu Formation being further subdivided into Morro do Ouro and Serra da Anta Members and Chapada dos Pilões Formation into the Serra da Urucânia and Hidrelétrica do Batalha Members. After this first work, Dardenne (2000) adopts the division of the group into four distinct formations: Serra do Landim, Paracatu, Serra da Urucânia and Serra do Batalha. The stratigraphic column of Fig.3 summarizes the group succession.

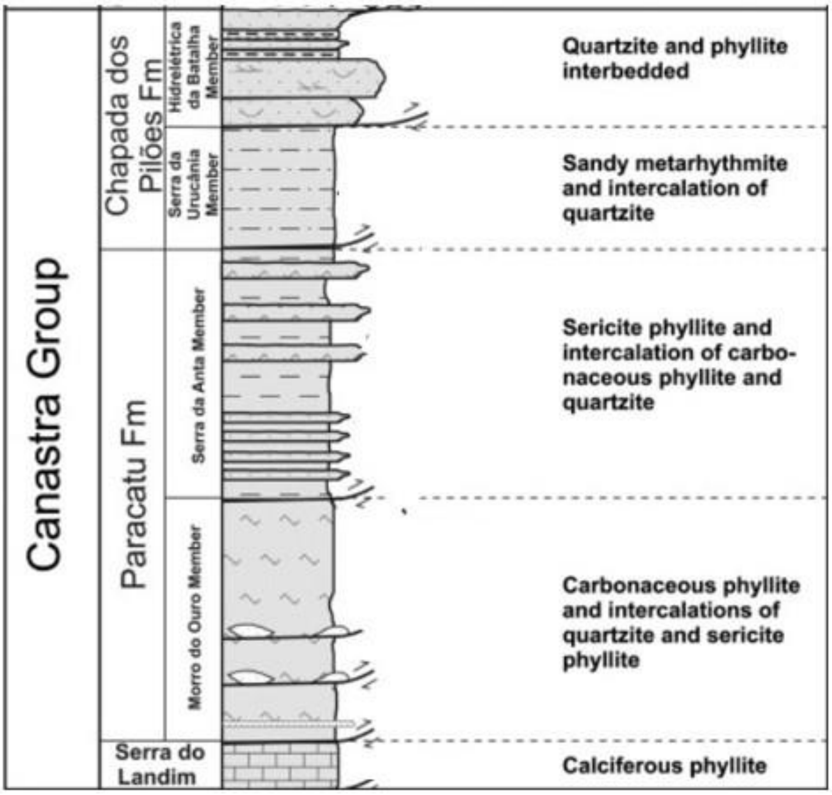



**Fig. 3 -** Canastra Group stratigraphic column (From Sial et al., 2009 in Pimentel et al., 2011).

The Serra do Landim Formation is characterized by the presence of marls and calcareous lenses that grade into calciphyllites and calcischists with rare quartzite intercalations.

The Paracatu Formation occurs immediately superimposed on the Serra do Landim Formation and is subdivided into two members. The basal member, called Morro do Ouro due to its gold content, is basically composed of dark carbonaceous phyllite with fine quartzite intercalations. Just above, there is the contact with the Serra da Anta Member, characterized by the presence of sericite phyllites interspersed with carbonaceous phyllite and fine quartzite.

The Serra da Urucânia Formation is composed of a sandy metarhythmites package with intercalations of fine quartzite, interpreted as deposited in deep to shallow marine environments, with an association of turbidite facies that pass to a storm dominated platform towards the top. Thus, in the set of metassediments, metapelites (phyllites) predominate.

Finally, at the top of the Canastra Group, there is the Serra do Batalha Formation with a large predominance of fine micaceous quartzite. Sedimentary structures such low-angle fishbones and tangential cross stratifications occur with certain frequency and allow the interpretation as a tidal platform deposit.

Detrital zircons geochronological data presented by Rodrigues (2008) indicate a maximum age of deposition about 1.05 Ga. Therefore, this group is currently interpreted as mesoproterozoic age, being chronocorrelate to the Paranoá Group that occurs in the outermost portion of the Brasília Fold Belt.

## 2.2 The Vazante Group

The rock sequence first described by Dardenne (1978) as Vazante Formation was elevated as a group years later (Dardenne *et al*., 1998) and represents a sedimentary carbonate succession deposited on a shallow marine shelf during a regressive cycle (Dardenne, 1981) in a passive margin basin geological context (Fuck *et al*., 1994 and Pimentel *et al*., 2001), which is of great economic interest due to host a variety of mineral deposits (zinc, lead, phosphate, clays and carbonate rocks).

The depositional systems initiated by a shoreface marine environment influenced by a glaciogenic event, passing to a platformal carbonate environment with coastal reef cords that finally ends up with tidal flat deposits. The Vazante Group is a low grade metamorphic sucession subdivided by Dardenne (2000) into seven formations: Retiro, Rocinha, Lagamar, Serra do Garrote, Serra do Poço Verde, Morro do Calcário and Serra da Lapa as shown at the stratigraphic column of Fig.4.

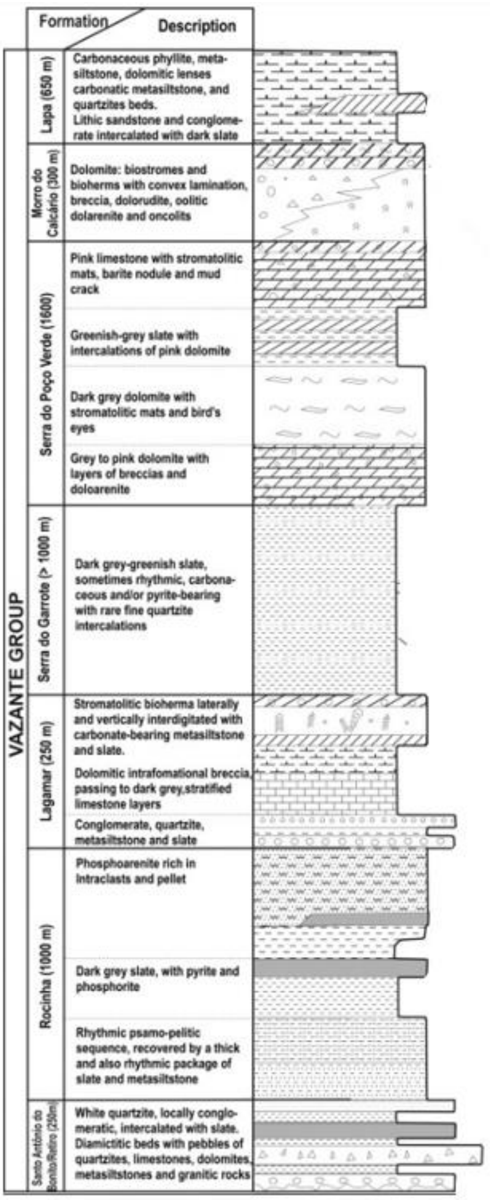



**Fig. 4 -** Stratigraphic column of the Vazante Group (from Pimentel et al., 2011).

The Retiro Formation is defined as an association of metric levels of whitish quartzite with thin pelitic intercalations and matrix-supported polymitic diamictite that grade to portions of polymitic conglomeratic sandstone. The pebbles of this conglomeratic sandstone/diamictite show variety nature, including metapelite, faceted quartzites with “iron flat” form and drag striations structures, granite, tonalite, dolomite and limestone. In direct contact, immediately above these diamictite, which locally have the phosphatized matrix, there are phosphated siltstones and phosphorites, identified by Dardenne (2000) as the phosphorite layer 1.

Just above the Retiro Formation, the Rocinha Formation comprises a rhythmic sequence marked by alternation of pelitic and sandy levels that pass into a thick package of siltstone and pelite with monotonous intercalations. The intercalations are not rarely superimposed by dark and pyritic mudstone with presence of fine phosphatic laminations that alternate between phospharenite and calciferous phospholutite (Nogueira, 1993). This phosphate level is called by Dardenne (2000) phosphorite layer 2 and hosts the world-class deposit of Rocinha (Souza, 1997 and Dardenne et al., 1998). Finally, at the upper portion of the Rocinha Formation, there are sandy rhythmites with phospharenites levels responsible for the Lagamar deposit (Nogueira, 1993), called the phosphorite layer 3.

The Lagamar Formation is subdivided into two distinct members: Arrependido and Sumidouro, where the last one is the first carbonate occurrence in the Vazante Group. The Arrependido Member is basically composed of a basal conglomerate followed by alternating quartzite, metasiltstone and mudstone. At the Sumidouro Member are present stromatolitic breccia followed by stratified dark limestone horizons intercalated by lamellar breccia and dolomite at the top. This dolomite are configured as stromatolytic bioherms forms, which are associated with microbial mats, dolarenites, dolorudites and columnar stromatolites *Conophyton Metula* type (Moeri, 1972; Cloud & Dardenne, 1973).

The Serra do Garrote Formation (Madalosso & Vale, 1978; Madalosso, 1980; Dardenne, 1978; Campos Neto, 1984; Dardenne et al., 1997, 1998), represents the deepest marine sequence of the group, where basically outcrops gray to dark green pyritic and carbonaceous mudstone with rare quartzite intercalations.

In contact with the Serra do Garrote Formation there is the Serra do Poço Verde Formation, which consists of a dominantly dolomitic sequence subdivided into four members: Morro do Pinheiro Inferior, Morro do Pinheiro Superior, Pamplona Inferior and Pamplona Médio. The Morro do Pinheiro Inferior Member is composed of gray to pink massive dolomite and rare dolarenite with carbonaceous and pyritic shale intercalations. The Morro do Pinheiro Superior Member presents dark dolomite with “bird’s eyes” structures and microbial mats, with subordinate amounts of dolarenite and pyritic carbonaceous shale. The Pamplona Inferior Member is characterized by the occurrence of calciferous shale, carbonaceous mudstone and fine dolomitic levels. Finally, the Pamplona Médio Member, which comprises light dolomite with subordinate algal laminations, dolarenitic levels, columnar stromatolite and rare dark shale lenses.

The Morro do Calcário Formation host the lead/zinc deposits and represents the Pamplona Superior Member, formed mainly by dolomite, biostrome and bioherms with convex laminations, dolorudite, oolitic and oncoliths dolarenite.

The upper unit of the Vazante Group stratigraphy is the Serra da Lapa Formation, where a sequence of carbonaceous phyllite and carbonate metasiltstone appears interspersed by dolomitic lenses, also mineralized in lead and zinc, with stromatolites, algal mats and thin quartzite levels.

Based on the Vazante Group stratigraphic succession thick (>2500m), emphasizing the massive presence of dolomitic rocks at the upper portion, Dardenne (1981) and Marini *et al.* (1981) suggest a high subsidence basin context conditioning the deposition. Dardenne (2000) also considers a foreland basin type, formed at the initial stages of the thrust fronts of the Brasília Fold Belt, as responsible for accommodating the sediments of the Vazante Group (Sanches, 2012).

## 2.3 The Bambuí Group

The Bambuí Group is a pelitic-carbonated succession with arkoses at the top portion that occurs in the southern and northern outer portions of the Brasília Fold Belt and even on the São Francisco Craton. In the Brasília Fold Belt, the units of this group that contain carbonates are predominantly pelitic and the carbonate rocks occur as lenses of different dimensions. Over the craton, the carbonates occur as continuous and thick successions that individual layers can be followed for hundreds of kilometers. From bottom to top, five units are recognized, formalized as formations: Jequitaí, Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade and Três Marias (Dardenne, 1978)  represented by the following stratigraphic column of Fig.5

The Jequitaí Formation is composed of glaciogenic diamictite with lateral restricted occurrence and around 40 meters thick. In the clay-silty matrix float quartzite, arkose, granite and carbonate clasts which are angular shaped and variable sized. The nature of the sediments in this unit allows the interpretation of a continental glaciation event from the expansion of ice caps that reached out distal zones of glacial centers (Martins-Ferreira *et al.*, 2013).

The Sete Lagoas Formation is defined, at the Brasília Fold Belt, as interdigitated marl and shale with dolomite and limestone lenses. At the belt, carbonate facies are not predominant; however, they are always recognized in areas undoubtedly related to this unit.

The Serra de Santa Helena Formation is composed of rich detrital muscovite siltstone, generally oriented in the bedding planes. There are rarely fine to very fine sandstone and greywacke layers.

The Lagoa do Jacaré Formation is represented by siltstone and marl intercalated with oolitic and oncolitic organic matter rich limestone lenses deposited on a shallow water platform under wave and storm action.

The Serra da Saudade Formation is essentially pelitic, composed of green laminated shale and siltstone (illite rich) and practically devoid of carbonate and psamite. Lastly, the Três Marias Formation represents the final silting up of the Bambuí basin, being characterized by laminated siltstone intercalated with arkose that are predominating at the top of the unit.

A striking fact in the Bambuí Group stratigraphy is the absence of psamites in the basal units, and the presence of arkosean facies only at the Três Marias Formation. The units where carbonate are present (Sete Lagoas and Lagoa do Jacaré Formations) are devoid of lenses or layers of sandy rocks. Apparently, the relief after the glacial event was flat, with the formation of shallow valleys which did not contribute to the transport and deposition of psamitic sediments to the basin interior.

Warren *et al.* (2014) describes occurrence of Ediacaran guide fossils of *Cloudina sp*. in the Sete Lagoas Formation, which suggests an Upper Ediacaran age for the group, however most authors converge to a neoproterozoic age (600 My), obtained from detrital zircons U/pb analyzes (Pimentel *et al*., 2011).

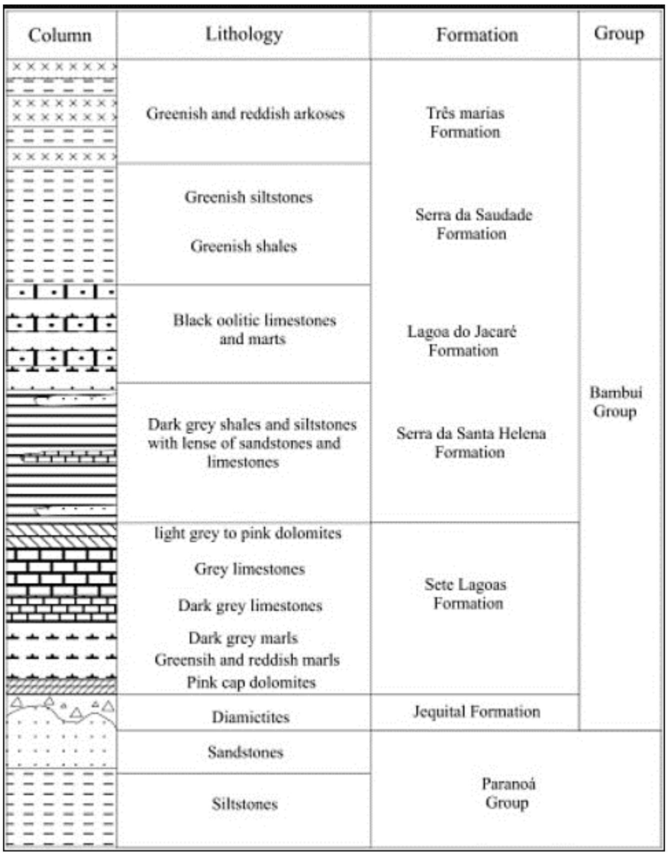



**Fig. 5 -** Bambui Group stratigraphic column showing the formations stacking (From Pimentel et al., 2011).

Based on the geological descriptions of the units and the classic work of Rodrigues (2008), these three groups are not correlated. The Canastra Group seems more likely to represent a regressive cycle deposition at a passive margin basin firsts stage at São Francisco-Congo Craton border in the Neoproterozoic. Otherwise, the Vazante Group is interpreted as a foreland basin sequence that shows younger Sm-Nd sources, possibly deriving from a juvenile arc. Finally, the Bambuí Group is younger than other units and understood as a succession of transgressive and regressive cycles at a foreland basin. Besides the age discussion, nowadays, lot of researches convert to a Cambrian age.

The cartographic product presented at Fig. 6 shows the spacial relationship between the rocks and the regional units at the study area. This map demonstrates that de Vazante Group occurs as a structural window under de Canastra Group nappe, and that the Vazante rocks outcrops at an erosive depression (Santo Antônio river valley).

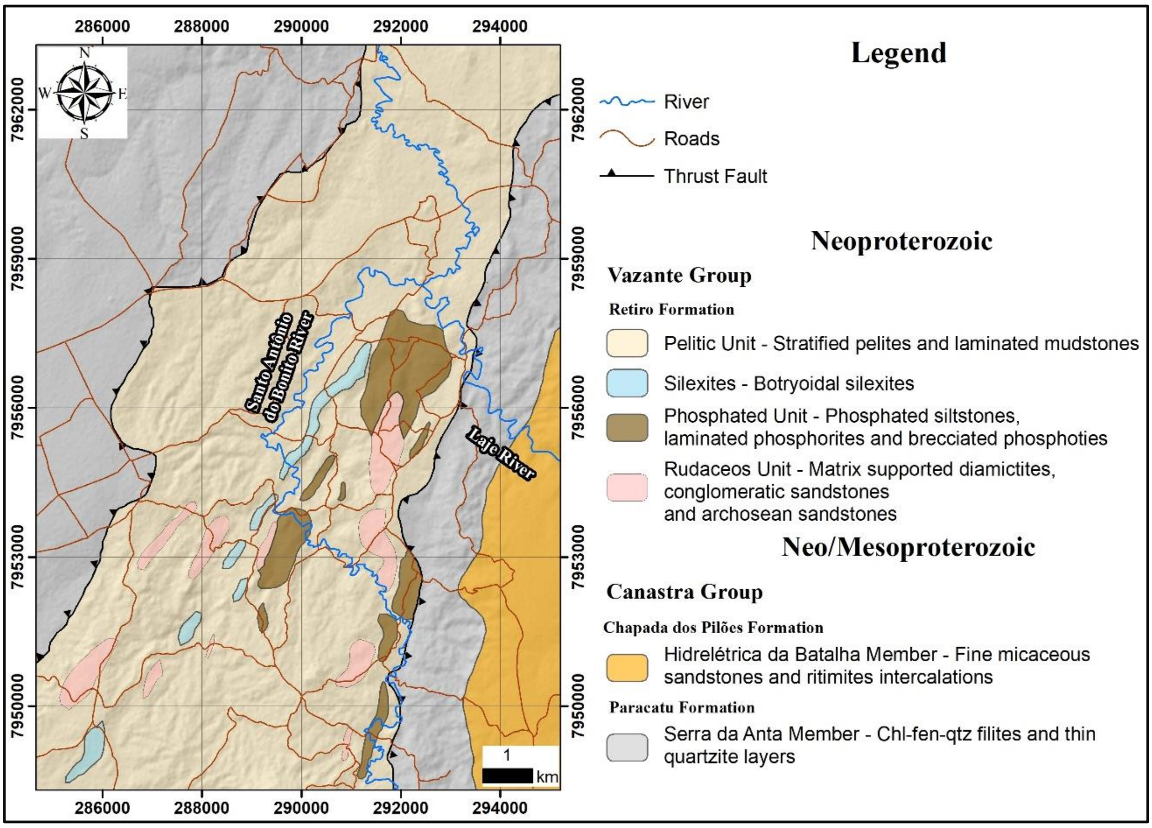



**Fig. 6 -** Geological map of the study area showing the Retiro Formation rocks outcrops.

## 3. Material and methods

This work used already known and traditional field and laboratorial techniques to aims the proposed objectives. At first, the field campaigns were realized based on the Vazante Group classic bibliographic literature and remote sensing interpretation, using images from the *ALOS PALSAR* and *Landsat 8* sensors.

At the field campaigns, were visited 162 outcrops points used to the lithologies characterization, based especially on the siliciclastic rudaceous rock classification and faciological description from the main characteristics of the outcrops and each sedimentation environments. In this amount, 43 hand samples were selected comprising rocks of the siliciclastic and phosphated units of the Retiro Formation. The phosphate rock samples were chosen after field tests (nitric acid attack and ammonium molybdate reaction) with positive results (formation of ammonium phosphomolybdate yellow precipitate). Thin sections of selected samples were studied and the phosphate levels analyzed by X Ray diffractometry and fluorescence.

The preparation of the X Ray samples started with manual pulverization of 7 grams of rock in an agathe disc. The powder was placed in a dug slide (2.0 x 1.5 x 0.005 cm) and the analysis played by a DRX Rigaku - Ultima IV diffractometer, equipped with copper tube, nickel filter under 35Kv/ 15mA and DTEX / ULTRA detector. The scan was performed in the 2θ range from 3° to 80°, step 0.05, speed 1°/min. Minerals were identified using the Jade XRD 9.0 (Materials Data) program with a PC-PDF (Powder Diffraction File - PDF for PC) database.

The preparation of XRF beads consisted of weighing 0.9 grams of sample, 6.0 grams of lithium and 3.0 grams of lithium metaborate, which were homogenized in a platinum crucible with 2 drops of lithium bromide solution (50% w/v) and melted to glazing. After this initial procedure, the samples were inserted in the X Ray Spectrometer Rigaku model - ZSX Primus II, and measured values recalculated to oxides percentage.

## 4. Results

### 4.1 Facies Description

Based on the proposal objectives and the applied methodology, the results basically consist of the faciological descriptions, facies mapping and phosphate rock chemical analysis.

In total, were separated 8 different facies from the main characteristics of the outcrops and sedimentation environments that comprises from base to top: Matrix-Supported Massive Diamictites, Matrix-Supported Massive Conglomeratic Sandstones, Fine Arkoses, Phosphated Siltstone, Laminated Phosphorite, Brecciated Phosphorite, Stratified Pelites and Laminated Mudstones.

*Matrix-Supported Massive Diamictite Facies (Dmm)*

This facies occurs mainly in elongated bodies forms, in which outcrops rocks with clayey matrix and coarse framework, generally quite weathered, which gives a whitish and porous appearance to most of the observed samples. In more preserved portions, the diamictites have a purplish coloration due to a higher proportion of matrix and a great compositional and shape diversity of the clasts.

The diacmictite lithoclasts are mainly composed of pelite, granite, tonalite, dolomite, limestone and predominantly quartzite immersed in pelitic matrix. These lithoclasts are irregular shaped and ranging size from few centimeters pebbles, as the case of most pelitic lithoclasts to metric-sized lithoclasts, as the granite blocks (Fig. 7A). At specific locations, in weathered outcrops, there are vugs generated from the dissolution of carbonatic clasts (Fig. 7B). In less weathered samples, the preserved carbonate clasts can be observed in microscopic thin sections.

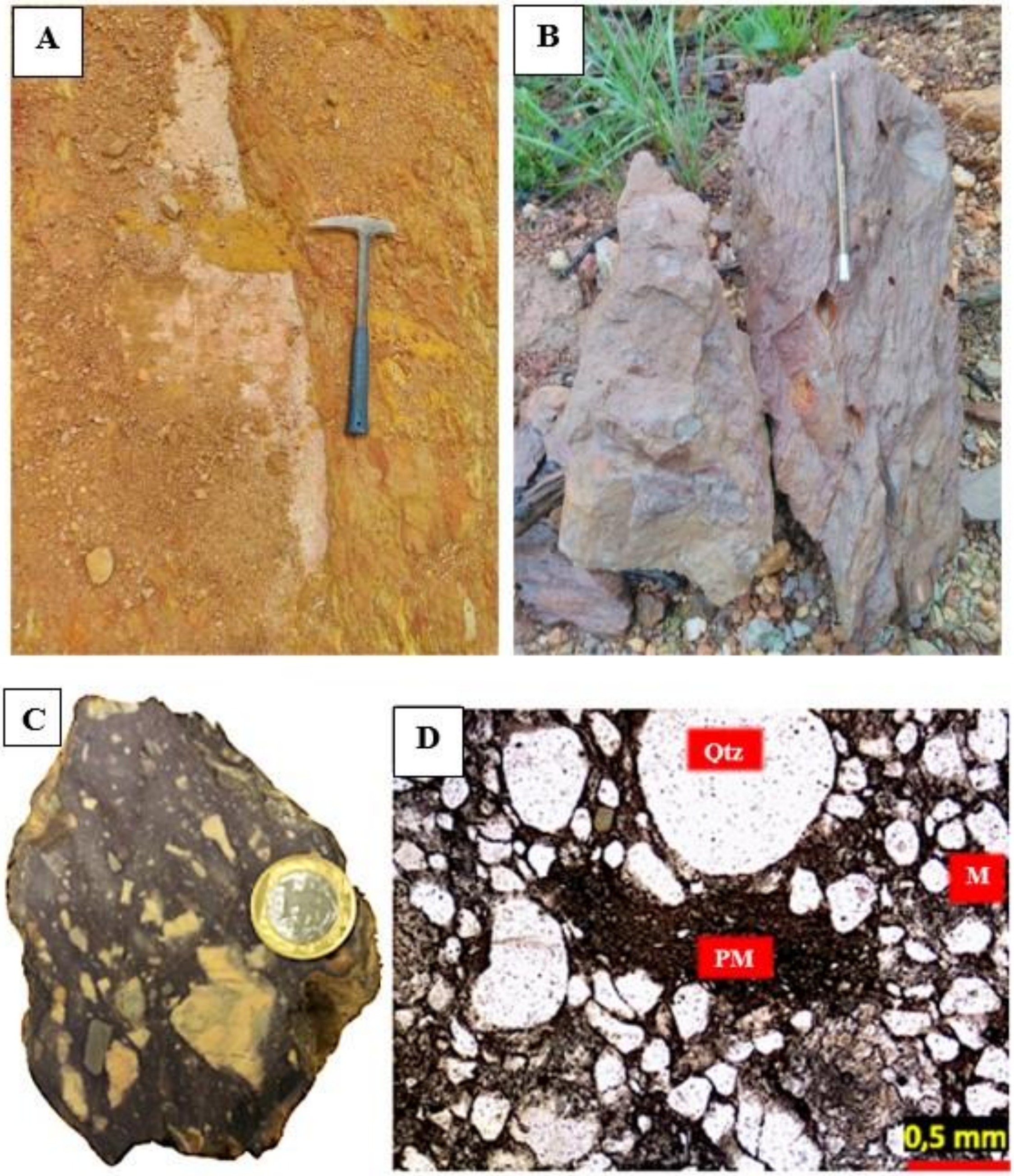



**Fig. 7 - (A)** Decimetric block of weathering granitic rock immersed in the pelitc matrix of the Retiro Formation diamictite. **(B)** Diamictite with ghost clasts cavities probably generated by carbonate dissolution. **(C)** Diamictite macroscopic sample showing the general aspects of these rocks **(D)** Photomicrography of diamictite framework consisting of quartz grains with different degrees of roundness and angularity and pelitic lithoclast arranged in the form of pseudomatrix. (Qtz = Quartz, PM = Pseudomatrix, M = Matrix) (N//, 1.25x).

Petrographically, these diamictite are composed of approximately 60% of matrix, 35% of framework and 5% of carbonate that occurs associated with few lithoclasts (Fig. 7C). The matrix is basically of silt-clay grain size with portions where fine micaceous minerals are present.

At thin section, the framework is composed of 60% poorly selected quartz grains, ranging from 0.1 to 0.8 mm. These grains show the association of different shapes, which alternate between very rounded to angular, typical characteristic of glacial deposits (Fig. 7D). The 40% remaining of the framework is represented by 35% lithoclasts and 5% of rare saussuritized plagioclase grains. The lithoclasts are of angular shapes and ranging sizes from 0.4 mm to 1.5 cm in length. Compositionally, 4 distinct rock types can be observed: pelite, which often acts as a pseudomatrix, greywacke, fine sandstone and dolomite fragments.

*Matrix-Supported Massive Conglomeratic Sandstones Facies (Scmm)*

This facies occurs associated with the vicinities of diamictite bodies and is characterized by the presence of brightly colored and intensely weathered psamitic rock outcrops. Amidst the sandy framework and the finer matrix, there is a great variety of different compositions, size and shape pebbles.

Conglomeratic sandstone pebbles are the same composition as those found in diamictite, but which occur surrounded by a subordinate amount of silty matrix and a large amount of quartz grains with grain size ranging from fine to medium sand. There is an intrinsic relationship between the matrix contents and the number of pebbles in the coarse-grained unit. Much more matrix, smaller the amount of pebbles present, with most comprising lithoclasts of pelitic rocks and quartzite (Fig. 8A and 8B).

In contrast to diamictite, conglomeratic sandstone is a subordinate amount of matrix, which makes up about 10% of the thin section, while the framework represents other 90%. The matrix is basically composed of silty grains, interspersed with quartz grains and a smaller amount of lithoclasts (Fig. 8C).

The framework is formed predominantly (70%) by poorly selected quartz grains with contrasting shapes, as observed in diamictite. These grain sizes vary from 0.2 mm to 0.5 mm, and the fine sand (0.2 mm) predominates throughout the section. The remaining 30% of the framework is composed of monotonous lithoclasts of pelitic rocks and fine quartzites (25%) that vary in size from 0.3 to 0.8 mm and 5% of plagioclase altered to saussurite domains (Fig. 8D).

The extinction of quartz grains varies from straight passing to weakly undulating, which demonstrates the variety of materials that make up its source area, including plutonic to different metamorphic rocks degrees (maybe including granite, gneiss, granulite and other acid felsic rocks).

Due to the quartz grains size variability and thick lithoclasts presence, these rocks have a well-marked conglomeratic texture, as well as massive structure and closed arrangement, marked by the smallest amount of matrix and grains planar contacts.

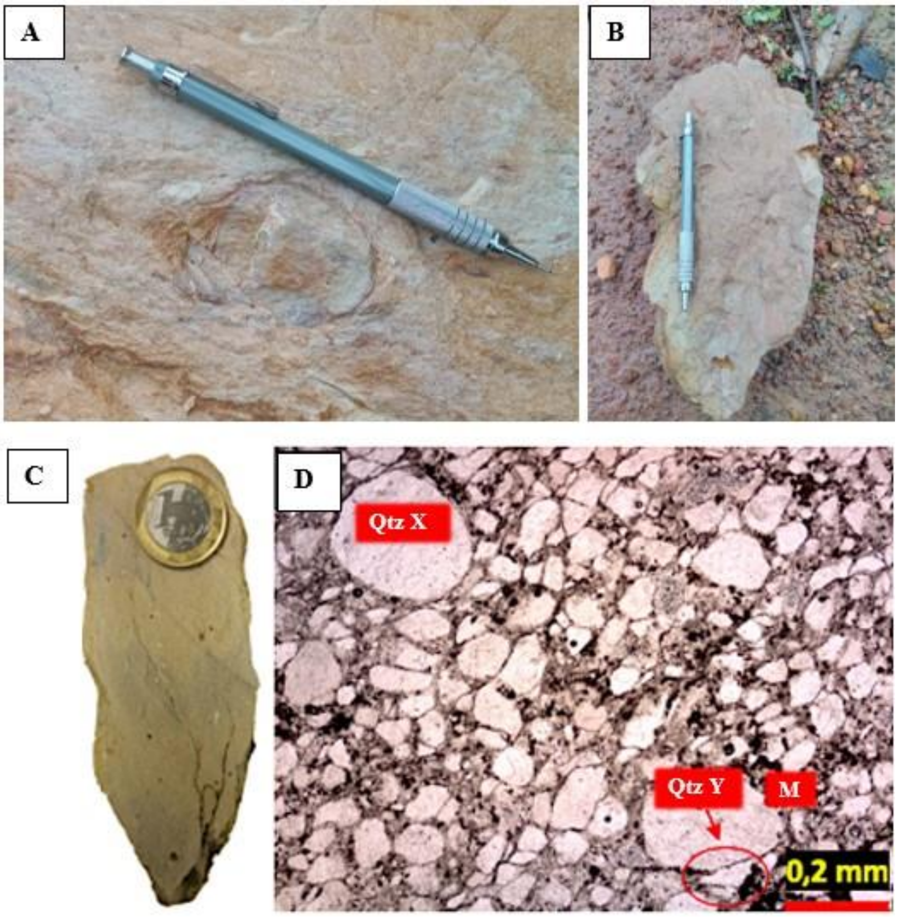



**Fig. 8 - (A)** Conglomeratic sandstones with isolated quartzite pebbles around 4 cm in diameter. **(B)** General aspect of the conglomeratic blocks found in the studied area. **(C)** Macroscopic sample of the arenites where is possible to observe lithoclasts of pelitic and quartizic compositions. **(D)** Photomicrography of conglomeratic sandstone showing the predominance of quartz grains with sizes ranging from 0.12mm to 0.2mm. Note that quartz grains have different degrees of roundness and angularity (Qtz X = rounded quartz grain, Qtz Y = angular quartz grain, M = Matrix) (N// 1.25x).

*Fine Arkose Facies (Saf)*

These rocks occur as decimetric to metric layers intercalated with diamictite and conglomeratic sandstone, with well-preserved bedding and open folds (Fig. 9A and 9B). Outcrops of whitish sandstone occur in the area in a non-systematic way and almost always following a pattern of lenses, which are most pronounced at the marginal regions of the conglomeratic lithofacies.

The arkoses show a massive structure, resulting from the random dissemination of the framework grains through the rock and a closed arrangement, where the grains touch each other through punctual and planar contacts, but it is not uncommon to observe concave-convex contacts (Fig. 9C).

Under the petrographic microscope, these rock facies is formed by 90% of framework grains and only 10% of silty-clay matrix, which occurs only associated with specific locations of the thin section. The framework grains are predominantly composed of quartz (85%) and plagioclase (15%). These grains are moderately selected, sub-angular and fine sand size (0.15 mm) (Fig. 9D).

Thus, from the observed petrographic characteristics, it is noted that the transition from the base to the top of the first association of lithofacies is marked by a gradual decrease in the amount of matrix and framework lithoclasts, as well the modal increase of psamitic phase.

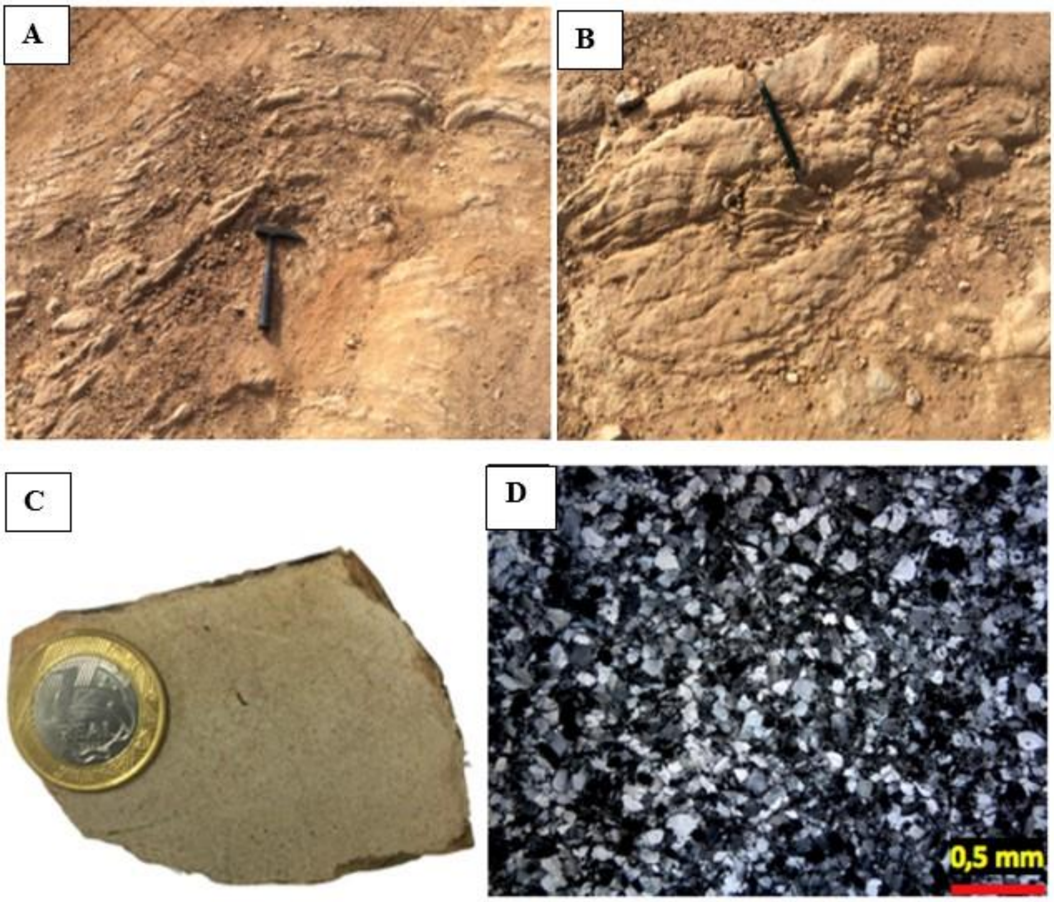



**Fig. 9 - (A)** Outcrop of fine whitish archosean sandstone smoothly folded. **(B)** Exposed detail of whitish archosean sandstone showing primary sedimentary bedding of decimetric thick. **(C)** Macroscopic sample of the archosean sandstone showing the massive aspect of these rocks. **(D)** Photomicrography of the general granulometric tendency (0.15mm), moderate selection and subangular to angular shaped form quartz grains (NX 4x).

*Phosphated Siltstone Facies (Sph)*

Phosphate siltstone represents the most expressive facies at phosphatic unit rocks and generally outcrops at the vicinity of the rudaceous facies as soft hills (Fig. 10A). This siltstone facies, especially the most preserved from weathering has a predominant dark color that contrasts with minor domains of whitish color.

In macroscopic terms, phosphate siltstones exhibit discontinuous, black-colored and plane-parallel laminations composed of phospholutite which show a strong reaction to ammonium molybdate (Fig. 10B). The rest of the rock is basically formed by terrigenous grains of silty and silty-clay mixtures.

As the weathering processes take place, the siltstone is altered and the phosphate is completely leached. As a result of this process, the most preserved outcrops are found only in recent cuts and most siltstones occur as saprolites with colors ranging from greenish gray to pale yellow and show little or no reaction to ammonium molybdate.

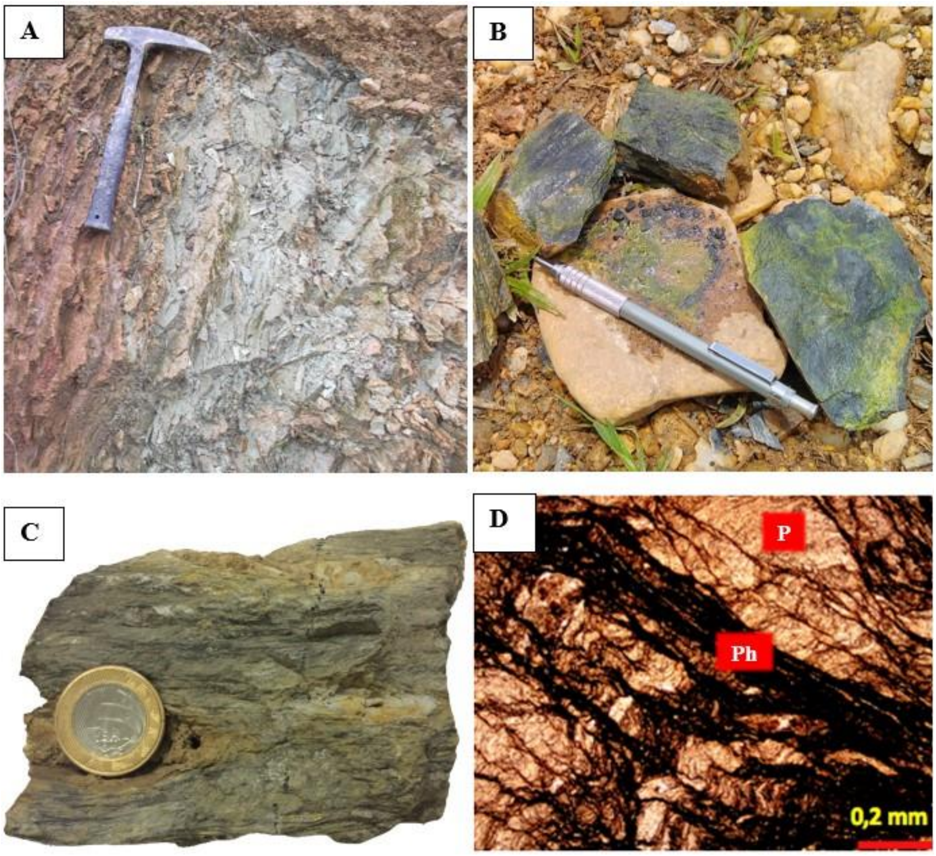



**Fig. 10 - (A)** Weathering phosphated siltstone in road cut showing the comum preservation stage of the facies. **(B)** Most preserved blocks with intense ammonium molybdite reaction, especially at the dark-colored laminations, suggesting higher concentrations of colofanite at these portions. **(C)** Macroscopic sample of the phosphated siltstone exhibiting the laminar aspect of pelitic and phosphatic composition arrangement. **(D)** Photomicrography showing two different portions of the phosphate siltstone. The lighter portions are basically pelitic composition and phospholutite dark laminations (P= Pelitic, Ph= Phosphatic) (N// 2,5x).

Due to the thick siltstone saprolite covers, it can be empirically inferred that the phosphate in the region is of high solubility and easily removed from the surface portions. This characteristic is corroborated by fact that the fluorapatite present in these rocks are of clay size, which increases the area of contact of the grains with meteoric fluids and consequent solubilization.

Under the petrographic microscope, phosphate siltstone is composed of 85% silty/clay-sized grains of terrigenous components and 15% of phospholutite that occurs as fine millimeter sheets pervasively distributed throughout the rock (Fig. 10C). Commonly, pelitic intraclasts with sizes ranging from 0.2 mm to 0.5 mm are observed bordered by phospholutite and filled with fractures by fine quartz and apatite crystals. Due to the relief similarity and interference colors of these minerals, it is difficult to distinguish them under polarizing light (Fig. 10D).

Phospholutite sheets, on the other hand, contrast with the terrigenous portion and show a structure that suggests the concomitant precipitation of phosphate minerals and pelitic muddy. This feature is marked by the alternation of laminae interspersed with the pelitic part and festooning of intraclasts in syn-digenetic phases.

*Laminated Phosphorite Facies (PHl)*

Laminated phosphorite, unlike siltstone, occurs arranged as densely vegetated mounds with smoothed and rounded slopes. These rocks are characterized by intercalation of dark phospharenite sheets with ranging thick from a few millimeters to 1 cm and thicker pale beige sheets composed of phospholutite (Fig. 11A and 11B). At the superficial portions of mounds, phosphorite outcrops as intense silified small blocks that have little or no reaction to ammonium molybdate, but still preserve the primary structures. At areas preserved from weathering it can be found less altered blocks that strongly react to ammonium molybdate.

In thin sections, phospholutite (colophanite) occurs as massive domains associated to rare disseminated phosphointraclasts with an average size of 0.1 mm. The smallest amounts of phosphointraclasts, together with the largest amounts of phospholutite, mark the transition between the phospharenite sheets. At the dark laminae, in turn, there is a significant increase in the amount of phosphointraclasts ranging in size from 0.1 mm to 0.3 mm, which form a portion of phospharenite that is easily identified both on thin section and on macroscopic analysis (Fig. 11C and 11D).

In addition to phosphate intraclasts, phospharenite have small vugs and fractures that are filled with fine wavellite crystals. The wavellite crystals are arranged radially, suggesting subsequent cavities filling.

Unlike phosphatic siltstone, where the phosphatic laminations are totally isotropic, in laminated phosphorite, the entire phosphatic assembly has a reddish color that suggests more evident weathering actions and the presence of iron oxide colloids.

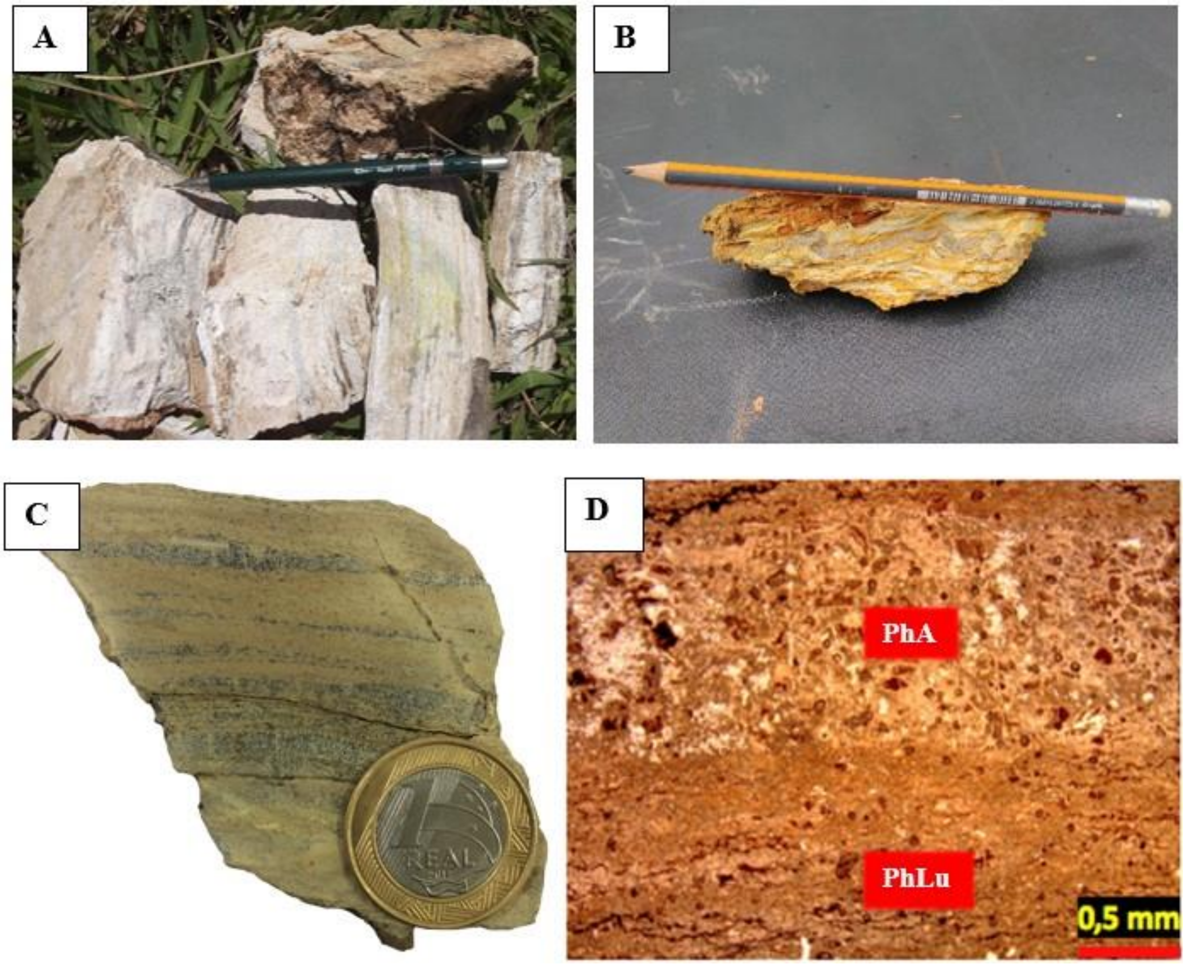



**Fig. 11 - (A)** Macroscopic sample of laminated phosphorites with ammonium molybdate positive reactions. **(B)** Macroscopic sample of laminated phosphorite showing smoothly banded phospharenite layers. **(C)** Macroscopic sample of laminated phosphorites evidencing the the visual aspects between the whitish phospholutite portions and the dark laminations of phospharenites. **(D)** Photomicrography exhibiting phospholutite layers basically composed of colofanite and the phospharenite layer as phosphointraclasts accumulation (PhA - Phospharenite, PhLu - Phospholutite, 1,25x N//).

*Brecciated Phosphorite Facies (PHb)*

The last phosphated facies is marked by the brecciated phosphorite. These rocks outcrop in the area like small botryoidal shape form blocks with intense silicification, usually associated with middle portions of the laminated phosphorite occurrences. The main distinguish factor between these facies is that the brecciated phosphorite did not preserve the primary structures like sedimentary lamination. In general, the brecciated phosphorite facies is characterized by concretionary and nodular textures marked by presence of laminated phosphorite intraclasts intertwined with whitish matrix of phospholutite. In addition, it still possible to be observed quartz segregation domains and cavities filled up by the same mineral. Reactions to ammonium molybdate occur throughout the whole rock, but are more prominent in matrix-dominated sites, suggesting supergenic $P_2O_5$ accumulation in these portions (Fig. 12A).

The friable aspect of these rocks makes it considerably difficult to make thin sections, but one of the most preserved blocks could be sliced (Fig. 12B). Under the petrographic microscopy, this phosphorite is mostly (75%) composed of a phospholutite matrix with a brownish color, due to the oxidation of iron colloids, which leaches portions of quartz crystals (25%), resulting from the segregation of silica during the weathering process (Fig. 12C). Quartz crystals show sizes ranging from 0.2mm to 1.0mm and compose granular pockets with well-marked edges that corroborate the idea of a subsequent filling due to circulation of siliceous fluid (Fig. 12D). Locally, more rounded grains occur and are interpreted as detrital clasts, defined as extraclasts.

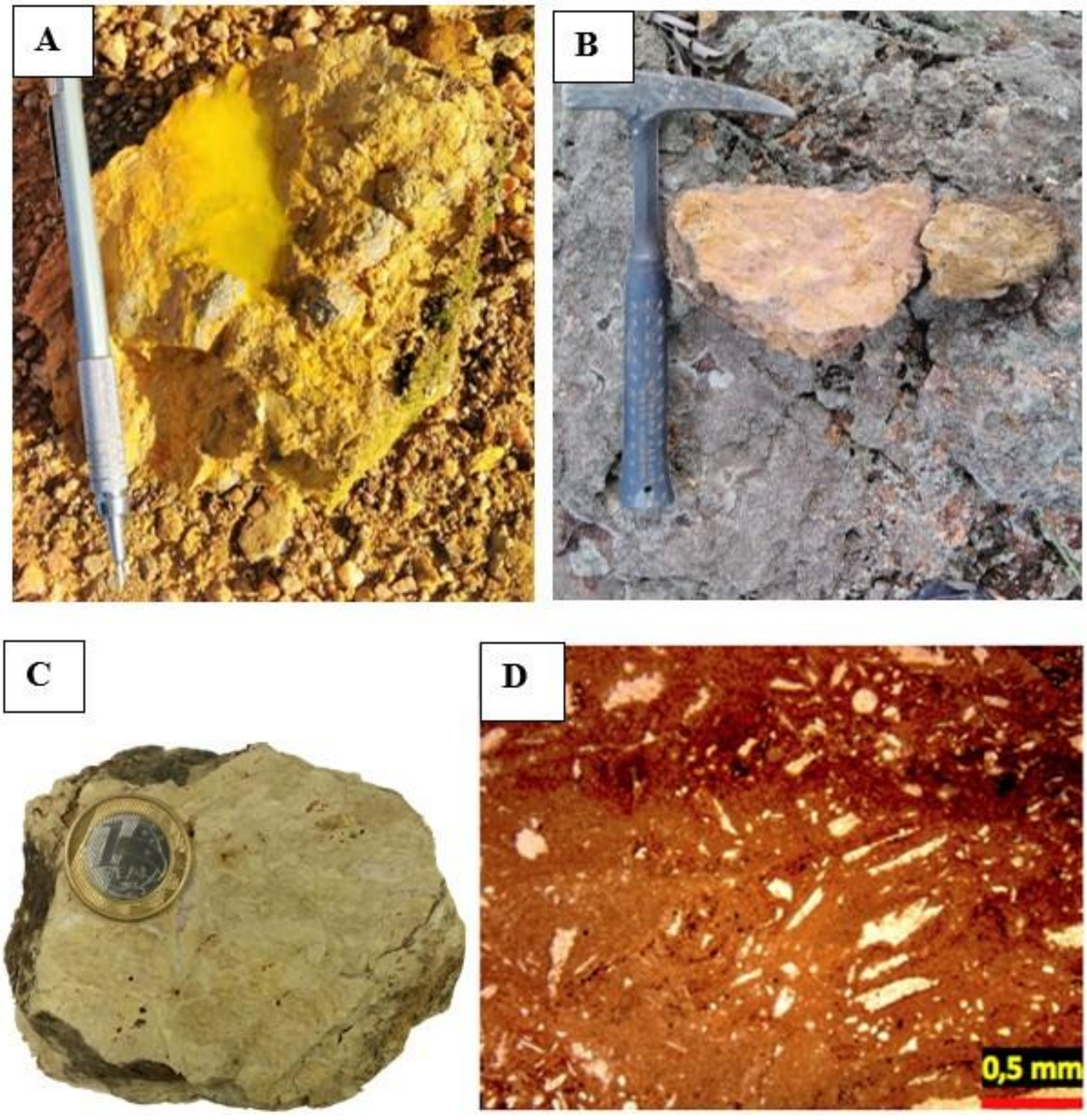



**Fig. 12 - (A)** Macroscopic sample of brecciated phosphorite with intense ammonium molybdate positive reaction. **(B)** Macroscopic appearance of brecciated phosphorite. In the lighter portions, can be noted the presence of nodules formed during the pedogenesis. **(C)** Macroscopic sample of the brecciated phosphorites showing the silicious rich domains immersed in the phosphatic matrix. **(D)** Photomicrography of thin section representing the silicious domains and the phosphatic matrix.

*Stratified Pelites Facies (Ps)*

Finally, the Retiro Formation stratigraphic sequence ends up with a pelitic sedimentation. The stratified pelites are basically composed of clay and subordinate amounts of silt, which were deposited in a low energy but high sedimentation rate environment that led the formation of horizontal stratifications of centimetric scale (Fig. 13A). In perpendicular field sections the outcrops, show more massive structure bedding layers with discrete presence of internal laminations (Fig. 13B).

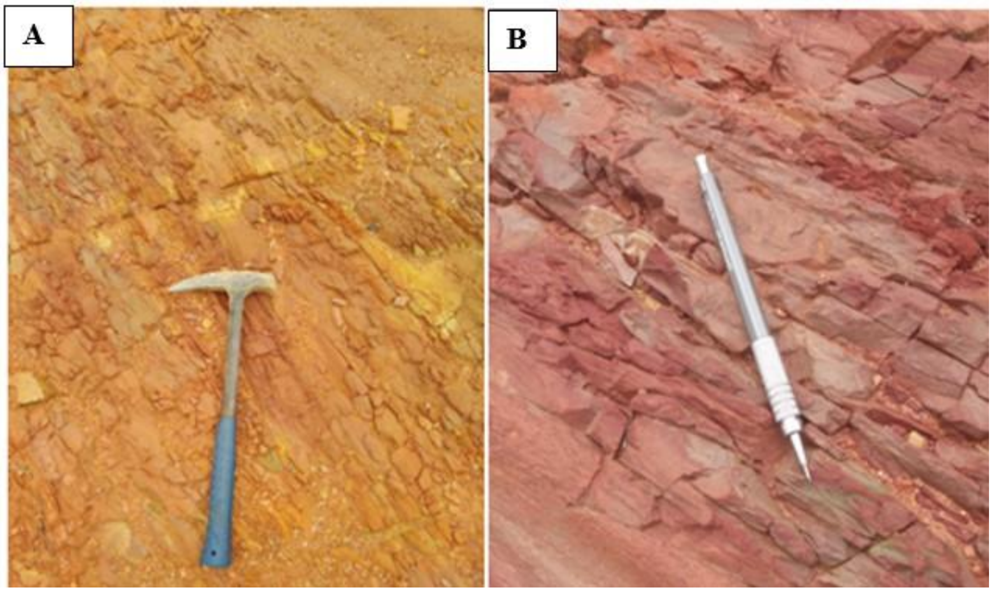



**Fig. 13 - (A)** Stratified pelites outcrop showing the general tendencies of these rocks at the studied area. The yellowish tons are related to the advanced weathering processes. **(B)** Aspects of the freshener portions of the stratified pelites.

*Laminated Mudstones Facies (Ml)*

Laminated mudstones are characterized by fine laminations and a wide range of alteration colors that depict different chemical compositions. Within this range of variations, the purplish laminated pelites are the most abundant and form the most expressive outcrops, followed by the other types that present pale yellow color and fine intercalations of dark laminae (Fig. 14A and 14B).

Compositionally, these pelites are formed entirely by grains of clay granulometry that were deposited in an environment with lower sedimentation rates. In contrast to the stratified facies, it is noted that these rocks do not have any silty participation, which is one of the distinguishing factors between the two lithofacies.

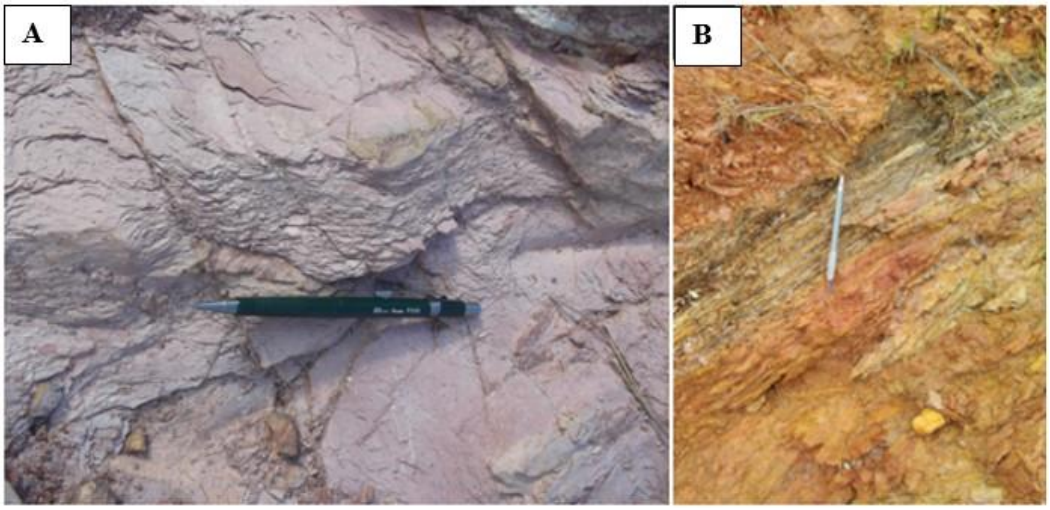


**Fig. 14 - (A)** Laminated mudstones outcrop exhibiting the characteristic thin laminations of the facies. **(B)** Another common type of laminated mudstones. Between the thin laminations there are dark levels organic matter rich and sometimes even phosphated.

4.2 Major element chemistry

The X-Ray fluorescence chemical results are summarized in Table 1. These results are exclusive from phosphate facies including laminated and brecciated phosphorite and phosphate siltstone. All these material types are considered to be phosphate ore after different processing: solubilization, flotation, physical separation and other.

The silica, aluminium and iron contents are higher in the siltstone facies and less abundant in the phosphorite. The opposite behavior is detected to calcium and phosphate. This major element content are commonly observed to sedimentary phosphate ore deposits.

**Table 1 -** X Ray Fluorescence table showing the phosphated rocks major elements. The samples marked with blue color are Phosphated Siltstones, the green color samples are Laminated Phosphorites and the yellow ones, brecciated phosphorites.

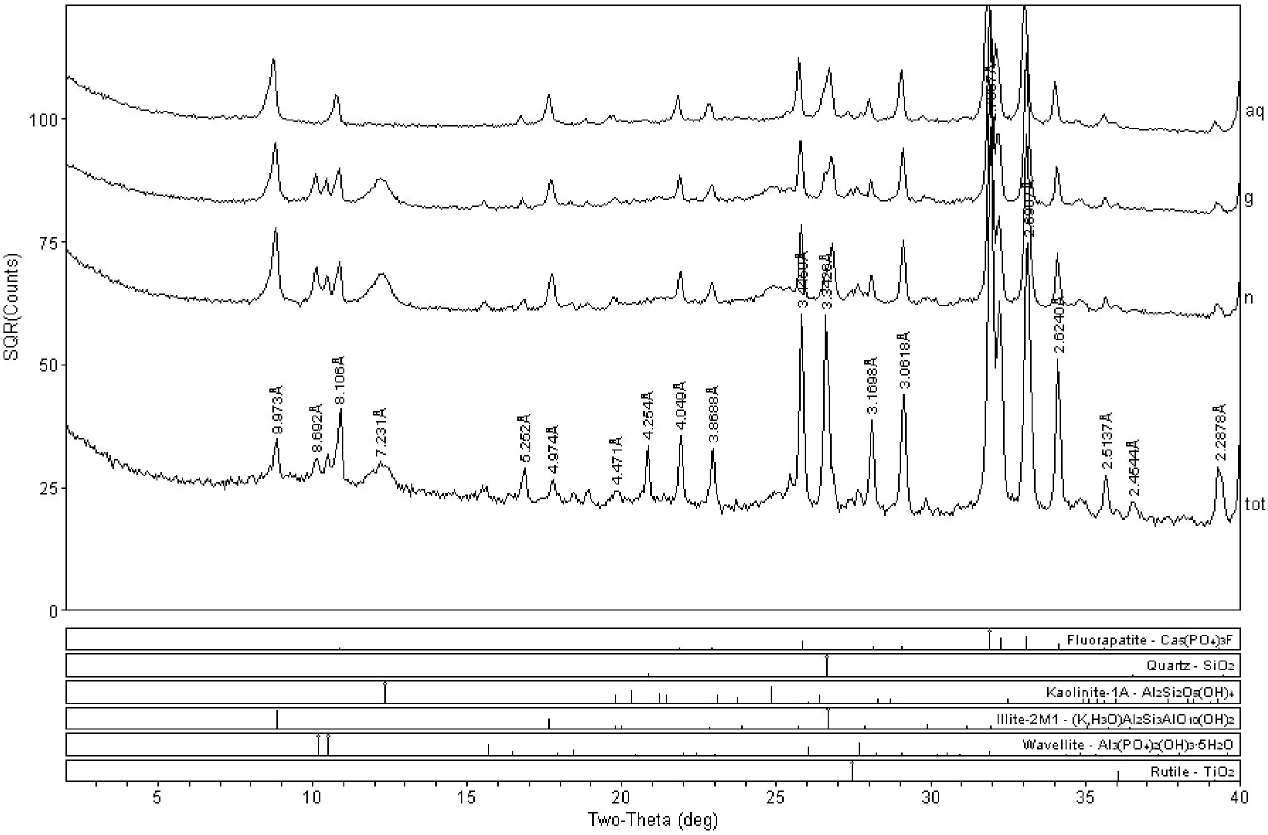
| Sample | $SiO_2$ | $Al_2O_3$ | MgO | $Fe_2O_3$ | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | MnO |
|---|---|---|---|---|---|---|---|---|---|---|
| LTC-09B | 65,89 | 14,52 | 1,94 | 5,02 | 0,99 | 0,41 | 3,09 | 0,77 | 2,65 | 0,03 |
| LTC-53 | 65,71 | 16,13 | 2,08 | 4,29 | 8,33 | 0,25 | 1,95 | 0,48 | 8,80 | 0,02 |
| LTC-89A | 49,33 | 13,21 | 3,06 | 4,87 | 10,61 | 0,44 | 3,39 | 0,66 | 9,06 | 0,03 |
| LTC-26 | 11,06 | 3,79 | 0,31 | 1,28 | 44,23 | 0,30 | 0,52 | 0,17 | 34,29 | 0,06 |
| LTC-30 | 26,82 | 10,25 | 0,67 | 3,45 | 28,12 | 0,28 | 1,65 | 0,42 | 22,19 | 0,08 |
| LTC - 46 | 31,03 | 4,50 | 0,51 | 2,22 | 31,54 | 0,29 | 1,14 | 0,18 | 24,59 | 0,26 |
| LTC-90A | 24,14 | 4,88 | 0,66 | 1,85 | 35,44 | 0,36 | 1,36 | 0,23 | 27,32 | 0,09 |
| LTC-90B | 26,01 | 3,29 | 0,56 | 1,96 | 36,48 | 0,28 | 1,00 | 0,30 | 27,32 | 0,09 |
| LTC-90C | 19,72 | 2,01 | 0,40 | 1,00 | 42,37 | 0,29 | 0,94 | 0,21 | 30,32 | 0,04 |

4.3 X Ray mineralogy analysis

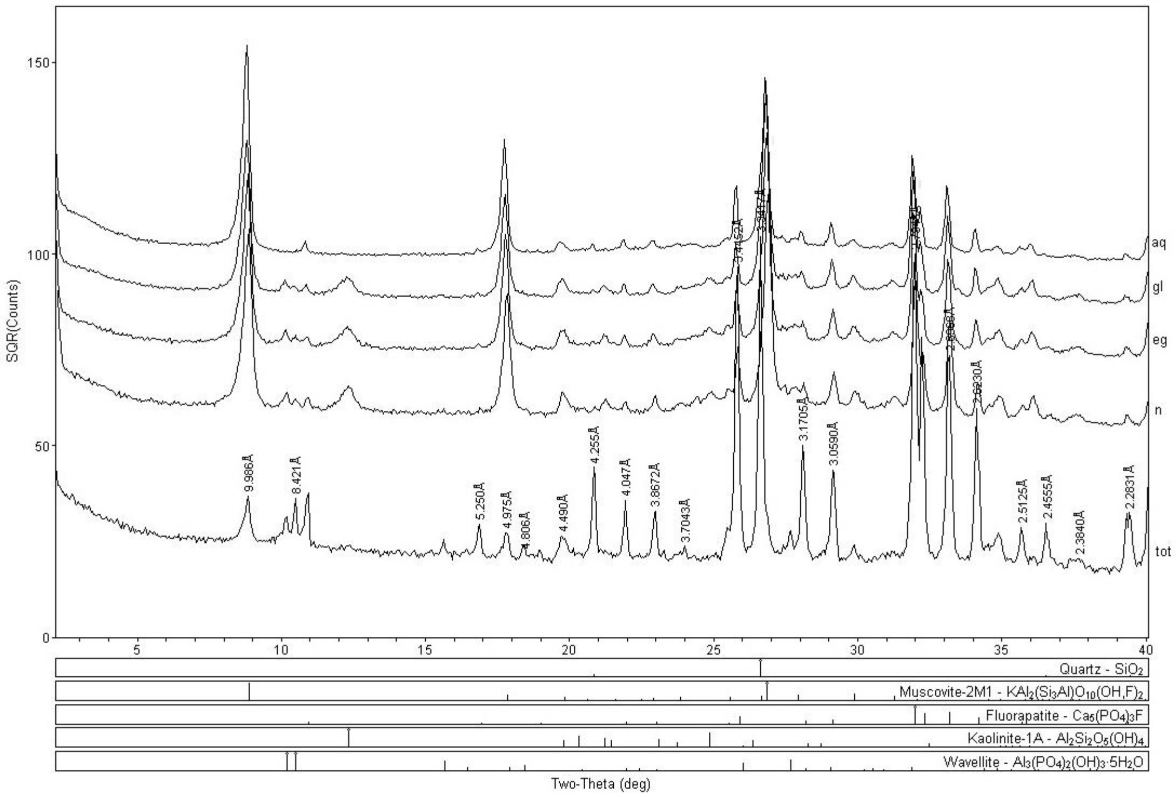
Fig. 15A and 15B show examples of X Ray analysis difractrometry where is possible to indentify the following assemblage: quartz, muscovite and rutile, as detritic minerals; kaolinite and illite, as secondary clayminerals and fluorapatite and wawellite, as primary and secondary phosphate phases. Quartz may also represent a secondary mineral filling dissolution vugs and fractures.

The main kaolinite peak disapearence in the heated treated section indicates that this mineral is expansive.

The relative size of the peaks related to fluorapatite and wavellite indicates high content of phosphate minerals in the samples.




**A**




**B**

**Fig. 15 -** Representative Diffractograms of the phosphote rock facies (laminated and brecciated), showing the mineral assemblege (aq = heated, g = glycol treated, eg = etilglycol and tot = total).

## 5. Discussions

The discussions will include the facies association, depositional environment interpretations and a phosphogenetic model befitting with these environmental contexts.

### 5.1 Facies association and depositional environments

Based on the facies associations and on the geological framework of the Cryogenian Period, it was possible to infer about the series of depositional environments that influenced the sedimentation of the Retiro Formation.

The main rock types were grouped into three facies associations to able a depositional interpretation. The facies associations and proposed environments are summarized in Table 2.

The first facies association suggests that the beginning of the sedimentation of the Retiro Formation occurred in the geological context of a glaciomarine environment, dominated by terminal glaciers responsible for the erosion of extensive continental areas and the accumulation of large amounts of sediments. The displacement of ice masses caused the simultaneous transport of a varied compositional and granulometric nature of lithoclasts, including large pebbles and rock blocks, in addition to fine materials generated by the abrasion of the glacier on the pavement. From the described processes, matrix-supported polymitic diamictites were formed.

**Table 2 -** Summary table of the principal rock facies, facies association and depositional environments of the Retiro Formation**.**

<table>
<tr><th>Facies Association</th><th>Facies</th><th>Rock types and structures</th><th>Environment</th></tr>
<tr><td rowspan="2">FA - 1</td><td rowspan="2">Dmm + Scmm +Saf</td><td rowspan="2">Massive Polymictic Diamictites, Massive Conglomeratic Sandstones and Fine arkoses</td><td>Terminal glaciogenic (glaciomarine)</td></tr>
<tr><td rowspan="2">Proximal portions of the outwash plain</td></tr>
<tr><td rowspan="2">FA - 2</td><td rowspan="2">Sph + PHl + PHb</td><td rowspan="2">Phosphated Siltstone, Laminated Phosphorites and Brecciated Phosphorites</td></tr>
<tr><td>Distal portions of the outwash plain</td></tr>
<tr><td>FA - 3</td><td>Ps + Ml</td><td>Stratified Pelites and Laminated Mudstones</td><td>Transgressive marine shoreface</td></tr>
</table>

The interpretation of the glaciomarine environment is supported by the following data:

- Presence of massive to little stratified diamictite, in the form of discontinuous bodies and scattered throughout the studied area, which show recurrence of sedimentary succession;
- Presence of a varied lithoclast nature in composition and shape, including granite, tonalite, dolomite, siltstone, and quartzite;
- Presence of abrasion striated quartzite blocks;
- Association of different forms of quartz grains, which vary from very rounded to very angular in the same portion of the petrographic section. That feature is interpreted as the glacier incorporation of sediments from proximal and distal source areas;
- General faciology of rudaceous and pelitic rocks, typical of the association of shallow marine processes reworked sediments (wave and tidal action);
- Close relationship of lateral and vertical interfingering of the rudaceous and psamitic rocks with pelite of marine environment.

Diamictite associated with continental glacial environments shows small thickness (generally less than 50 meters), with restricted recurrence in sedimentary succession and complex faciology, without been reworked by marine processes.

At the final portion of the glacier, due to the large masses of melting water, was established an outwash plain, which part of the pelitic matrix of the diamictites was washed out and, consequently, an increase in the modal proportion of the psamitic phase, culminating at the polymictic conglomeratic sandstone formation. Due to the greater distance of these deposits from the source area, most of the larger and denser lithoclasts were deposited in the proximal portions of the glacier and only part of the pelitic rocks and quartzite clasts were added to the conglomeratic sandstone framework.

The end of the first facies association is followed by the arrival of glacial sediments in a coastal environment, where they are reworked by waves action. Thus, almost the remaining matrix is washed, leaving only moderately selected quartz and plagioclase grains that compose the fine whitish arkosean sandstones. The arkosean character of this sandstone facies, defined from the significant amount of plagioclase grains, corroborates the continental source of sediments.

At marginal limits of the glaciers, favorable conditions for chemical precipitation of phosphates were developed, in which were deposited the rocks of the second facies association. These environments are of medium oxidation-reduction conditions, low temperatures and slightly alkaline pH, in addition to low biological activity, which made it possible to increase the availability of free $P_2O_5$ to form phosphorite and phosphate siltstone. The sedimentation of the Phosphatic Unit was marked by the combination of direct chemical precipitation of fluorapatite and deposition of pelitic sediments. In the portions where phosphate siltstone occurs, there is an increase in $P_2O_5$ levels and decrease in the pelitic charge as the center of occurrences approaches, so that phosphate siltstone lenses generally have phosphorite cores.

The lenticular nature of the phosphate deposits led to the interpretation that these sediments are linked to isolated or channalized environments, such as lagoons or tidal plains that kept the physico-chemical conditions to $P_2O_5$ precipitation. The brecciated facies are interpreted as the reworking of laminated phosphorite in the slope portions of channel environment. Furthermore, the intrinsically association of the rudaceous rocks and phosphate facies suggest a precipitation mechanism similar to what happens with ediacaran and proterozoic glacial carbonate covers known as “cap dolomites”. These sequences are worldwide distributed at cryogenic and pos cryogenic basins, for example the ediacaran Shennongjia basin at south China (Kuang *et al*., 2022) and the proterozoic\ediacaran Sete Lagoas Formation, Bambuí Group, Central Brazil (Alvarenga *et al*., 2003).

The deposition of the third facies association, unlike the two sotoposto associations, is directly influenced by deglaciation events. With the melting of the ice masses, there is an increase in the eustatic sea level and consequent marine transgression, in this way, pelitic sediments are deposited, marked by the presence of reddish stratified siltstone and varied laminated mudstone. A small portion of phosphate, which was not precipitated in the vicinity of the glaciogenic conditions, is transported to this environmental condition and with the influence of sea level variations (as a result of transgressions) precipitates and form lenses in the midst of the pelitic facies.

## 5.2 Phosphogenetic Model

Large sedimentary phosphate rocks accumulations occurred on a global scale at well-defined geological ages (Donnelly, 1990). Important phosphogenetic peaks were recorded during the Proterozoic/Cambrian transition. According to Cook & Shergold (1984), these peaks would be related to available phosphorus concentration increasing during the Proterozoic, as result of the development of anoxic oceanic environments with greater $P_2O_5$ storage capacity in deep oceanic reservoirs and followed by upwelling currents influence. These currents were responsible for transporting older, colder and phosphorous concentrated waters to shallower and oxidizing environmental conditions, resulting in phosphate deposition. Cook (1992) supports the idea that the sea level rise, caused by deglaciation, may be a direct influence factor on the soluble phosphorus circulation and suggests an intrinsic correlation between phosphogenesis events and glaciations.

At the Neoproterozoic/Paleozoic transition, the abundance of phosphatic deposits coincides with the Neoproterozoic Oxidation Event (NOE), which allowed greater chemical weathering of continental rocks, mainly in $P_2O_5$-rich carbonatitic cores, further increasing the phosphate contribution to oceanic waters (Papineau, 2010; Pufahl, 2010; Pufahl & Hiatt, 2012). These events were decisive for the genesis of the most world widely disseminated sedimentary phosphate deposits, called Resurgence Deposits.

The "Resurgence Theory" proposed by Kazakov (1937) is related to the placing of deep water to the platformal conditions by upwelling currents action, where dissolved phosphate ($HPO_4^-$ and other anions) precipitates originally as colophanite or amorphous phases.

In the case of the Coromandel deposit, it is considered that mechanisms linked to the glacial event were important to the phosphogenesis control; however, the role of Resurgence Theory can not be applied. Specifically, the high concentrations of $P_2O_5$ were caused by chemical weathering of continental source rocks, intense erosion and glacial transport, in addition to favorable depositional conditions caused by the presence of the glacier, allowing the anomalous accumulation of phosphate.

Some observations support the interpretation of the continental character of the phosphate source area of the Coromandel deposit. The presence of chlorite group minerals such as clinochlore and the amphibole group such as ferroactinolite (identified by X-ray diffractograms), suggests a possible participation at the sedimentary provenance from the disaggregation of rocks with phosphorus contents, which were carried and accumulated by terminal glaciers.

The depositional conditions developed at englacial and supraglacial portions influenced the direct chemical precipitation of phosphate (Fig.16), in the form of fine crystals of amorphous fluorapatite (colophanite), which, according to its modal proportion in relation to the content of siliciclastics, gave rise to phosphate siltstone and phosphorite. In this environment, intermediate conditions to slightly more oxidizing redox predominated, with higher pH (alkaline) and lower temperatures that resulted in a decrease in phosphate solubility and its immediate precipitation.

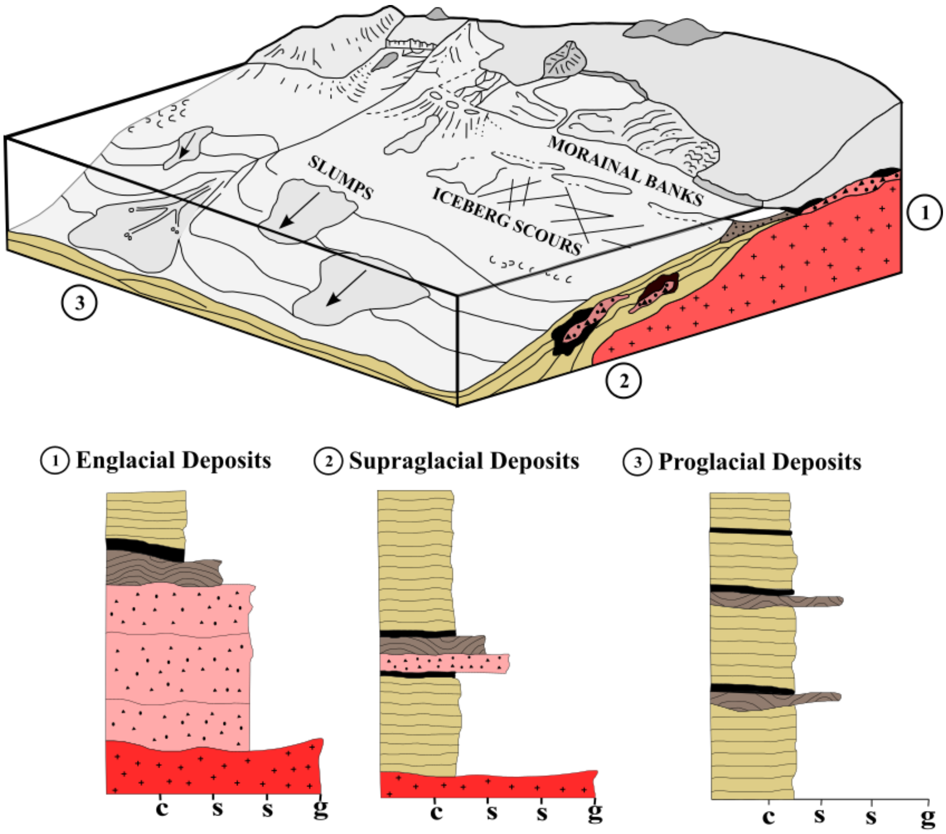



**Fig. 16 -** Depositional environments and their respective stratigraphic association for the glacial phosphate deposit of the Retiro Formation. It is important to notice that the model is based on an evolutive sequence trough a glaciotransitional depositional system (modified from Eyles and Eyles, 1992).

Another factor that must be considered in relation to the genetic issue of phosphate facies is the restricted organic production due to low water temperatures. In this glacial/pro-glacial context, the melting cold waters inhibits the development of marine organic activity and thus $PO_4^{2-}$ as an essential nutrient would have its consumption limited, so that most of the phosphate existing in the basin may have deposited chemically or in association with fine terrigens. If warm water conditions prevail, a greater volume of carbonate rocks would be expected to be deposit, and consequently greater consumption of $PO_4^{2-}$, thus hindering its accumulation in the sedimentary rocks.

The Resurgence Theory is not expected to be applied to the Retiro Formation, once there was no deep water, as the shallow marine conditions had been just installed. In this case, the marine phosphate reservoir still not existed, and the $P_2O_5$ would be from continental sources. By the other hand, the phosphate deposits associated to the Rocinha Formation could fit with the Kazakov Theory, where the upwelling currunts would transport dissolved phosphate from deep water, in the environment conditons for deposition of the Serra do Garrote Formation (Fig. 17A).

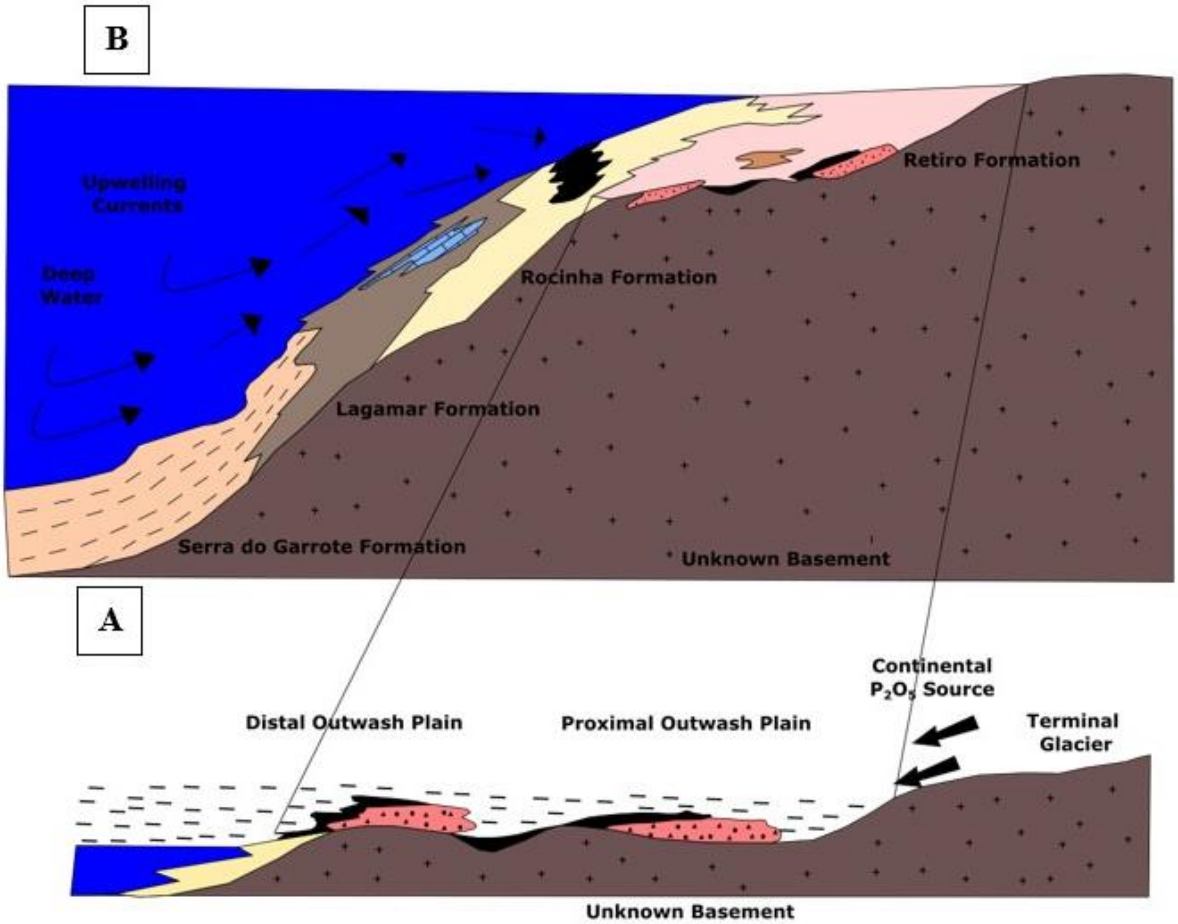



**Fig. 17 -** Proposed phosphogenetic model to the Vazante Group deposits. (**A)** The Rocinha deposits were established by the Kazakov Theory mechanism, where upwelling currents driven cold, deep and $PO_4$ rich ancient waters to shallower conditions and direct precipitation of fluorapatite. (**B)** The Retiro Formation phosphate deposits were deposited in a glaciotransitional to shallow marine environment fed by phosphorus from continental sources.

It is important to point out that the deposition of the Rocinha Formation occurred at a later time in the basin evolution, when another physiography was established, including deep water conditions (linked to the deposition of the Serra do Garrote Formation) and shallow water platform (during the deposition of the Rocinha and Lagamar Formations) (Fig. 17B).

Phosphate siltstone was deposited in situations where the participation of terrigenous sediments prevailed, with subordinate proportions of phospholutite, which were concentrated in fine laminations and resulted in low levels of $P_2O_5$, ranging from 2% to 9%, with some samples showing 16%. Laminated phosphorite was formed predominantly by precipitation of phosphate minerals with little pelitic contribution. These rocks were generated from the cyclic association of moments of lower depositional energy, which the phospholutite laminations were precipitated, and moments of greater agitation that reworked the unconsolidated portions of phospholutites, forming phosphatic intraclasts and phospharenite laminations. The $P_2O_5$ contents of these rocks fluctuate between 19% and 24%, and some samples reachs anomalous value of 34% (possibly resulting from the presence of cavities filled with wavellite crystals).

These environmental conditions of relative shallow, cold, alkaline and low energy waters in association with high Ca/Mg ratios and a super-rich $P_2O_5$ system can be related to a cap dolomite genetic mechanism, although the chemical sediment is marked by phosphated instead carbonated phases like a cap phosphorite.

The third facies represent the brecciated phosphorites and is interpreted as the materialization of post-depositional reworking of laminated phosphorite facies due to currents or margins instabilities of the main phosphorite lenses in slope conditions. The increase in $P_2O_5$ contents (about 3.5% in relation to laminated phosphorites) is attributed to the reconcentration of the phosphate phases in relation to the pelitic material, that is more easily transported along through fine distal facies.

In relation to the other elements, the data are consistent with the mineralogical assemblages of the phosphate facies determined by the X-Ray diffractograms. Phosphate siltstone shows high silica, aluminum and potassium contents that reflect the presence of higher amounts of quartz and muscovite in these rocks. Similarly, in laminated and brecciated phosphorite, there is an increase in the amount of calcium together with phosphorus, as a result of the presence of a greater amount of fluorapatite. In addition, the increase of aluminum marks the samples richer in wavellite, kaolinite and illite.

## 6. Conclusions

The Retiro Formation, basal unit of the Vazante Group, is interpreted as glacigenic origin and includes the following facies: massive polymictic diamictite; massive conglomeratic sandstone; fine arkosean sandstones; stratified siltstone; laminate mudstone; phosphate siltstone, laminate and brecciate phosphorite.

Due to the intrinsic stratigraphic correlation between the Rudaceous Unit and the Phosphate Unit, it can be concluded that the accumulation of phosphate in the Retiro Formation is directly controlled by the environmental oxi-reduction and alkalinity conditions generated by the presence of the glacier, in addition with the contribution of $P_2O_5$ leached from continental sources and restricted rates of phosphorus-metabolizing biological activity, established by water low temperature.

The Phosphate Unit is marked mainly by the presence of phosphate siltstone, laminated and brecciated phosphorite facies. The differences in $P_2O_5$ content, sedimentary structures, textures and distribution of occurrences throughout the study area are the result of differences in flow energy, input of siliciclastic sediments and intensification of the conditions to phosphate precipitation within the deposition environments of the Retiro Formation.

The $P_2O_5$ contents (from 2 to 34%), the similarity between the facies and the geological context of the Phosphated Unit, approximate the genesis of the Retiro deposits to those observed at the base of the Bambuí Group. However, the greater complexity of the mineralogical assemblages, the discret paleogeographic control and morphological differences between both basins (Vazante and Bambuí Groups) do not allow the inclusion of the Retiro Formation deposit as the same metallogenetic model of the Sete Lagoas Formation. Therefore, it is possible to propose a metallogenesis model of "Coromandel type" that encompasses all the observed characteristics for the deposit of the Retiro Formation.

Due to the outstanding characteristics of the Coromandel type deposit, it is still possible to establish a series of important exploratory vectors that indicate the areas with greater favorability to find phosphate rocks in the studied area. The presence of the Rudaceous Unit becomes the main exploration vector, followed by the occurrence of yellowish laminated pebbles and silexites, in addition to the strong association of phosphate rocks with uranium and thorium that result in good responses to gammaspectrometry data.

## 7. References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# CAPÍTULO 3 - ARTIGO 2

(Artigo a ser submetido a revista Journal of South American Earth Sciencies - Dezembro de 2023)

## FACIOLOGICAL CHARACTERIZATION AND METALOGENESIS OF THE CAMPOS BELOS PHOSPHORITE TYPE-DEPOSIT, BAMBUÍ GROUP, CENTRAL BRAZIL

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**Abstract** - The phosphorite and phosphatic marls/siltstone found in Campos Belos (Goiás State) and Arraias (Tocantins State) are related to the Sete Lagoas Formation, at the base of the Bambuí Group, along the western margin of the São Francisco Craton. The phosphate mineralized rocks are interbedded with each other, near the contact or directly over the Paleoproterozoic granitic basement represented by the Aurumina Suite. Based on petrographic, mineralogical, and chemical studies, four facies of phosphatic rocks were defined: the *Phosphatic Siltstone Facies*, which can show carbonate contribution; the *Stratified Primary Phosphorite Facies*, subdivided into laminated phosphorite and bedded phosphorite; the *Brecciated Phosphorite Facies*, formed from reworking of primary phosphorites; and the *Pedogenic Phosphorite Facies*, grouped into lateritic phosphorite and concretionary phosphorite types. The Phosphatic Siltstone Facies shows the widest volumes of the phosphate reserve in the region, with average grades ranging from 3 to 6 wt% $P_2O_5$. All the facies commonly have phosphate grades exceeding 20 wt% $P_2O_5$, and the main ore mineral has an intermediate composition between francolite and fluorapatite, occurring as aggregates of micro to cryptocrystalline crystals, intergrown either with clay minerals or quartz, and as disseminations form. Phosphate sedimentation occurred in cold (post-glacial) waters, in an area characterized by the presence of irregular and discontinuous paleo channels excavated in the basement, within the context of a restricted sedimentary basin influenced by a transgressive regime. Flank failures of the channels resulted in the reworking of deposited sediments, forming sedimentary phosphorite breccias. Subsequently weathering processes led to laterization and partial silicification of the phosphorites.

**Keywords** - Sedimentary phosphate, Bambuí Group, Sete Lagoas Formation.

## 1. Introduction

The Metais de Goiás Company discovered the first occurrences of sedimentary phosphate in the Campos Belos (Goiás State) and Arraias (Tocantins State) regions in the 1970s. At the early 2000s, Itafós Mining Company started producing phosphate rock concentrate on a small scale, extracting only phosphorite rocks. In 2007, the Canadian company MbAC Fertilizers Corporation acquired Itafós and elevated the phosphate occurrences and small deposits to the category of phosphate deposits, which have been mined on an industrial scale since 2013. Advanced exploration allowed the estimation of measured reserves of approximately 79 Mt at an average grade of ~4.93% $P_2O_5$, and other inferred reserves of approximately 12.7 Mt at an average grade of ~3.86% $P_2O_5$.The estimated reserves in the study area consist primarily of phosphate siltstones, which exhibit significant lateral and vertical continuity, interbedded with phosphorite. The phosphorite occur as small bodies with commonly high grades, ranging between 20 and 37% $P_2O_5$ (Monteiro, 2009).

Currently, the Upwelling Theory proposed by Kazakov (1937) is the main phosphogenesis model used to explain the formation of recent and ancient marine phosphate deposits. The theory suggests that phosphate accumulations are formed from upwelling marine currents, which allow the circulation of soluble phosphorus, under deep anoxic conditions, to platform zones where the precipitation of phosphorus as $P_2O_5$ would occur at depths between 50 and 200 meters. These conditions involve a decrease in the partial pressure of $CO_2$, accompanied by an increase in pH and low temperature. However, this theory does not fully apply to the studied phosphate deposit since the sedimentation of the Bambuí Group occurred in shallow waters (Campos et al., 2012) as the Bambuí Group represents a mixed platform within the context of a foreland basin setting. Therefore, it means that it is not possible that the solubilized phosphorus could be originated from deep waters.

Other authors presented important contributions on the theory of sedimentary phosphorous deposits and economic accumulations of phosphate ores in the Proterozoic or in the Proterozoic Phanerozoic boundary (Cook and McElhinny, 1979; Cook and Shergold, 1984, 1986; Donnelly, 1990; Cook et al., 1990; Cook, 1992; Hoffman et al., 2011).

In this way, the main purpose of this research is to provide a detailed description of the main phosphate rocks, their faciological associations, and consequently, the depositional environments and mechanisms involved in the genesis of the deposit. The study is based on field observations and description of outcrops, thin sections petrography, X-ray diffraction to clay minerals identification, and geochemistry of major elements.

Because of the peculiar characteristics of the ore facies and stratigraphic position (at the bottom of the Bambuí Group), it is purposed to denominate this phosphate occurrence as the

Campos Belos deposit-type, which is marked to be a high volume and low mean grade sedimentary deposit.

## 2. Study Area and Geological Setting

The occurrences of phosphate rocks and phosphorite are located in the northeastern portion of the Brasília Fold Belt, more specifically at the region between Campos Belos (GO) and Arraias (TO) cities, around 400 km distance from Brasília (Fig. 1). Paved Federal and state highways, and small county roads allow reaching the study area.

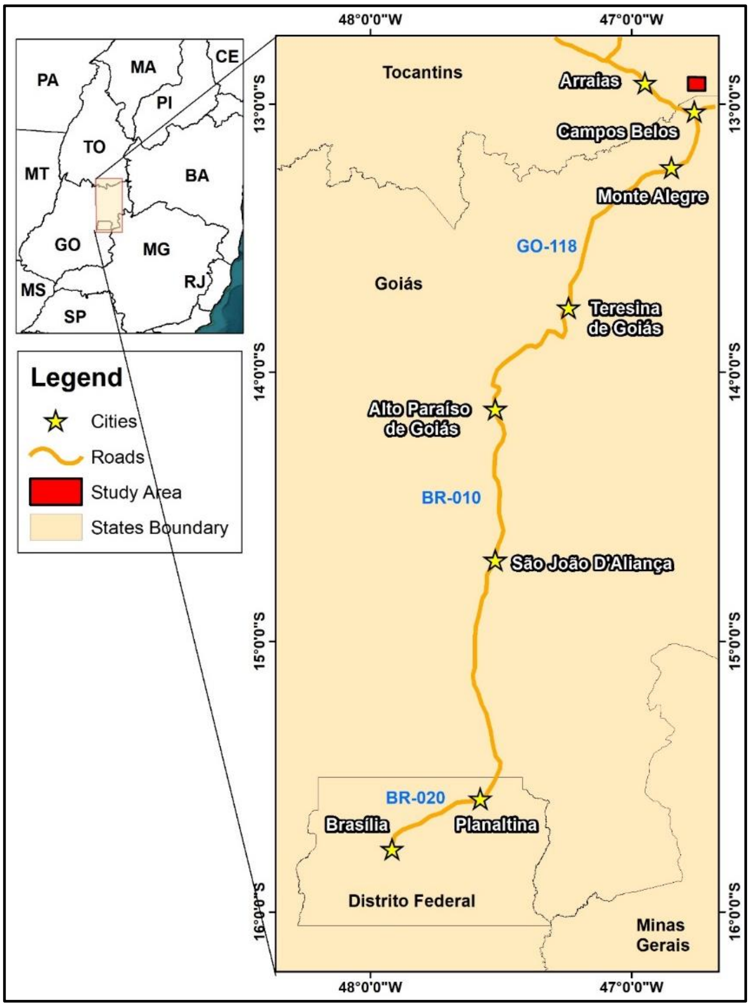


**Fig. 1 -** Localization map showing the main roads and access to the study area.

The geological context includes, from bottom to top, the following lithostratigraphic units: the Aurumina Suite, which includes syn-, late-, and post-tectonic granitic rocks; the Araí Group, which comprises a set of anquimetamorphic to low-grade greenschist metasedimentary and metavolcanic paleoproterozoic rocks; and the Bambuí Group (Dardenne 1978 and 2000), represented by neoproterozoic/cambrian pelitic and carbonate sedimentary rocks (Fig. 2). The Aurumina suite represents the regional basement at the north portion of the Brasília Belt (Martins-

Ferreira et al., 2018). The Araí Group is a rift bearing succession associated to continental sedimentary and subaerial volcanic and pyroclastic rocks.

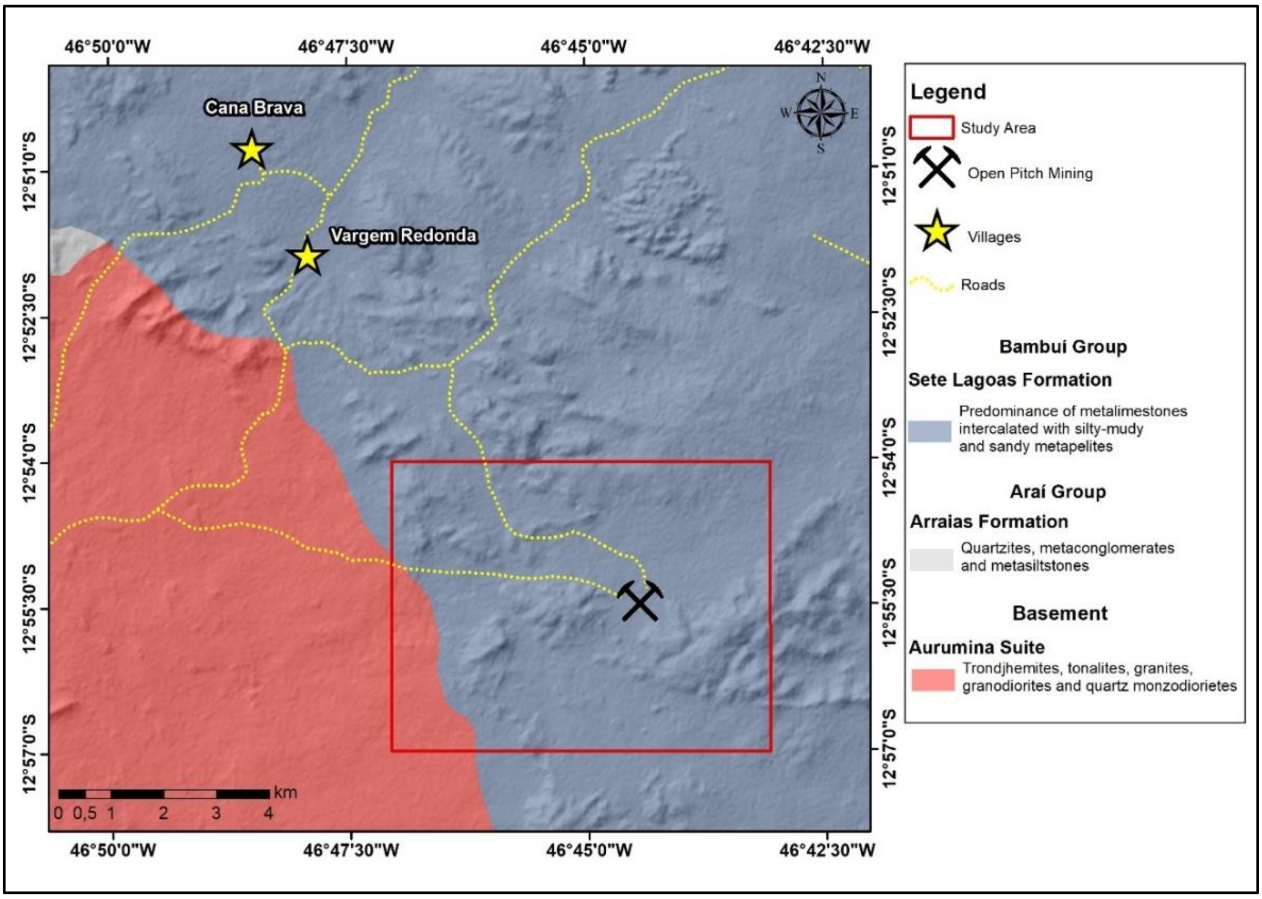


**Fig. 2 -** Geological map of the study area and adjacencies modified from Carneiro et al. (2007) and Martins-Ferreira et al. (2018).

Aurumina Suite

In outcrops, muscovite granite and biotite-muscovite granite are recognized, with medium to coarse grain size that belongs respectively to Au1 and Au2 facies of the Aurumina Suite (Botelho et al., 2006). The outcrops occur mainly as weathered rock blocks, with a color variation ranging from whitish to yellowish. The exposures mostly show sericitization and saussuritization. Locally, grayish granodioritic and quartz-dioritic rocks, attributed to the same Suite, were intercepted by drilling holes.

Araí Group

The Arraias Group was first described as the basal Araí Group formation (Dyer, 1970) and then elevated as a group status by Martins-Ferreira et al. (2018). It represents a thick package of continental sedimentary rocks with bimodal volcanic intercalations at the bottom of the succession.

In these terms, at the study area and adjacencies outcrops rocks of the Prata Formation that comprises quartzite, arkose, metasiltstone and polymictic and matrix-supported conglomerate. At the conglomerate are distinguish milimetric to decimetric lithic fragments of granite, quartzite and quartz pebbles immersed in a greenish, sandy matrix, with a degree of rounding ranging from subangular to rounded. The thickness of these metaconglomerate in drill holes does not exceed 2 meters.

Bambuí Group

The Bambuí Group rocks are the main phosphorite facies hostes and it outcrops make up the majority observed at the study area. According to Dardenne (1978), the group stratigrapgy sequence can be divided into five units, formalized as formations: Jequitaí, Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade and Três Marias. However, at the study are identified only the Jequitaí, Sete lagoas and Serra de Santa Helena Formations.

The Jequitaí Formation is characterized by polimitic diamictites wich contains decimetric to centimetric and rounded to angular peebles of quartzites, arkoses, carbonates and shales immersed in a silty-clay greenish matrix. Martins-Ferreira et al. (2013), based on these rocks nature, suggested a continental glaciation event as the depositional sedimentary environment for the Jequitaí Formation. In one hand, at the study area, the outcrops are represented by small occurrences that stands out between the Sete Lagoas rocks.

At the other hand, the Sete Lagoas Formation represents the first and most basal carbonated unit of the group. At the Brasília Fold Belt geological context, the carbonated facies are not dominant due to the massive presence of marly rocks. Therefore, at the São Francisco cratonic basement, the carbonated sequences are the most expressive ones. At the study area are recognized three facies associations of the Sete Lagoas Formation.

The first facies is basically composed of marls, silty-muddy and silty-sandy rythmite, fine sandstone, intraformational breccia, siltstone, phosphate siltstone, phosphorite and chert. The thickness of this facies varies according to its distance from the basement, and it can range from a few to approximately 120 meters (Monteiro, 2009).

The second facies association occurs overlaying the first association and represents the thinner interval of the unit. It is defined by laminated mudstone, sometimes intercalated with calciferous siltstones. Above the intercalated beds there are calcarenite and calcirudite rich in mudstones intraclasts.

The upper facies association is defined by a predominant dolomitic sequence. The rocks are commonly cryptocrystalline due to intense recrystallized with a sub-horizontal lamination. Therefore, sometimes, other sedimentary structures as low angle cross laminations and stratifications can also be observed. In addition to this stratigraphic level, there are stromatolite, biostroms, microbialite and ooids that suggest a shallow subtidal depositional environment to the Sete Lagoas Formation (Okubo et al., 2020).

Finally, the study area stratigraphic succession ends with the Serra de Santa Helena Formation. This unit is dominated by intense silicificated siltstone, with rare marls, most commun near at the contact with Sete Lagoas Formation. The Fig. 3 summarizes the stratigraphic column of the study area.

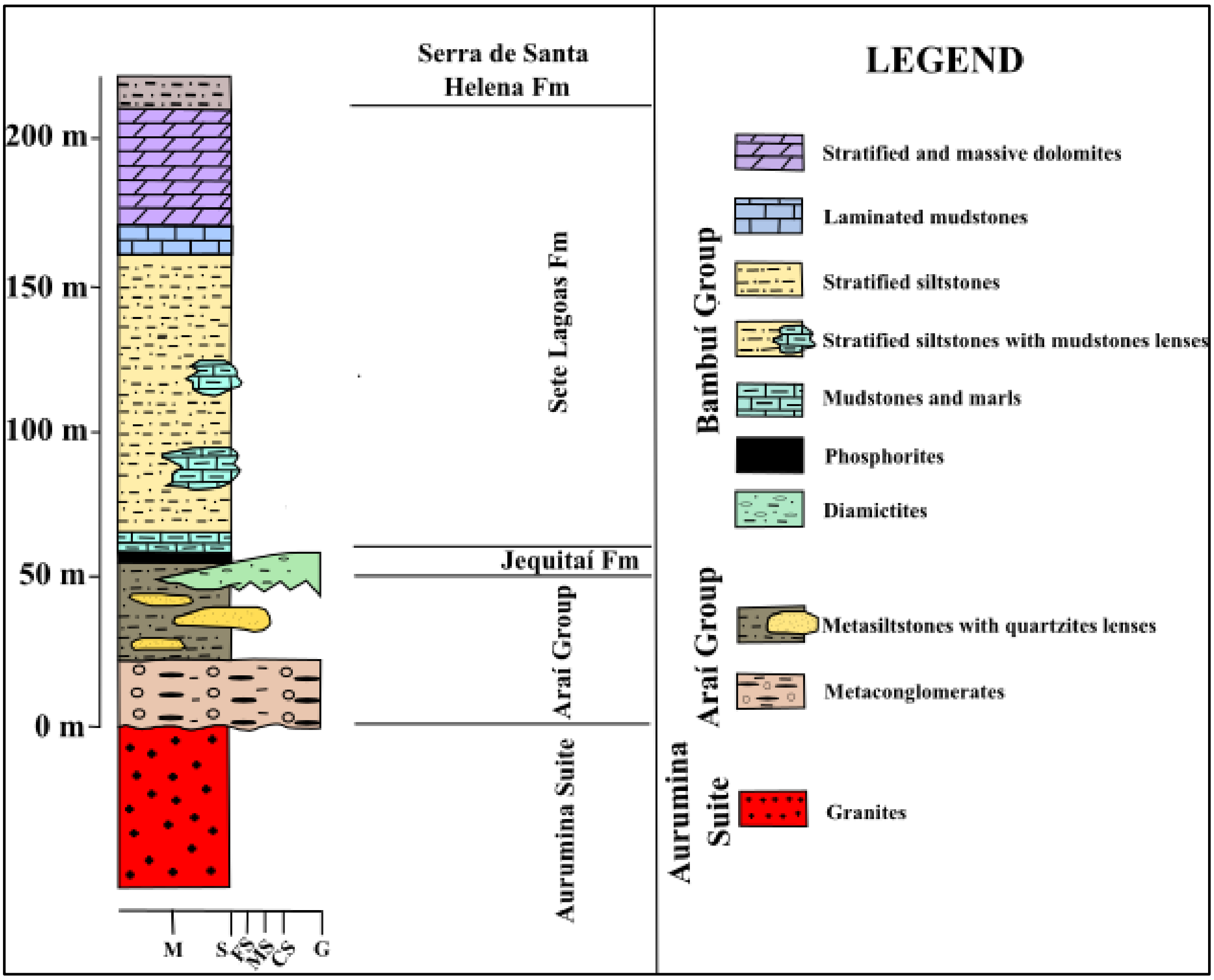


**Fig. 3 -** Schematic stratigraphic column of the study area (modified from Monteiro, 2009).

## 3. Material and methods

In order to achieve the proposed objectives of characterization and description of the deposit main mineralized facies and their possible genetic interpretations, based on faciological association, a series of key outcrops were visited. These outcrops were selected in order to faithfully represent the local geology. In this way, detailed sections were carried out for the characterization of the main rocks, sedimentary structures and their organization in facies association, focusing on phosphate siltstone and phosphorite.

In addition to the field data, some samples of the phosphate unit were selected for application of laboratory methods for quantitative chemical determination. Aiming the chemically characterizing the phosphate ore, 71 samples were analyzed, with 8 samples being duplicates. Out of these, 28 were from phosphorite and phosphate siltstone.

In order to identify the phosphate rocks main mineralogy, 7 grams of each selected samples were pulverized in an agate disc and the powder inserted in a dug slide to X Ray Diffraction analysis. A Rigaku – Ultima IV diffractometer that counts with a nickel filter, Copper tube and 35Kv / 15mA and DTEX / ULTRA detector, realized the analyses. The scan was performed in the $2\theta$ range from 3° to 80°, step 0.05, and speed 1°/min. The characteristics picks at the Jade XRD 9 software were applied to minerals identification.

All chemical analyses were conducted at ACME Analytical Laboratories Ltd in Vancouver, Canada. Major elements and loss on ignition (LOI) were analyzed using ICP-ES (Inductively Coupled Plasma Emission Spectrometer) after opening 2 grams of sample with lithium metaborate/tetraborate fusion and digestion in diluted nitric acid. Minor elements, traces, and rare earths were analyzed using ICP-MS (Inductively Coupled Plasma Mass Spectrometer) with lithium metaborate/tetraborate fusion opening and digestion in nitric acid.

## 4. Results

As proposed by Slansky (1979), the $P_2O_5$ content equivalent to 18% was considered in this paper as the limit for the classification of phosphorite and phosphate siltstone. Based on mineralogy, textures and sedimentary structures of phosphate ore were recognized four facies, presented as follows.

### 4.1 Phosphated Facies Description

*Stratified/Laminated Primary Phosphorite Facies (Sph)*

This facies can be subdivided into two main different rocks: stratified and laminated phosphorite, according to their sedimentary structures.

Stratified Phosphorite is composed of phospholutite and phospharenite that presents $P_2O_5$ high levels, with an average of 32%. This phosphorite is structured in centimetric layers with purple, pink, yellow and beige colors (Fig. 4A). The outcrops are advanced weathering, where can be seen fragmentation of the layers and the common presence of empty or full filled cavities.

Laminated phosphorite comprises phospholutite without well-defined sedimentary structure. However, at the times that the structure can be observed, it is represented by millimetric laminations. These rocks are intense silicified, shows a yellowish to whitish color tone (Fig. 4B).

On petrographic thin sections, the colophanitic material is arranged in layers of pure phospholutite, or less commonly, with rare submillimeter intraclasts of phospholutite. There are also intercalations between pure phospholutite and very fine phospharenite, in which submillimeter grains of quartz, muscovite lamellae, and oxide classified as hematites are present

(Fig. 4C). Fractures and cavities are usually filled by quartz and neoformed apatite, which grow from the edge towards the center of these spaces (Fig. 4D).

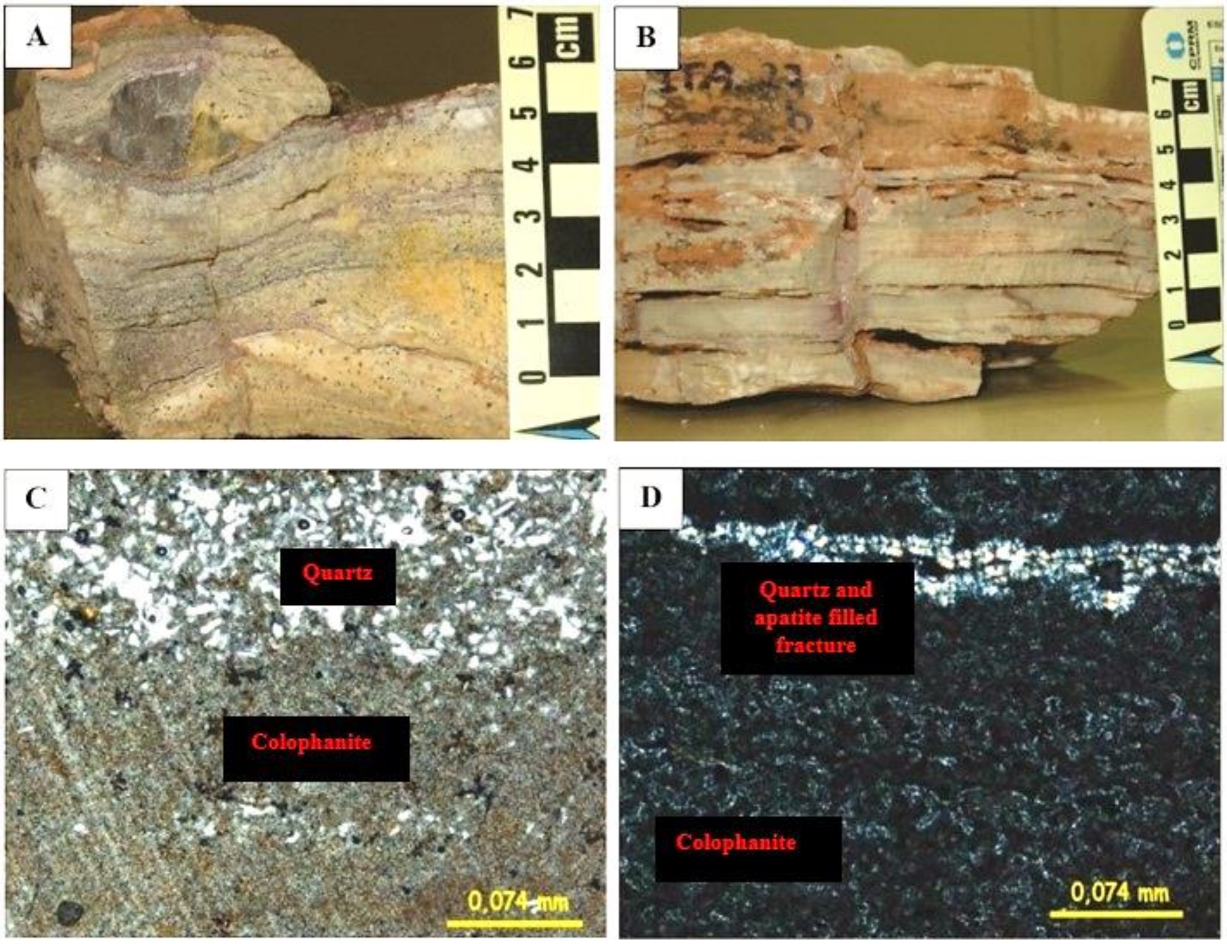


**Fig. 4 - (A)** Hand sample of Stratified Primary Phosphorite. **(B)** Hand sample of Laminated Primary Phosphorite with well-defined sedimentary planar structures. **(C)** Photomicrography of Stratified Primary Phosphorite thin section showing the relation between quartz and colophanitic domains. **(D)** Photomicrography of Laminated Primary Phosphorite exhibiting the portions with quartz and apatite filled fractures.

In these rocks, colophanite represents between 60% and 80% of the bulk rock composition and quartz occurs in amounts between 10% and 30%, either as clasts or as detrital grains that make up the matrix.

*Brecciated Phosphorite Facies (Bph)*

This facies is formed through the reworking of Stratified and Laminated phosphorite, with which they are laterally interfingered. Similar to the lateral primary facies, Brecciated Phosphorite also shows relatively high average of phosphorus content.

Within this facies, the main distinguishable characteristics are centimetric to decimetric and angular to rounded intraclasts and clasts, composed of phosphorite, phosphatic siltstone, yellow and purple siltstone, quartz, and silexite. These fragments are embedded in a collophanite matrix with a light purple or beige color (Fig. 5A). In some local cases, the intraclasts of phosphorite retain their original internal layering.

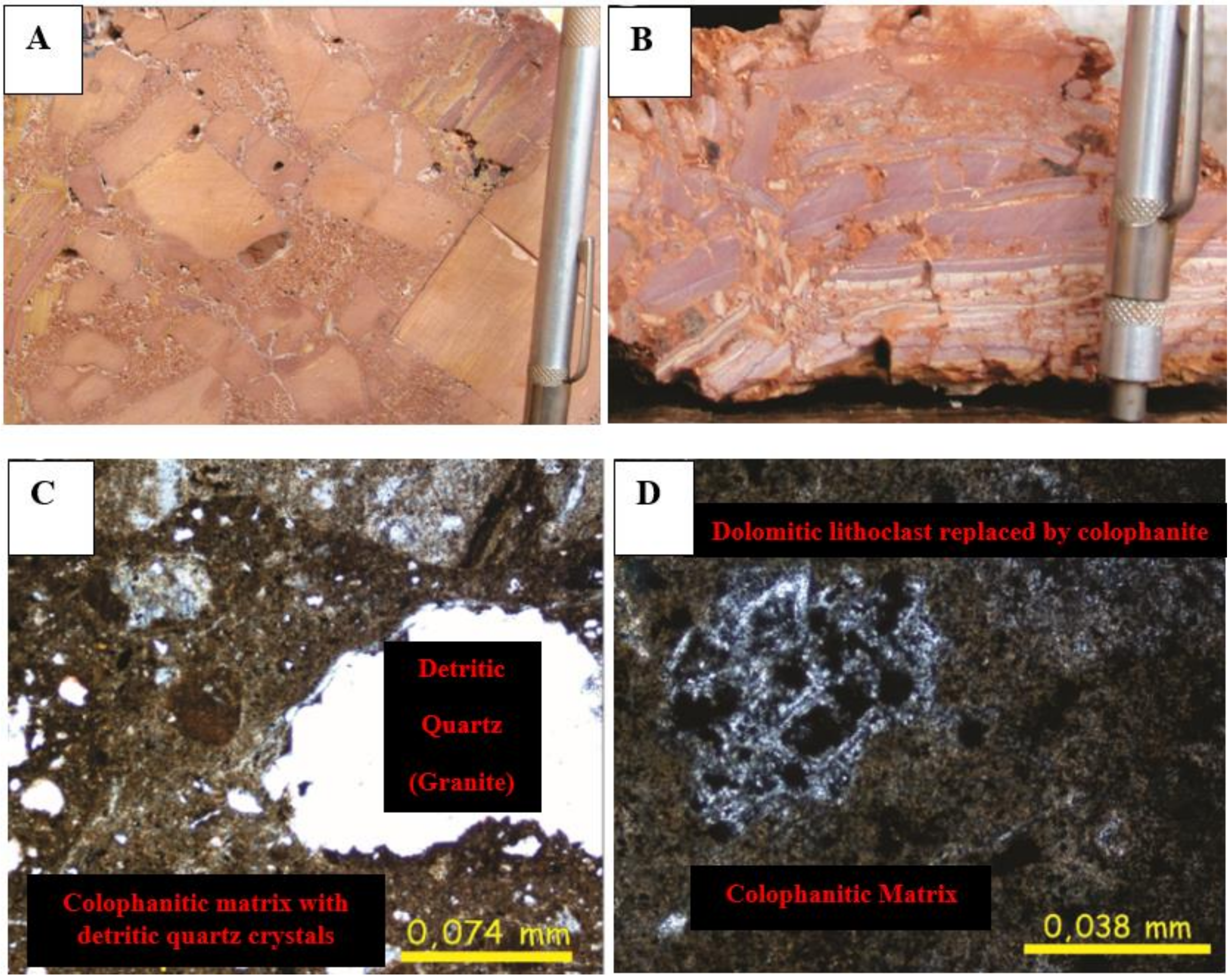


**Fig.** *5* **- (A)** Detailed Brecciated Phosphorite hand sample photography showing the amount of phosphate intraclasts in collophanitic matrix. **(B)** Example of the main texture of the Brecciated Phosphorite with reworked intraclasts and matrix empty cavities. **(C)** Photomicrography of Brecciated Phosphorite showing the relation between the phosphatic intraclasts and matrix with different size and shape quartz grains. **(D)** Dolomite lithoclast replaced by collophanite.

The presence of small cavities in the matrix, partially or completely filled with microcrystalline quartz, is common, which facilitated and resulted in the silicification of this type of phosphorite rock (Fig. 5B).

Petrographic description have shown that fractured phosphorites are composed of lithic fragments that make up an average of 40 to 60% of the rock volume. The most common fragments are intraclasts of phospholutite, followed by finely fractured phospharenite. The intraclasts and clasts are subangular to round in shape and range in size from millimeters to centimeters (Fig. 5C).

The presence of very fine quartz filling fractures and voids is common, and it is a minor component of the matrix along with collophane. Apatite is also found alongside quartz in fractures, although it is difficult to observe under the microscope. Local occurrences of dolomite replacement by collophanite are also observed (Fig. 5D).

*Pedogenetic Phosphorite Facies (Pph)*

This facies is represented by highly laterized phosphorites developed above Stratified and Brecciated Phosphorite, and two rocks types are recognized. The first one outcrops as large blocks of lateritic phosphorite with botryoidal habits. They have a black alteration cap and slightly lower $P_2O_5$ contents due to the higher silicification intensity.

Pedogenetic Phosphorite are differentiated from Brecciated Phosphorite due to their high contents of Fe, Al, and $SiO_2$, as well as their typical lateritic appearance. When formed over Brecciated Phosphorite, these lateritic facies contain clasts of siltstone and intraclasts of phosphorite embedded in a red or beige phospharenite matrix. It is typical in lateritic phosphorite to have numerous cavities of various shapes, mostly partially or completely filled with microcrystalline quartz.

In the Pedogenetic Phosphorite formed over stratified subgroup-type phosphorite, the original layering sometimes can be discerned, and occasionally are fragmented. Many cavities are also present following the bedding planes, with growth of microcrystalline quartz along their edges (Fig. 6A).

The second rock type is characterized by centimetric to decimetric phosphatic concretions in podzolic soil. These concretions are observed in mining fronts, resulting from the evolution of the lateritic profile, reaching an approximate thickness of 10 m and the concretions are composed of fragments of lateritic phosphorite (Fig. 6B).

In thin sections, features of laterization are observed, including percolation during which silica-rich fluids permeated the rock, leading to the complete or partial filling of cavities with microcrystalline quartz, and some neoformed apatite. Laterization also allowed the percolation of oxide-rich fluids into pre-existing fractures, contributing to the fragmentation (Fig. 6C). Pedogenic phosphorite appears as oxidized and silicified phosphorudite with a matrix composed of colophanite and detrital quartz, within which are embedded intraclasts of phospholutites and finely fractured phospharenites, as well as clasts of siltite, phosphatic siltite, and quartz. Hematite films (Fig. 6D) commonly envelop these fragments.

Once these facies are more resistant to the erosion reworking, they are applied as field exploration tools and denominate as the “silicified hats”. The small mounts are useful as a guide to reach the primary facies in depth.

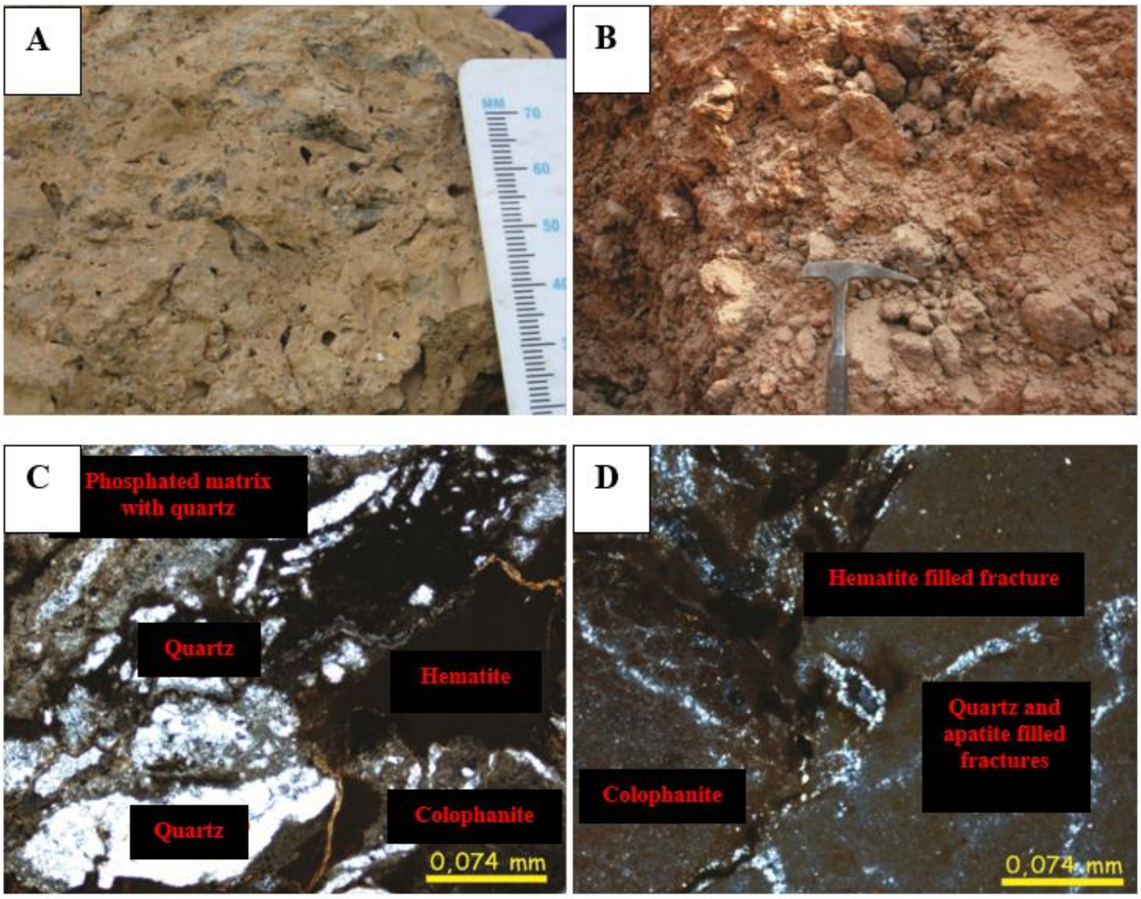


**Fig. 6 - (A)** Hand sample of the Pedogenetic Phosphorite developed over Stratified and Laminated Phosphorite. **(B)** Outcrop of Pedogenetic Phosphorite developed overlaying the brecciated facies. It is importante to notice the massive presence of the phosphatic concretions in a podzolic soil profile. **(C)** Photomicrography of a thin section of the Pedogenetic Phosphorite of the stratified and laminated facies showing the Colophanitic matrix and the neoformed quartz and hematite due the Evolution of the weathering. **(D)** Photomicrography of Pedogenetic Phosphorite of the brecciated facies exhibiting the Colophanitic matrix and posterior fractures filled with hematite, quartz and rares apatite.

*Phosphate Siltstone Facies (Phs)*

This facies is responsible for the majority of the ore volume defined by MbAC Fertilizers Corporation. The thickness of this package varies between 2 and 35 meters. Phosphate siltstone occurs bordering the phosphorite and have variable $P_2O_5$ content depending on their relative position.

These phosphate rocks are represented by laminated siltstone with a beige to yellowish alteration color (Fig. 7A and 7B). The average phosphate content in this type of rock is typically around 4% $P_2O_5$. In general, outcrops are quite weathered and fine neoformed apatite can be observed at edges of siltstone cavities (Fig. 7C).

Based on thin petrographic slides description the intercalation of millimetric levels of pure phosphorite and millimetric levels of phosphate siltstone with very fine detrital quartz can be observed. Colophanitic material accounts for approximately 35% of the bulk rock volume, while quartz, whether detrital or neoformed, and clay minerals together make up the rest 60% of the rocks. Some neoformed apatite is present along with quartz filling the edges of fractures and cavities (Fig. 7D).

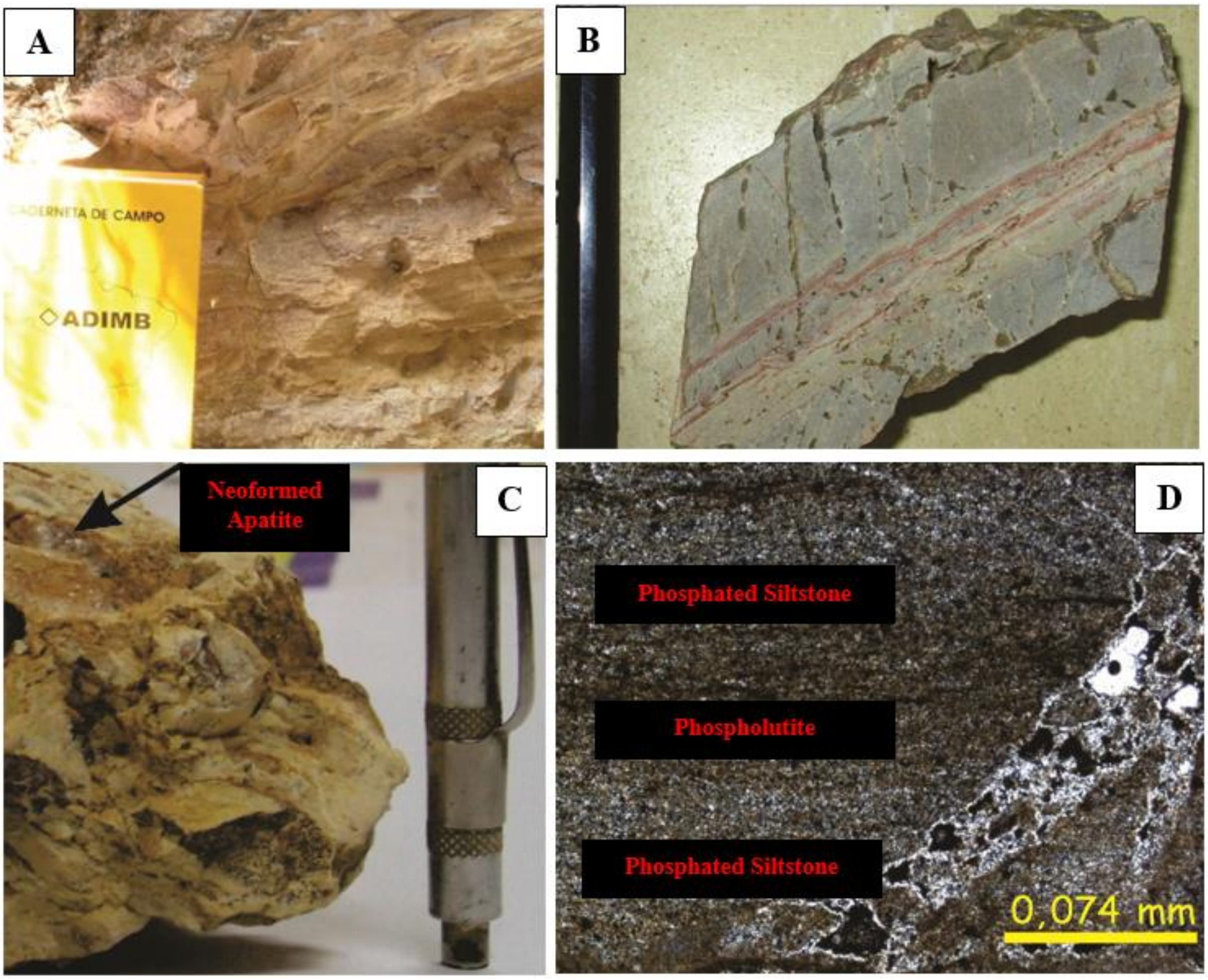


**Fig. 7 - (A)** Field aspect of the Phosphated siltstone facies outcrops. These rocks are generally weathered, however, the planar lamination still preserved. **(B)** Fresh hand sample of Phosphated Siltstone showing the original grayish with reddish stratification planes. **(C)** Neoformed apatite fine crystals filling hand sample cavities. **(D)** Photomicrography of thin slice showing the intercalation of impure and phospholutite rich domains.

4.2 Phosphated Facies Geochemistry

From the X-ray diffractions, it is possible to observe the low complexity of the mineral composition of the studied rocks. The assemblages of rocks from the facies resulting from direct deposition and precipitation are mainly composed of quartz and fluorapatite (Fig. 8A and 8B), as the case of laminated/stratified phosphorite and the brecciated ones, given that the latter represent only the materialization of the primary facies reworking.

For supergenic facies, the weathering profile development results in the presence of aluminous clay minerals, such as kaolinite, which are common under these environmental conditions (Fig. 9A). Similarly, in the phosphatic siltstone, the presence of illite can be interpreted as the alteration of feldspars and muscovite present in the source areas and deposited as detritic minerals alongside the siliciclastic portion of this facies (Fig. 9B).

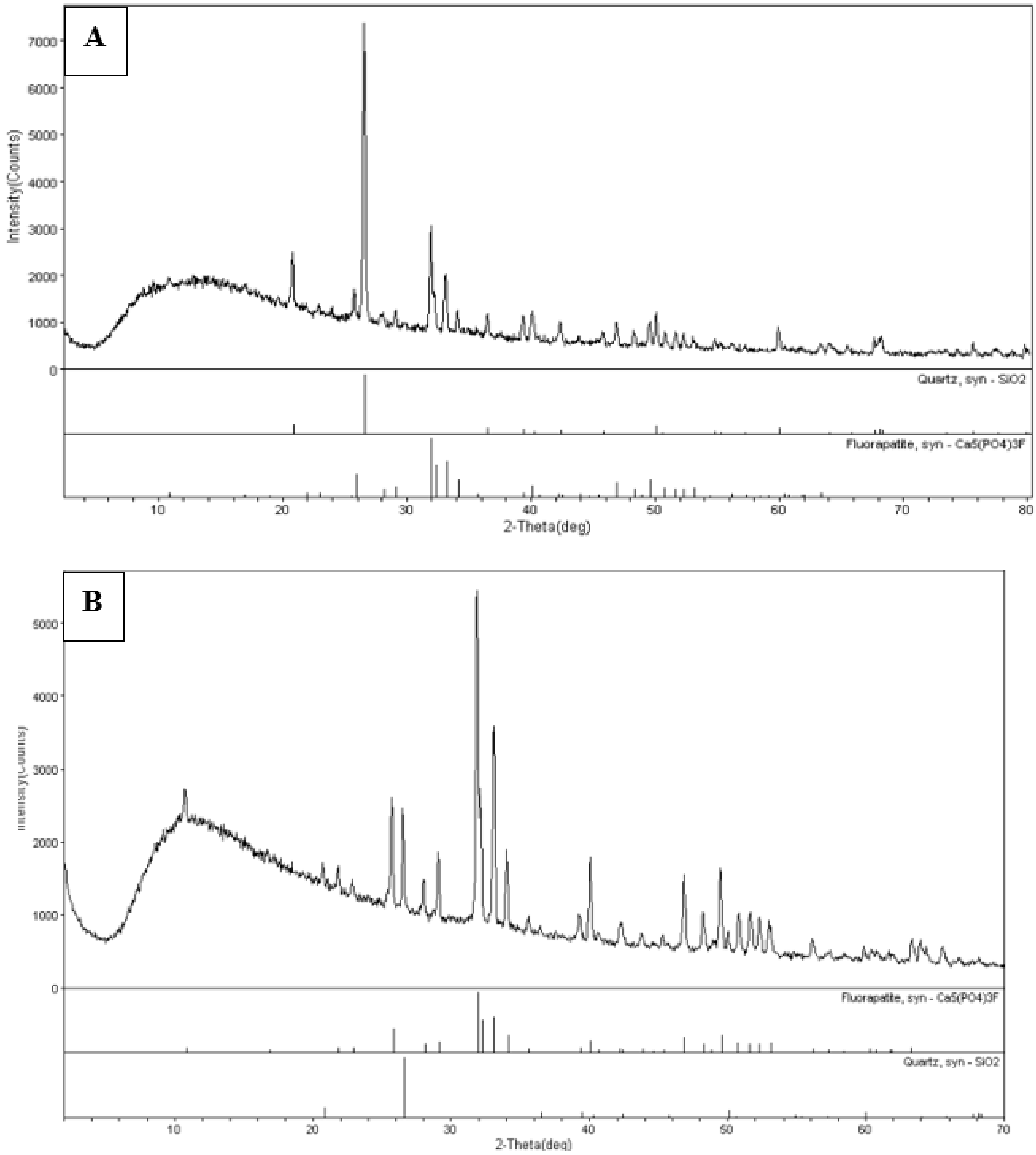


**Fig. 8 - (A)** X Ray diffraction showing the mineral composition of quartz and fluorapatite of the Laminated/stratified Phosphorite facies rocks. **(B)** X Ray diffraction of the Brecciated Phosphorite facies sample corroborating the same and simple mineralogy of the Laminated/stratified facies.

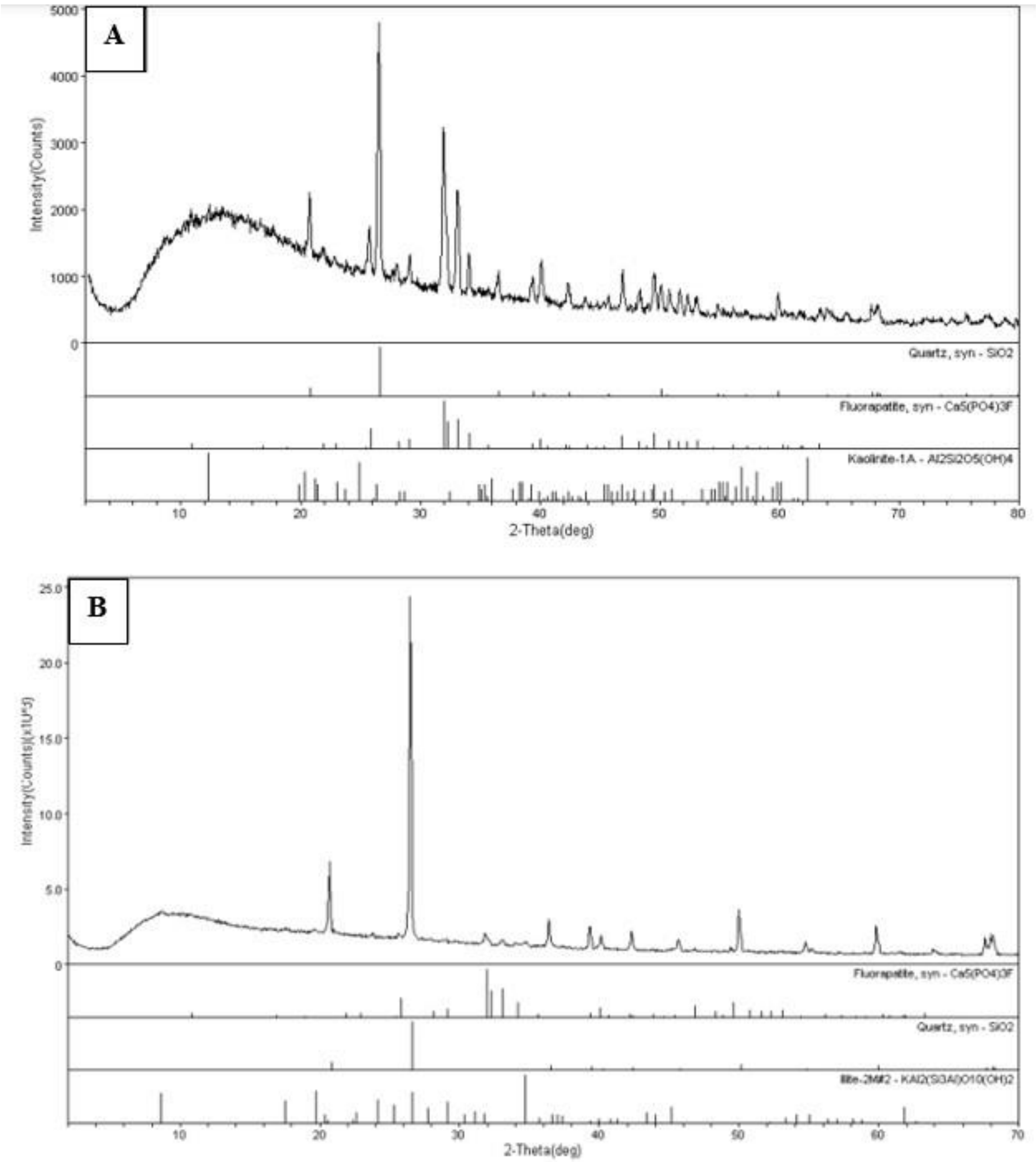


**Fig. 9 - (A)** X Ray diffraction of the Supergenic Facies. In this case, neoformed kaolinite appears in the mineral composition. **(B)** X Ray diffraction of the Phosphate Siltstone facies. Important to notice the presence of illite, that is interpreted as related to the weathering of source areas.

The mineralogy identified by X-ray diffraction is directly associated with the results of geochemistry of major element oxides. In facies dominated solely by precipitation of phosphorus, whether in the form of phosphorite, phospharenite, or colophanite and quartz contributes to the increased modal proportion of chemical sediments. Consequently, the percentages of $P_2O_5$ are considerably higher than those found in facies with superimposed supergenic processes or mixed siliciclastic sediments. Table 1 shows the major oxide percentage values for two representing phosphate rocks samples of each facies.

<table>
<tr><th>Facies</th><th>Sample</th><th>$P_2O_5$</th><th>CaO</th><th>$SiO_2$</th><th>$Al_2O_3$</th><th>$Fe_2O_3$</th><th>MnO</th><th>$K_2O$</th><th>MgO</th><th>$Na_2O$</th><th>$TiO_2$</th></tr>
<tr><td rowspan="2">Sph</td><td rowspan="2">Laminated Phosphorite</td><td>22.48</td><td>33.15</td><td>29.30</td><td>4.48</td><td>2.79</td><td>0.05</td><td>0.72</td><td>0.22</td><td>0.03</td><td>0.09</td></tr>
<tr><td>29.22</td><td>43.58</td><td>13.29</td><td>4.38</td><td>1.40</td><td>0.03</td><td>1.29</td><td>0.54</td><td>0.02</td><td>0.17</td></tr>
<tr><td rowspan="2">Bph</td><td rowspan="2">Brecciated Phosphorite</td><td>34.10</td><td>48.13</td><td>9.04</td><td>1.50</td><td>0.63</td><td>0.02</td><td>0.33</td><td>0.23</td><td>0.02</td><td>0.07</td></tr>
<tr><td>33.63</td><td>48.34</td><td>8.33</td><td>1.43</td><td>0.48</td><td>0.01</td><td>0.37</td><td>0.60</td><td>0.02</td><td>0.06</td></tr>
<tr><td rowspan="2">Pph</td><td rowspan="2">Pedogenic phosphorite</td><td>28.89</td><td>44.62</td><td>13.78</td><td>4.24</td><td>1.82</td><td>0.03</td><td>0.95</td><td>0.42</td><td>0.03</td><td>0.16</td></tr>
<tr><td>22.18</td><td>33.59</td><td>32.84</td><td>4.38</td><td>0.96</td><td>0.06</td><td>0.75</td><td>0.34</td><td>0.01</td><td>0.14</td></tr>
<tr><td rowspan="2">Phs</td><td rowspan="2">Phosphate siltstone</td><td>6.80</td><td>9.27</td><td>69.44</td><td>5.06</td><td>3.90</td><td>0.29</td><td>1.67</td><td>0.73</td><td>0.02</td><td>0.17</td></tr>
<tr><td>16.17</td><td>21.31</td><td>57.59</td><td>1.77</td><td>0.64</td><td><0.01</td><td>0.37</td><td>0.20</td><td><0.01</td><td>0.06</td></tr>
</table>

**Table 1 -** Major oxides percentage values for two representative rocks samples of each phosphate facies.

Based on the bulk-rock geochemistry data, it is clear that phosphate facies cannot only be identified by their sedimentary structures, texture, and mineralogical composition, but also by the concentration of major elements, which represents another important distinguishing factor. Within the analyzed oxides, the concentration of $P_2O_5$ directly reflects the efficiency of chemical precipitation of fluorapatite.

The Laminated/Stratified Phosphorite Facies is the one that has the highest concentrations resulting from direct chemical precipitation (primary facies), and the $P_2O_5$ values typically range around 24%. Because of reworking and concentration of previously enriched facies, brecciated phosphorite are the rocks that showed the highest percentages, taking account the all-genetic environments, reaching values above 30%.

In the case of Pedogenetic Phosphorite Facies, the $P_2O_5$ values found which average around 20%, were lower than those of primary rocks and suggest the lack of supergenetic accumulation development due to oxygen fugacity, favorability of apatite dissolution and leaching in these types of environments.

Finally, the lower $P_2O_5$ contents were found at the Phosphated Silstone Facies. According to the classification of phosphate rocks used in the paper, this facies, by definition, has values below 18% of $P_2O_5$, although both analyzed samples still had higher percentages than those typically found in the majority of siltstone of the Sete Lagoas Formation, which average around 4% and make up the largest ore volume of the study area.

It is important to point out that the siltstone of the Serra de Santa Helena Formation are virtually lacking in $P_2O_5$ content. In fieldwork the siltstone reaction with Ammonium Molybdate in acid medium is a tool to distinguish the siltstone, in cases where the stratigraphy are not well known (the two units siltstone are quite difficult to be differentiate only by field description).

In addition to the $P_2O_5$ values, another quite peculiar characteristic is that the other oxides are always similar among the different rocks of each facies. Furthermore, excluding the pedogenetic facies, there is not significant variation within the entire stratigraphic profile, suggesting quiescence of the depositional sedimentary environments and the involvement of common source areas.

The brecciate facies are interpreted as reworking of primary deposit in the edges of paleo channels where the main laminated phosphorite accumulates.

4.3 Phosphogenetic Model

The sedimentation of the Bambuí Group took place on restricted marine conditions, established by deglaciation events, as an epicontinental sea (Santos et al., 2000) in a foreland basin context. The stratigraphy of this unit begins with the deposition of glacial diamictite from the Jequitaí Formation immediately overlain by cold-water carbonate, known as the “cap dolomite” (Kuang et al., 2022). This dolomite mark the base of the Sete Lagoas Formation and three more transgressive-regressive megacycles that comprises from the top of Sete Lagoas Formation to the top of Três Marias Formation (Pimentel et al., 2011).

As the Sete Lagoas Formation hosts the phosphate deposit and is the main focus of this research, Guacaneme et al., (2017) presented isotopic data of $\delta^{13}C$ that range from strongly negative (-5‰ to 0‰), which abruptly become strongly positive (up to +16‰) at the transition between the upper and lower portions of the unit. This transition marks a significant isotopic range that subdivides the formation (Vieira et al., 2007) and justifies classifying the basal portion as belonging to the depositional cycle of the Jequitaí Formation and the top to the first pelite-carbonate megacycle.

This same pattern of $\delta^{13}C$ signal was stablished by Monteiro et al. (2009) to the Campos Belos region in a 6.0 meters dolomite section deposited directly over the granite basement rocks. In this case the $\delta^{13}C$ values fluctuate from -1.62‰ to -1.09‰.

Within the environmental depositional characteristics of the Bambuí Group base, which are marked by a marine environment of shallow, cold, and calm waters, the dominance of the post-glacial conditions and inputs from deglaciation still have a significant influence and play a primary role in controlling the boundary variables for phosphate precipitation. Teles and Campos (2023) describes a similar genetic model for the phosphate deposit in the Coromandel region (Minas Gerais State, Brazil). In this context, the moderate redox conditions, low temperatures, and reduced biological activity consuming phosphorus in the pro- and periglacial environments (Eyles and Eyles, 1992) favors phosphogenesis in the form of phosphorite cores surrounded by phosphated siltstone. The phosphorous deposition is more commonly in the colophanite phase, due to the concentration of phosphorous in the channel waters.

However, even though the mechanisms involved may exhibit similarities, in the case of the Campos Belos type-deposit, paleogeography plays an important role. These Phosphated facies were preferentially accumulated in irregular, discontinuous, and well-fitted paleo-valleys within the granitic basement or over the arkoses of the Araí Group. The discontinuity of the valleys and, therefore, the occurrences of phosphate bodies, is intimately related to the topography of the region at the time of deposition (Fig. 10A). In these depressed areas, phosphorites are found interbedded with phosphatic siltstones, with limited carbonate participation represented by calciferous siltstone (marl) and dolomite lenses (Fig. 10B).

Campos et al. (2012) have described the paleogeography controlling the mixed carbonate-siliciclastic deposition at the base of the Bambuí Group in the Brasília Belt in different regions. It seems that the same paleo topography arrangement was responsible for controlling the simultaneous deposition of fine siliciclastic and chemical deposits (phosphate and carbonate).

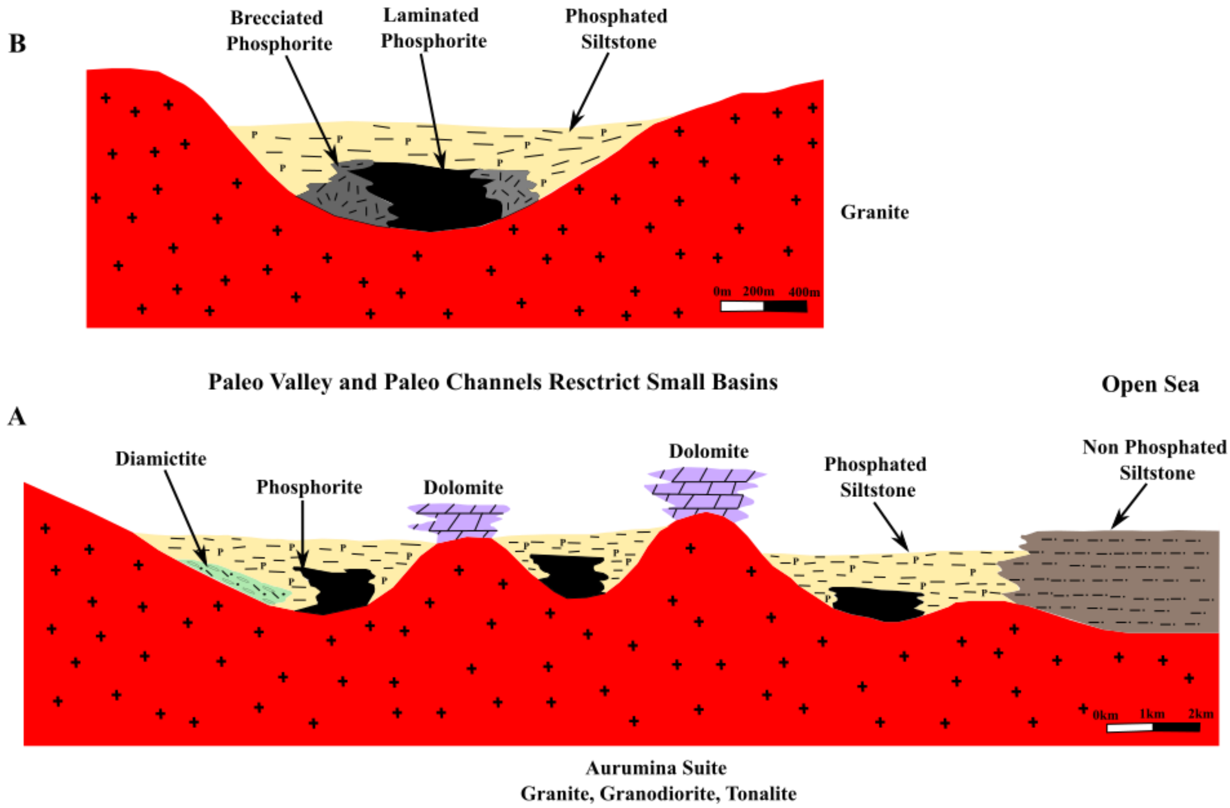


**Fig. 10 - (A)** Schematic cross section illustrating the general model of the depositional conditions on the base of the Bambuí Group (Sete Lagoas Formation) in the study area. Phosphate rocks occur only in the restrict basin conditions. **(B)** Detail on the phosphate facies, showing the primary phosphorite at the paleo valley or paleo channel; the brecciate facies at the edges of the phosphorite nuclei; and the interfingering of phosphate siltstone. Important to notice the proximity between the phosphate sediments and the presence of diamictite (Jequitaí Formation).

An important observation of the Campos Belos type-deposit is the relationship between the phosphatic facies and glacial diamictite. The locations where phosphatic siltstone and phosphorite are found are all marked by outcrops, which can even be small, of these rudaceous rocks, corroborating the strong influence of glaciation on the chemical precipitation of amorphous apatite (colophanite).

The restriction nature of the small basin where the phosphate rocks deposited, controlled by the basement paleo valleys and paleo channels is another important metalogenetic mechanism. When the basin gets an open sea condition, as the transgressive processes evolved, there is no more phosphate rocks occurrences. All the phosphate deposit are exclusively related to the basement proximity and this condition must be taken account in the exploration programs.

The phosphorous source of is considered as continental due to weathering and dissolution of crustal rocks. The glacial transport and sedimentation is responsible to denudation of great areas since the ice central cores up to the proglacial depositional regions. The study area is considered as terminal glacial environment, where the ice sheet melting is responsible to sediment of part of the basal pelite facies (Martins-Ferreira et al., 2013). The cold waters related to this glacial scenario would be important to keep the phosphate in dissolved condition.

**5. Discussions and final remarks**

Occurrences of phosphorite in the Sete Lagoas Formation, at the base of the Bambuí Group, were documented in the northwest edge of the São Francisco Craton. In the study area, pelitic-carbonate and phosphate rocks attributed to the Sete Lagoas Formation were identified. In the region, it was also observed granite associated with the Aurumina Suite basement; metasedimentary rocks attributed to the Araí Group (Paleoproterozoic age) and siltstone belonging to the Serra de Santa Helena Formation. Diamictite constituting the Jequitaí Formation, occurs widespread in the region, is an important guide to the phosphogenesis, and explore vector tool.

The petrographic, mineralogical, and chemical characterization of the phosphate ore were based on observations at mining fronts, field profiles and few drilling cores. Over this characterization, four main facies of phosphate ore can be observed: Phosphatic Siltstone, Stratified Primary Phosphorite, Brecciated Phosphorite, and Pedogenic Phosphorite, with the Stratified Primary Phosphorite and Brecciated Phosphorite types being the richest in phosphate content.

Another significant aspect resulting from the weathering processes is the leaching of phosphate in laterite rocks. In the laterite rocks of the pedogenic phosphorite facies, there is a higher concentration of oxides such as $SiO_2$, $Al_2O_3$, FeO, and MnO, with lower levels of $P_2O_5$, whereas in rocks of the brecciated phosphorite group and the stratified phosphorite subgroup, the opposite occurs.

The depositional environment of the phosphate ore was interpreted as a mixed carbonate platform with a significant contribution of terrigenous material, which graded into a carbonate platform. This environment was established after a marine transgression, triggered by the melting of one of the major neoproterozoic glaciations, resulting in the deposition of sediments from which the diamictite of the Jequitaí Formation, the unit preceding the deposition of the Sete Lagoas Formation. The physicochemical conditions of this environment were responsible for achieving the ideal conditions for phosphate precipitation, in a model similar to the cap phosphorite described for the Coromandel-type deposit, with the intrinsic participation of paleotopography and less proximity to the proglacial area becoming distinctive aspects.

Finally, phosphorite and phosphate siltstones occur interbedded with siltstones with limited carbonate participation. Phosphate precipitation was primarily controlled by the bottom paleotopography of the basement and paleo-climate. Based on stratigraphic relationships observed in mining fronts, it was evident that significant phosphate accumulation occurred in paleo channels incised into the granitic basement, associated with the Aurumina Suite.

The carbonate main lenses precipitated in paleo highs of the basement. The environment was cold, suboxic to anoxic, and had calcium availability, favoring phosphate precipitation. The high calcium rates in the seawater were due to the dolomitization processes widespread in the close basin controlled by paleo channels.

The restrict primary organic growth, due to cold environment, is an important clue to the deposition control once the phosphate could be concentrated in seawater and not be consume by the neoproterozoic and ediacaran organisms.

This category of mineral occurrences is called the Campos Belos phosphorite type-deposit, which is widespread in the São Francisco western margin including the northeast of Goiás State and southeast of Tocantins State. Future studies must be developed to seek the relations of these deposits group with the Coromandel type-deposit in the Vazante Belt.

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**CAPÍTULO 4 - ARTIGO 3**

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# LIGHT ON THE ORIGIN OF THE VERDETE SILTSTONE, BAMBUÍ GROUP, CENTRAL MINAS GERAIS STATE, BRAZIL

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**Abstract**

The Verdete is a variety of a greenish siltstone that occurs occasionally at different stratigraphic levels of the Serra da Saudade Formation, Bambuí Group (Neoproterozoic to Cambrian age). The main rock types related to the Verdete are potassium rich and show the follow mineralogy: quartz, illite/glauconite, orthoclase, albite, ilmenite, fluorapatite and dawsonite. Conventionally, the Verdete has been considered as formed by diagenetic processes in transgressive conditions at calm water environments. However, the present research based on different data considers the Verdete as result of potassic metasomatism in preexisting detritic sedimentary rock (siltstone, fine sandstone and greywacke). The main arguments that support the potassic metasomatic alteration hypothesis are: i) coincidence of the Verdete main occurrences with geophysical anomalies interpreted as alkaline intrusions in depth; ii) presence of dawsonite which is one hydrothermal sodium carbonate; iii) local presence of brecciated facies of phosphorite cross cutting the Verdete facies; iv) lateral discontinuity of the beds and v) microscopic evidence of substitution in coarser facies. The potassic fluids percolated in fracture zone in a northeast trend in the main area of occurrence in central Minas Gerais State (Cedro do Abaeté Town), and besides this region there are also incidence in other areas. The Verdete is considered as a possible source of potassium to be applied to agromineral or industrial supply for fertilization production. In this way, the understanding of its origin must be important to develop new processes or improve the methods to the potassium recover (chemical, biological and thermal routes).

**Keywords -** Applied mineralogy, hydrothermal mineral, geophysical anomaly.

## 1. Introduction

The Serra da Saudade Formation is a predominantly pelitic succession deposited in a transgressive cycle at the upper portion of the Bambuí Group stratigraphic column (Dardenne, 1978). That succession is mainly represented by grayish rhythmites, pale greenish siltstones and rare sandstones and greywackes. However, among the grayish and pale greenish rock package, stands out a strong greenish rhythmite and siltstone, related to an exotic rock type, also known as the "Verdete siltstone" or simply the "Verdete". These unusual rocks are known to be composed by a mineral assemblage related to quartz, K-feldspar, illite and glauconite that contains from 7% to 14% of $K_2O$ (Lima *et al*., 2007).

Locally the Serra da Saudade Formation is interfingered with the Lagoa Formosa Formation (Uhlein *et al*. 2010 and Uhlein *et al*. 2011) which is composed of diamictite, conglomerate, immature sandstone, siltstone with grayish to greenish colors when fresh, and yellowish to pinkish colors when weathered. This unit is interpreted as the result of submarine debris flow and turbiditic currents in a foreland basin. It is important to remark that the Verdete is also present where the Lagoa Formosa outcrops, but these occurrences are local and widespread in the whole basin.

Piza *et al*. (2009) present the Verdete with the follow average composition: 24% of quartz, 37% of glauconite, 10% of caulinite, 7% of detritic mica (mostly muscovite), 14% of detritic clay matter, and 7% of iron oxide, besides traces of detritic microcline and fine grains of zircon.

Over the last years, due to the increasing necessity of agromineral resources, a lot of work has been developed related to the use of the Verdete as a possible potassium source (Duarte, 2019; Santos *et al*., 2017; Santos *et al*., 2016; Santos *et al*., 2015; Martins *et al*., 2015; Silva *et al*., 2012; Toledo *et al*., 2011) but small efforts have been dedicated to the metallogenic process and origin of these rocks.

The main researches are related to the Verdete composition (ex. Piza *et al*., 2009), potassium extraction by acid attacks (ex. Silva and Lana, 2015), by biogenic processes (ex. Duarte, 2019) or by thermal methods (ex. Silva *et al*., 2013).

Up to the present time, the potassium enrichment of the Verdete is interpreted as being processed by sedimentary and diagenetic interactions in transgressive conditions that favored glauconite formation (Moreira *et al*. 2016). According to the Clauer *et al.* (1992) model, the glauconite genesis occurs in specific conditions that can be divided into two different stages. The first is marked by the dissolution of precursor clayish minerals and simultaneous crystallization in equilibrium with the dominant chemical environment until it reaches 4,5% of $K_2O$ in the mineral. The second is marked by the maturation of the crystals and increase in K contents in equilibrium with the marine depositional system. In this sense, the Serra da Saudade Formation glauconite would be formed by substitution on previous deposited clay minerals in reducing environment conditions.

The present work aims to shed light over the Verdete origin based on the integration of geophysical, mineralogical and geological data to propose a new metallogenetic interpretation for these rocks.

## 2. Geological Setting and the Verdete Siltstone

The studied area is located in the geotectonic context of the southwestern limit of the São Francisco Craton and the Brasília Fold Belt (Fig. 1). This portion comprises rocks from the Bambuí, Areado and Mata da Corda groups covered by Cenozoic sediments (Tuller and Silva, 2003).

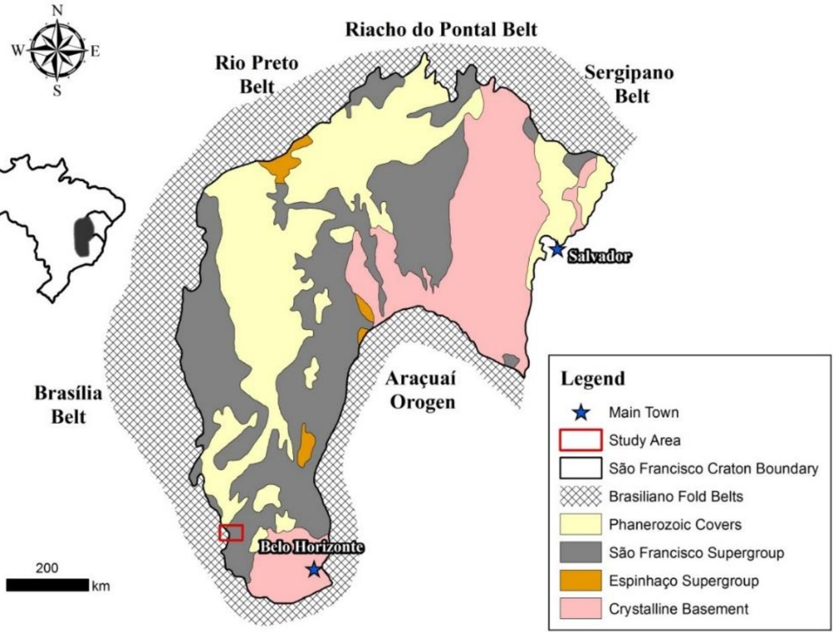


**Fig. 1.** Regional location of the studied area in the geological context of the São Francisco Craton and the Brasília Fold Belt (modified from Alkmim, 2004).

### 2.1 Bambuí Group

The Bambuí Group represents an extensive pelitic-carbonated succession with arkoses at the upper portion of the stratigraphy. It is interpreted as a deposition that starts with a glaciogenic episode followed by three transgressive/regressive megacycles (Dardenne, 1978).According to Dardenne (2000), the Bambuí Group can be divided into six formations, from the base to the top: Jequitaí, Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade and Três Marias.

The Jequitaí Formation stands out for the Sturtian glacial episode and has a lateral restricted occurrence with up to 40 meters thickness. The compositional nature of these sediments supports the interpretation of a continental glaciation followed by the expansion of the ice sheets that reached distal portions of the glacial core (Martins-Ferreira *et al.*, 2013). That formation is characterized by the presence of a glaciogenic diamictite with greenish-grey matrix where a large compositional variety of pebbles including limestone, quartzite, dolomite, schist, granodiorite, granite and tonalite are immersed.

The Sete Lagoas Formation represents the first appearance of carbonate bearing pelitic sediments. These rocks are suggested to be formed on a post glacial moment whereas the melting of the ice sheet allowed the development of shallow water marine environments (Dardenne, 2000). In one hand, at the Brasilia Fold Belt, the carbonate occurs interfingered with lenses of dark grey to black calcilutites, dolomites, marls and shales. These lenses are usually tens of meters thick and hundreds of meters long. In the other hand, over the São Francisco Craton, the carbonate layers are more continuous and thicker, being up to 200 meters thick and tens of kilometers long.

The Serra de Santa Helena Formation is a predominant pelitic succession that is composed by siltstone rich in detrital muscovite at the bedding plans, rare fine sandstone and fine to very fine greywacke beds. The carbonate contribution is restricted to small lenses and beds of centimetric thickness.

The Lagoa do Jacaré Formation is constituted of siltstone and marl with presence of oolitic limestone rich in organic matter. That association proposes a deposition in a shallow water wave dominated platform. Locally hummocky and cross stratifications are observed, showing the storm influence in the deposition.

The Serra da Saudade Formation is characterized by pelitic-sandy rocks like siltstone, shale and fine sandstone deposited on a platform context periodically influenced by storms. According to Lima *et al.* (2007) this succession can be divided in five different lithofacies: pelitic-psamitic rhythmites, hummocky cross stratified sandstones, green glauconitic rhythmite, phosphatic rhythmite and reworked carbonates.

The Três Marias Formation materializes the final stage of the basin, when a storm dominated platform was responsible to arkose and siltstone (and minor conglomerate) deposition. This moment of the basin represents the main erosion and reworking of the mountain ranges associated to the orogenetic processes in the Brasilia Fold Belt.

In geochronological terms, Cloud and Dardenne (1973) first proposed a Neoproterozoic age based on stromatolite occurrences. The first Rb-Sr isotopic data obtained from Parenti Couto *et al.* (1981) and Bonhomme *et al.* (1982) converted to 600 Ma and this age was supported by the researchers for a long time. Babinski *et al*. (2007), based on isotopic data considered a younger age to the Sete Lagoas Formation and the presence of a discordance at the upper portion of this unit. Warren *et al.* (2014) described the presence of *Cloudina* sp. in the Sete Lagoas Formation and recently, many authors have new data which corroborate a younger age to the Bambuí Group deposition (Kuchenbecker *et al*., 2015; Ulhein *et al*., 2017; Denezine, 2018; Baptista, 2020). The discovery of these index fossils supported a late Ediacaran age for the basal portion of the Bambuí Group and allowed an interpretation of younger age for the entire group.

Paula Santos *et al*. (2015) found detrital zircons as young as 560 Ma and Moreira *et al*. (2020) published U-Pb analyses based on zircons collected in a volcanoclastic level in the Serra da Saudade Formation which converts to a concordant age of 520 Ma.

## 2.2 Areado Group

The Areado Group represents the middle unit of the Sanfranciscan basin (Fragoso, 2011). This unit is divided into three formations: Abaeté, Quiricó and Três Barras that shows intense lateral interfingering as a result of concomitant depositional environments.

The Abaeté Formation is predominantly composed of sandstone and conglomerate that outcrop discontinuously along the basin (Campos and Dardenne, 1997b). Sgarbi (2000) described two different rock associations related to distinct environments. The first is marked by matrix-supported conglomerate and lithic sandstone deposited in alluvial fans, and the second is composed of clast-supported conglomerate and sandstone deposited in a high energy braided fluvial system. Ventifact faceted clasts are commonly observed at the top of the conglomerate beds.

The Quiricó Formation is mainly formed of pelite and subordinated sandy contribution (Campos and Dardenne, 1997b) however there are also rare micritic carbonates and black shale (Kattah, 1991). Campos and Dardenne, (1997b) interpreted the depositional environment of this formation as an extensive N-S elongated lake.

Finally, at the top of the Areado Group there is the Três Barras Formation which is characterized by the presence of several sandstones deposited in aeolian, braided river and fluvial delta environments.

Due to the absence of volcanic levels, the ages of the Areado Group are based on relative fossils analyses. Carvalho (2002) and Arai *et al*. (1995) describes species of fish, ostracods and rest of plants that place this unit through the Cretaceous, from the Aptian to the Barresian.

## 2.3 Mata da Corda Group

The Mata da Corda is the youngest unit in the geological context of the study area and is divided into Patos and Capacete formations. Differing from the other units, the Mata da Corda is predominantly composed of igneous rocks and their reworked products (Fig. 2).

Effusive and pyroclastic alkali volcanic rocks mark the Patos Formation. According to Sgarbi and Valença (1991), these rocks can be classified as kimberlites with high potassium affinity. Therefore, the Capacete Formation shows the result of the Patos Formation reworked into lithic greywackes, volcanic sandstone and conglomerates, all rich in volcanic rocks fragments and minerals derived from them: olivine, pyroxene, perovskite, magnetite, titanite and other trace minerals.

Geochronological data obtained by Hasui and Cordani (1968) and Bizzi *et al*. (1995) point to ages ranging from 119 to 68 Ma. The older rocks (Lower Cretaceous) are related to carbonatitic major intrusions (like the Catalão I and Catalão II bodies). The younger ages (Upper Cretaceous) are more commonly observed as alkaline effusive and pyroclastic facies and the related intrusive.

According to Fernandes (2013) the lava flows are about 20 meters thick and the derived sediments are up to 45 meters.

## 2.4 Cenozoic Cover

The Cenozoic covers are represented by clay-silt-sand sediments, sandy unconsolidated covers, sandy soil and lateritic horizons. The main deposits are preserved in the high plateaus areas and are related to the Chapadão Formation (Campos and Dardenne, 1997).

The geological map of the study area is attributed to Tuller and Silva (2003) and the spatial relationship and the lateral distribution of facies can be summarized in Fig. 2.

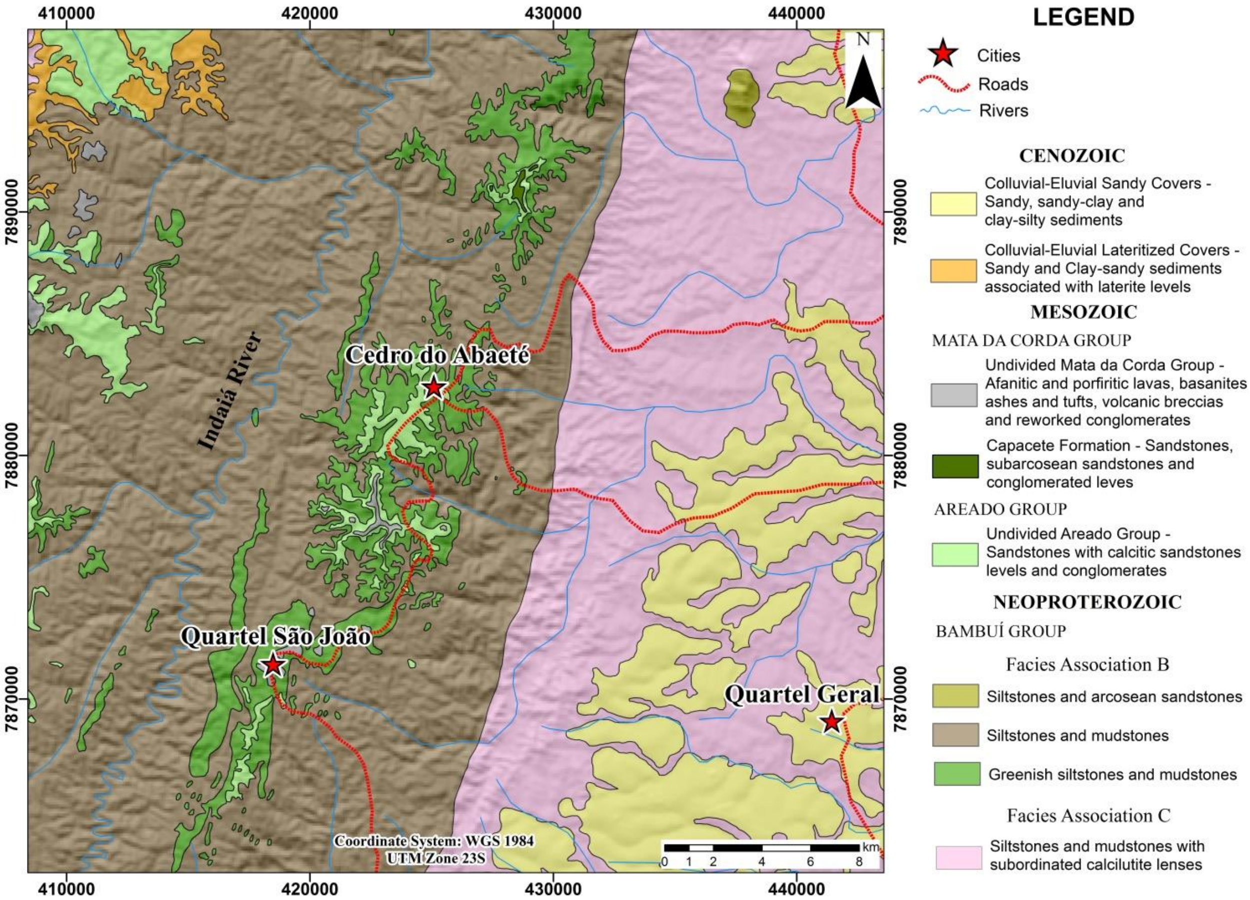

**Fig. 2.** Geological map of the study area focusing on the main Verdete occurrence belt (Tuller and Silva, 2003).

2.5 The Verdete Siltstone

According to Lima *et al.* (2007) the Verdete is a well stratified rock with fining upward pattern, marked by fine sandy texture at the basal portion that gradates to silty clay at the top. Based on the textural characteristics and presence of hummocky cross stratification, Uhlein et al. (2004) interpreted this succession as a stormy dominated environment (Fig. 3).

The horizontal bedding and lamination are the main well developed structures in all outcrops, and is marked by the alternation of shale, greywacke, siltstone, fine sandstone, all showing the characteristic green color.

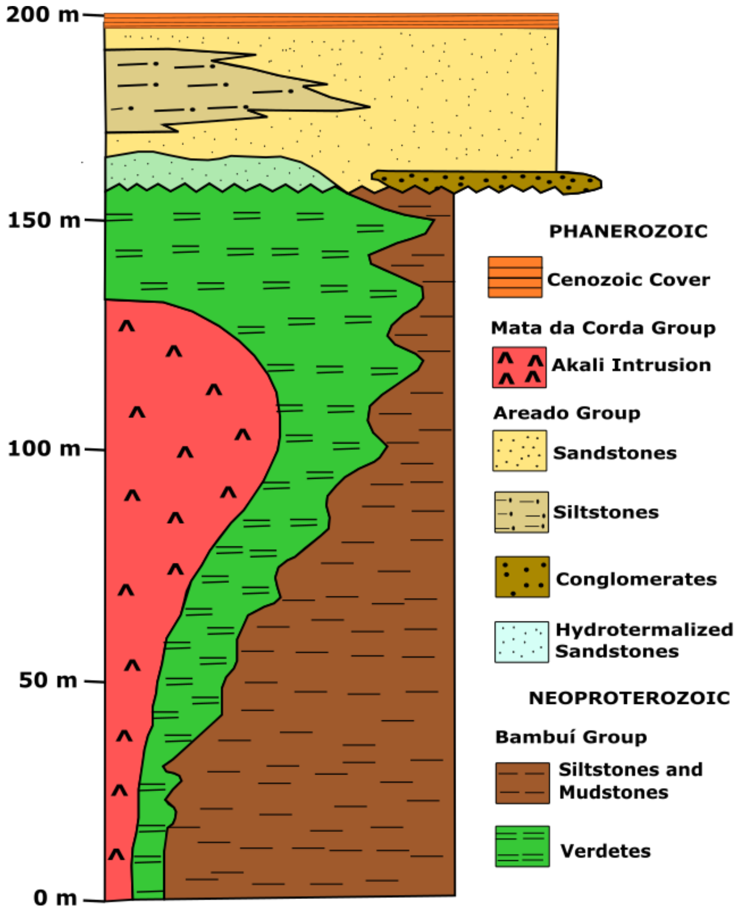


**Fig. 3.** Stratigraphic column showing the relationships between the Verdete and the other rocks at the study area (Modified from Lima, 2005).

In genetic terms, Moreira *et al.* (2016) suggest that the glauconite is an authigenic mineral formed as diagenetic phases in illite-rich sediments deposited on an extensive flooding at the Bambuí basin. The potassium necessary to this substitution is considered as leached out from continental felsic rocks and accumulated in deep marine water. Subsequently the iron, potassium and other elements were transported by upwelling currents to shallower portions after a regional transgression event, when the original illite was enriched in K transforming into glauconite (Fig. 4).

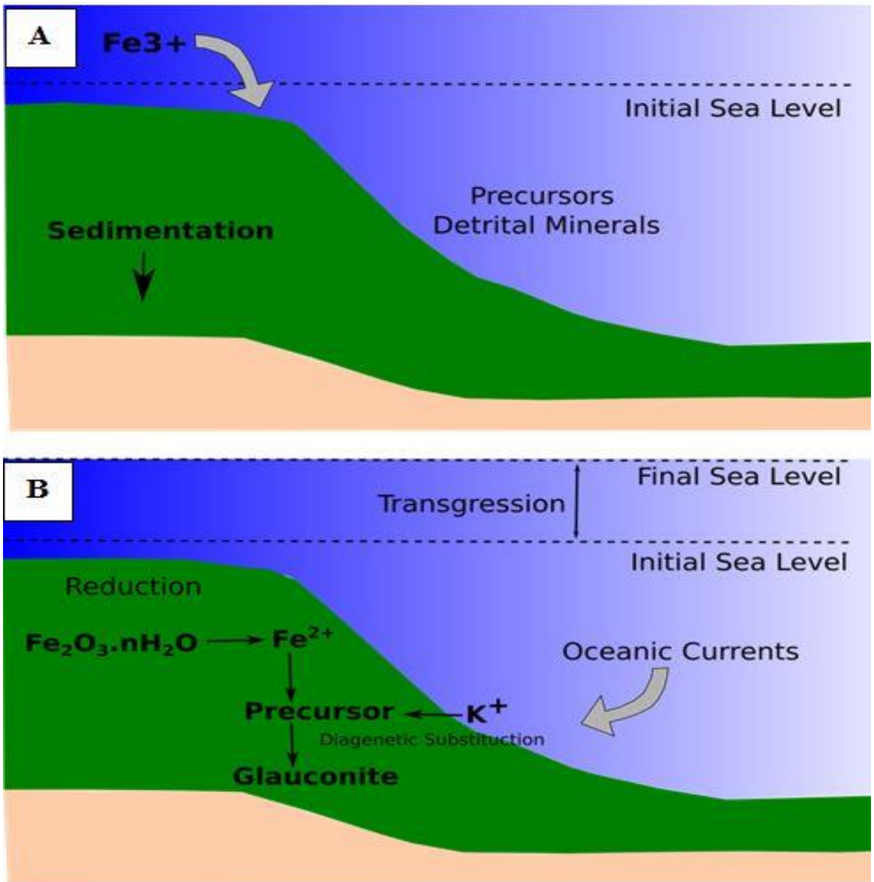


**Fig. 4.** Schematic representation of the glauconite diagenetic genesis in the Serra da Saudade Formation (modified from Moreira et al., 2016).

Although the proposed sedimentary model for the mineralization is up to now the main hypothesis, there are others features that point out to a hydrothermal contribution. First, the magnetometric and radiometric geophysical data shows an intrusive igneous body in depth that are immediately below the Verdete occurrences at the surface. Besides the regional geophysical anomalies, the shape and restrict occurrence of the Verdete outcrops, the presence of hydrothermal mineral in the assemblage and brecciated facies suggest the influence of potassic metasomatism as a determinant genetic factor.

## 3. Material and methods

The study integrated different techniques starting with a field campaign to collect rock samples in order to closely represent the entire Verdete occurrence. Field observations and description of hand samples and outcrops along the entire Verdete occurrence areas and its boundaries let to geological interpretation.

For better mineralogical understanding, 9 different samples were analyzed at the X-ray Diffractometry Laboratory of the University of Brasília. The selected samples were pulverized in a ball mill for 5 minutes at 400 rpm. To prepare the analysis of bulk sample, the powder was placed in a dug slide (2.0 x 1.5 x 0.005 cm) and the samples were processed in a DRX Rigaku - Ultima IV diffractometer, equipped with copper tube, nickel filter under 35 kV/ 15 mA and DTEX / ULTRA detector. The scan was performed in the 2θ range from 3° to 80°, step 0.05, speed 1°/min. Minerals were identified using the Jade XRD 9.0 (Materials Data) program with a PC-PDF (Powder Diffraction File - PDF for PC) database.

For textural observation associated with the mineral chemistry, two samples were evaluated with the Scanning Electron Microscope - SEM. The samples were carbon-coated and powdered sample recovered with silver paint (RTC-48-B-PO). Textural analyzes were performed in the secondary electrons mode (secondary electron - SE) and compositional variations in the backscattered electrons mode (backscattered electron - BSE) using FEI QUANTA 450 SEM operating at 20 kV, with working distance of 10.7 mm and electron beam diameter of 10 µm.

The aerogeophysical data of the study area was provided by CODEMIG (Minas Gerais State Development Agency) Geophysical Survey Project - Area 10. This survey was performed and processed by Prospectors Aerolevantamentos e Sistemas LTDA and counted on N-S flight lines spaced 0.5 km and E-W control lines every 10 km at 100 meters height (Prospectors, 2008). Nine selected samples were submitted to whole rock geochemical analysis following the ACME Laboratory (www.acmelab.com) routine. For whole rock analysis, 0.2 g of each sample was fused with lithium meta/tetraborate, dissolved by nitric acid digestion and measured by ICP Atomic Emission Spectroscopy. Otherwise, to analyze trace elements and base metals, 0.5 g of the samples fused with lithium meta/tetraborate was digested in aqua regia and analyzed by ICP Mass Spectrometry.

## 4. Results and Discussion

The geological field observations suggest that the Verdete rocks occur dominantly along a N10E elongated zone. In this context, the greenish rocks crop out like discontinuous thin lenses streaked in the siltstone and mudstone of the Serra da Saudade Formation. Additionally, at the vicinities of the main occurrence there are restricted and isolated bodies with minor areal and volumetric expression.

At the road cuts is possible to notice an intense variety of textural and compositional features of the Verdete (Fig. 5). In the middle portion of the study area, the outcrops show a dominance of the Verdete siltstones and rarely presence of other pelitic rocks. However, upward to the stratigraphy sequence, it is easy to notice the increase of sandy rocks that maintain higher relief morphologies. Theses sandstone are correlated to the Areado Group, once it is commonly observed isolated clasts and conglomerate beds at the base. Between the Verdete sequence and this sandstone there is a clearly erosive surface that marks the contact of the Bambuí and the

Areado groups. At his surface it is observed ventifact clasts with the typical polished faces because of the wind reworking.

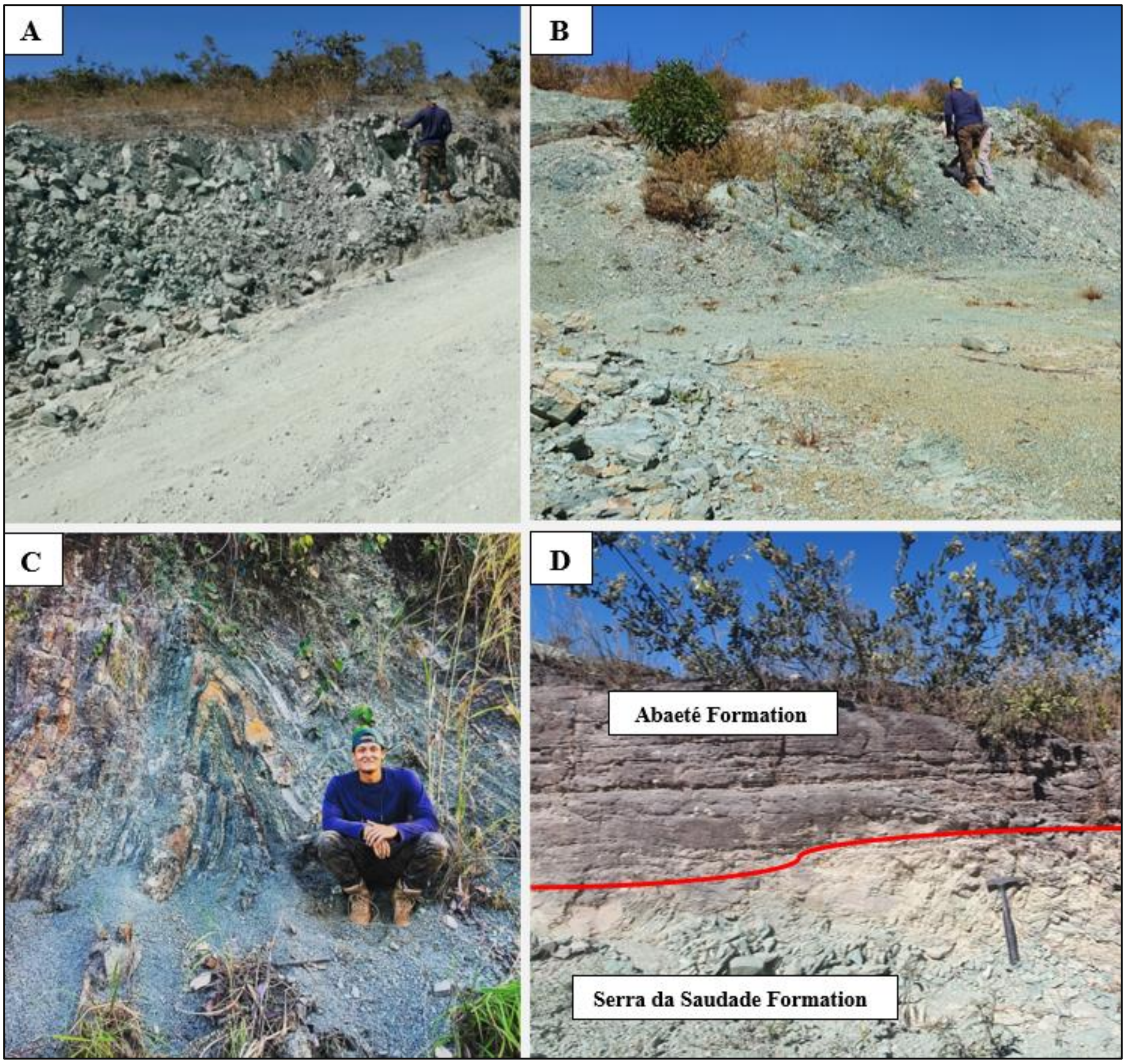


**Fig. 5.** General aspects of the main Verdete outcrops at road cuts showing an intense variation of textural and compositional features. **(A)** Road cut with massive muddy rocks and dark greenish tone. **(B)** Road cut showing a well stratified silty rock with pale gr greenish tone. **(C)** Greenish rhytmite with chevron type fold that is an ordinary feature of this facies. **(D)** Erosive surface pointing out the relation between the Serra da Saudade Formation (Bambuí Group) and the Abaeté Formation (Areado Group).

The greenish tone and K contents are both linked to the modal percentage of the mineral glauconite. In fact, the most pelitic levels shows a stronger green color and K enrichment because the higher concentration of glauconite as a clay mineral.

The observation of outcrops and the hand samples allow noticing three different facies of Verdete that can be distinguished in the field. Features like texture, structures and color are essential tools to separate the types.

The first facies is represented by a massive grey to dark green siltstone. The second one is characterized by a mudstone with a strong greenish tone that commonly is rhythmically interleaved with thin sandy layers and deformed by symmetrical boxes and chevrons folds. The last facies is composed by intense weathering brecciated level (Fig. 6).

One important factor is the presence of thin percolation surfaces at the greener facies suggests fluid circulation due to these portions. The brecciated facies also shows fluid circulation pattern, resulting in a boxwork texture.

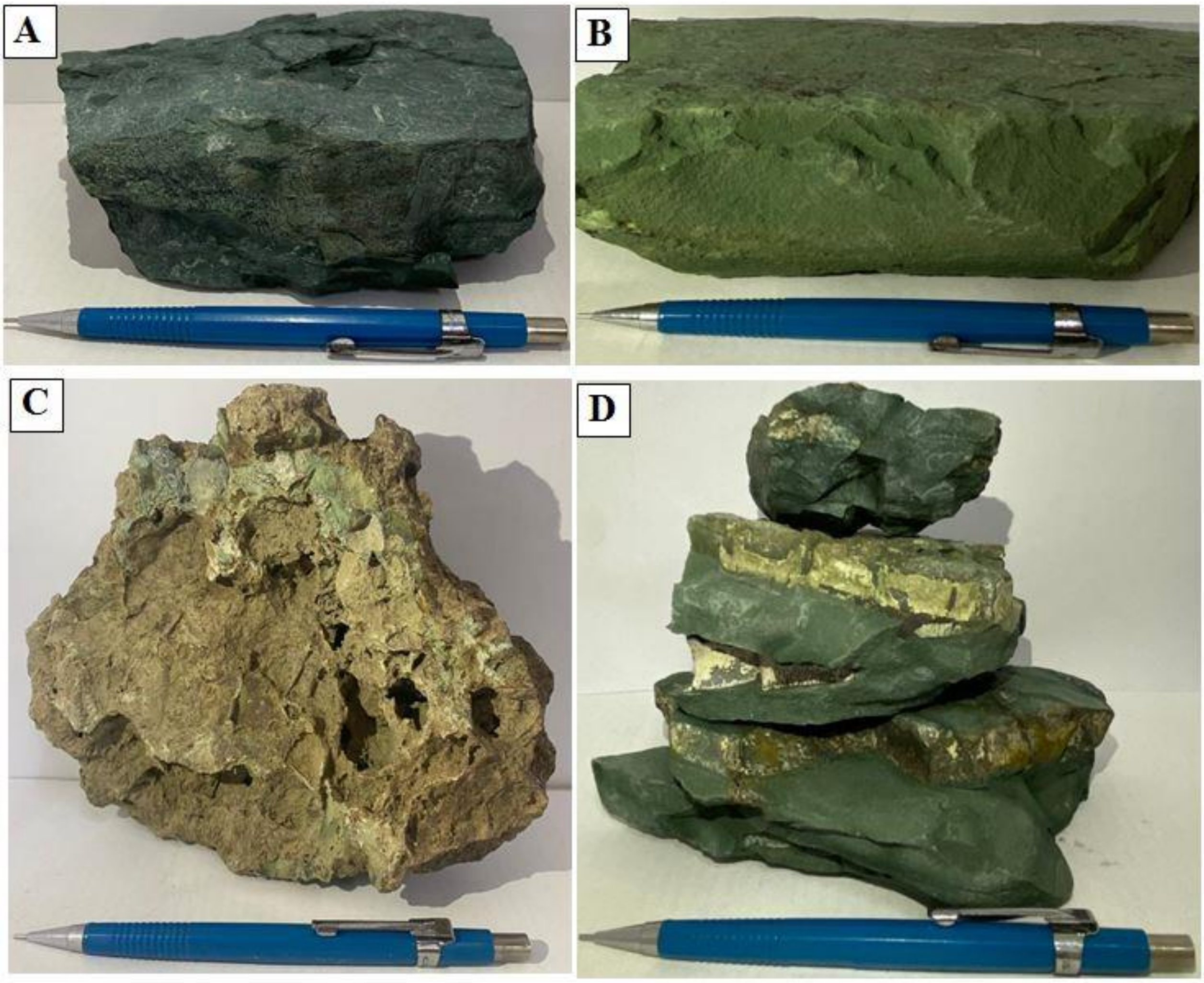


**Fig. 6**. **(A)** Grey to dark green massive siltstone. **(B)** Strong greenish mudstone that is part of the rhythmitic sequence. **(C)** Brecciated Verdete with vugs and advanced weathering. **(D)** Whitish percolation surfaces in the Verdete hand samples.

The mineralogical data resulting of the association of X-Ray diffraction combined with the scanning electron microscope showed that the Verdete is a substantial potassium-rich resource but cannot be considered as a phosphate source. X-Ray diffraction identified an assembly composed by quartz, illite/glauconite, orthoclase, albite, ilmenite, fluorapatite and dawsonite, a hydrated sodium carbonate (Table 1 and Fig. 7).

Locally there are phosphate rich facies, related to brecciated rocks in stockwork pattern, but these rocks are rarely observed.

| Samples Number | 36A | 39A | 48A | 48B | 49 | 53A Fresh | 53A Altered | 53B | 55 |
|---|---|---|---|---|---|---|---|---|---|
| **Minerals** | | | | | | | | | |
| **Rock facies** | **1** | **2** | **1** | **3** | **2** | **2** | **2** | **2** | **4** |
| Quartz | X | X | X | X | X | | | | X |
| Illite / Glaconite | X | X | X | X | X | X | X | X | |
| Orthoclase | X | | X | X | X | | | | X |
| Albite | | X | | | | | | | |
| Muscovite | | X | | | | | | | X |
| Ilmenite | | X | | | | | | | |
| Fluorapatite | | | | | | X | X | X | |
| Dawsonite | | X | | | | X | X | X | |

**Table 1.** Minerals found in different facies of the Verdete and siltstone (determined by X-Ray analysis). Rock facies: 1 - fine sandstone; 2 - Verdete; 3 - fine greywacke; 4 - siltstone (not Verdete type).

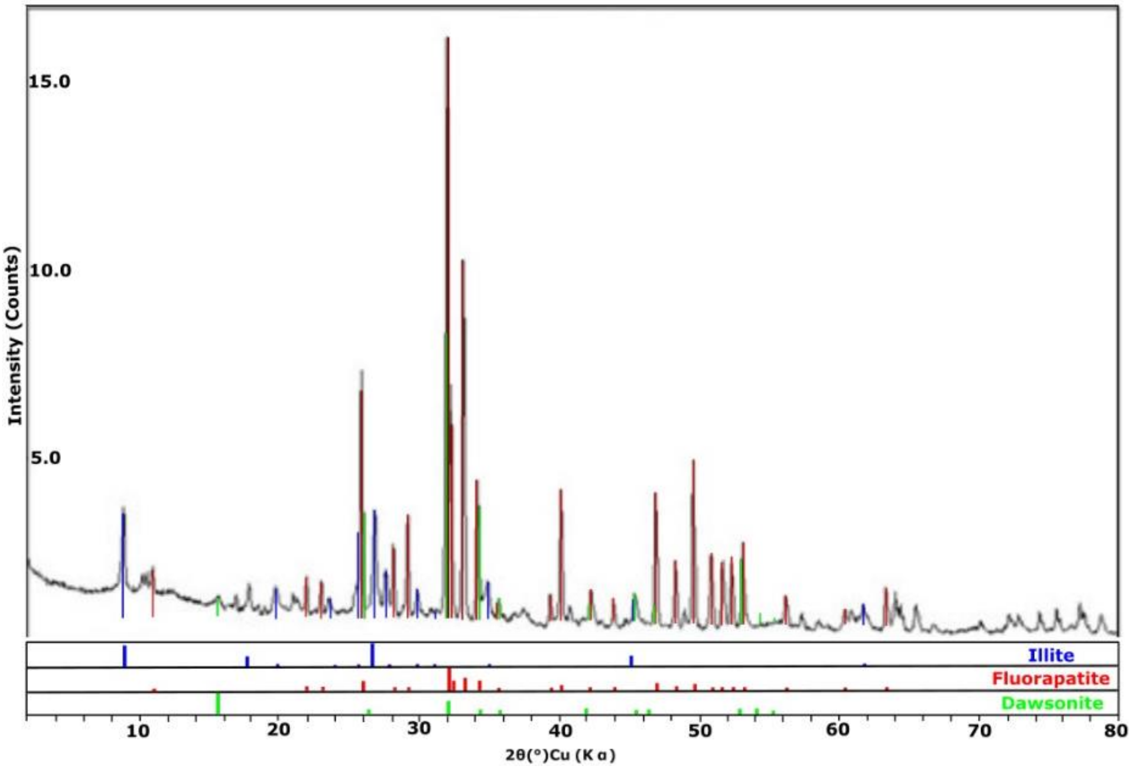


**Fig. 7.** X-Ray diffraction pattern showing the common mineral assemblage (illite, fluorapatite and dawsonite) in typical Verdete samples with textural features similar to Fig. 6D.

According to Coveney and Kelly (1971) and Ferrini *et al*. (2003), dawsonite is a product of low temperature hydrothermal alteration of Na bearing aluminum silicates that can be found in different types of magmatic rocks, specifically on alkali members. This mineral is also described in sedimentary facies submitted to diagenetic conditions. In both cases, whether related to low temperature alteration or diagenetic context, the mineral formation temperatures are similar and close to 105°C.

Quartz, orthoclase, albite, muscovite and ilmenite are interpreted as detritic minerals transported from de source areas. Illite is considered an authigenic mineral, linked to the sedimentary environment. Glauconite, fluorapatite and dawsonite are considered as hydrothermal minerals.

In addition to mineralogical results, the geochemical analyses show a discrepant value of the keys elements used by Sgarbi *et al*. (1991) to classify the Mata da Corda magmatism (Table 2). These elements higher values can be interpreted as a heritage from the magmatic potassic fluid circulation added to the precursor sediments chemical system. The magmatism related to the Upper Cretaceous in the Alto do Paranaíba region is truly of the alkaline type, more properly of the potassic to ultrapotassic composition (Sgarbi and Valença, 1995 and Quintão *et al.*, 2017). This magmatic character explains the high average contents of $K_2O$ and slight enrichment of MgO which must be related to the diffusion of the fluids into the sedimentary layered host rocks (siltstone, lithic fine sandstone and greywacke).

| **Sample** | **Rock Type** | **Formation/Group** | **$SiO_2$ (%)** | **$TiO_2$ (%)** | **$Al_2O_3$ (%)** | **$Fe_2O_3$ (%)** | **MgO (%)** | **CaO (%)** | **$K_2O$ (%)** | **$Na_2O$ (%)** |
|---|---|---|---|---|---|---|---|---|---|---|
| RCT 36A | Verdete Siltstone | Serra da Saudade/ Bambuí | 59.62 | 0.86 | 15.40 | 6.26 | 3.16 | 0.06 | 10.86 | 0.09 |
| RCT 42 | Verdete Siltstone | Serra da Saudade/ Bambuí | 62.37 | 0.95 | 15.21 | 5.58 | 2.38 | 0.01 | 9.30 | 0.10 |
| RCT 48A | Verdete Siltstone | Serra da Saudade/ Bambuí | 58.24 | 0.83 | 15.72 | 6.65 | 2.98 | 0.03 | 10.77 | 0.09 |
| RCT 45 | Siltstone | Serra da Saudade/ Bambuí | 61.53 | 1.01 | 18.68 | 7.13 | 0.94 | <0.01 | 3.54 | 0.05 |
| RCT 37A | Volcanic Sandstone | Capacete/Mata da Corda | 37.27 | 17.53 | 3.80 | 24.85 | 3.25 | 3.06 | 3.27 | 0.08 |
| * Sgarbi *et al.* (1991) | Ultrapotassic volcanic | Patos/Mata da Corda | 44.00 | 5.50 | 8.50 | 3.50 | 7.50 | 10.00 | 5.50 | 1.00 |

**Table 2.** Chemical analysis results of samples from the Serra da Saudade Formation and the Mata da Corda Group in the São Gonçalo do Abaeté and Alto do Paranaíba regions. * Mean values of 27 samples analysis.

The Capacete Formation sample (RTC 37A) is represented by volcanic sandstone related to the reworking of pyroclastic rocks of the Patos Formation. Sample RCT 45 is a yellowish to brown siltstone from de Serra da Saudade Formation out of the Verdete siltstone domain.

Besides the $K_2O$ and MgO, the enrichment of Cobalt, Vanadium and Cerium, in relation to the regular sediments of the Serra da Saudade Formation, is interpreted as result of the interaction of the plutonic alkaline rock with the pelitic proterozoic siltstone.

An important association of the Verdete rocks occurrences and distribution are related to strong correlation to geophysical anomalies.

In fact, the geophysical data comprises aerogammaespectrometry shallow anomalies and aeromagnetometry anomalies of deep intrusive bodies intrinsically correlated to the main Verdete occurrence areas (Fig. 8 and 9). Based on the regional geological setting, even though these intrusions do not outcrop, they can be correlated to the ultrabasic and ultrapotassic intrusions of the Mata da Corda Group, since the same pattern is present in the plutonic and volcanic occurrences of the magmatic outcropping rocks. Due to the size of the geophysical signature, the possibility of these intrusions to be correlated to carbonatite bodies as those that outcrop in Catalão and Araxá regions (respectively Goiás and Minas Gerais states) is not discarded. By the other hand the chemical signature of the Verdete Siltstone can be more likely associated to the ultrapotassic magmatism of the Mata da Corda Group.

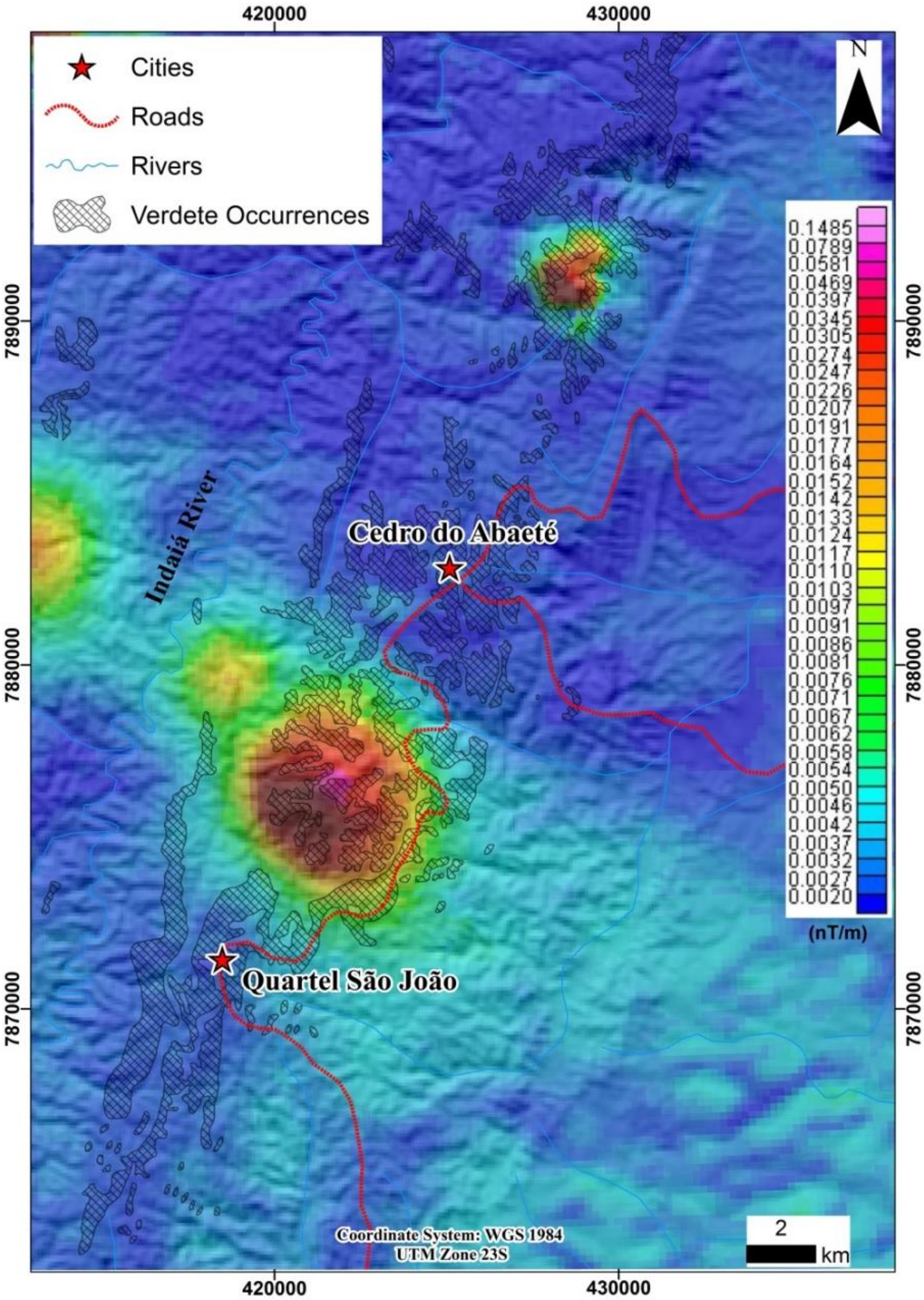


**Fig. 8.** Analytical signal map showing the direct relationship between the positive magnetic anomalies and the main Verdete occurrences. The geophysical anomalies, in this case, are interpreted as alkaline intrusions at depth.

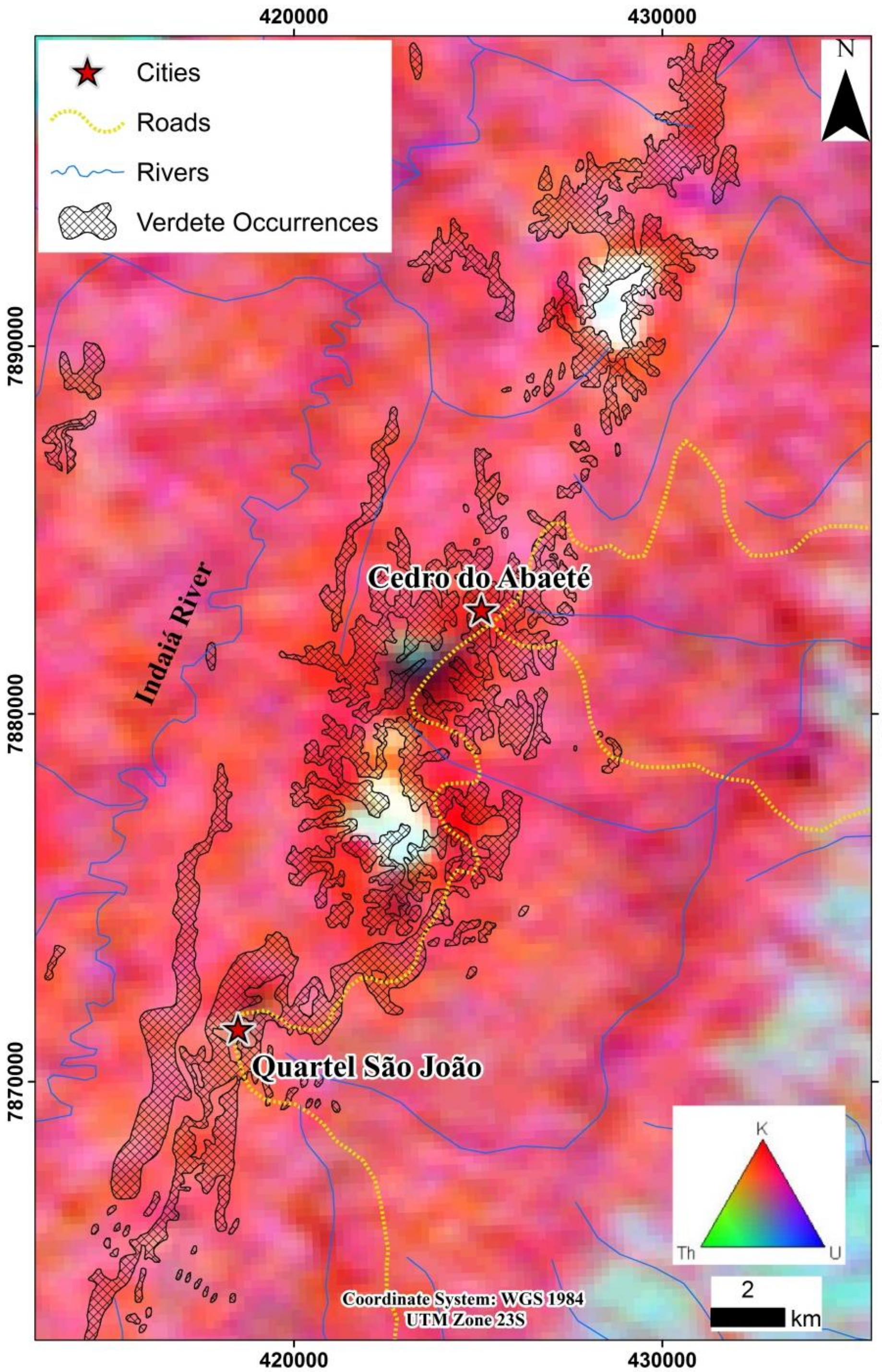


**Fig. 9.** Gammaespectrometry map and the Verdete occurrences. The NE trend of the Verdete distribution corroborates the magnetic anomalies and is partially coincident to the high K, Th and U cores. It is possible to notice a high K fringe surrounding the anomalies.

Based on the compilation of the geological, geophysical and mineralogical data obtained is possible to strongly suggest that the Verdete is a product of a low temperature metasomatic alteration of the preexisting siltstone of the Serra da Saudade Formation. Deep cretaceous alkali intrusions of the Mata da Corda Group are the principal sources of heat and fluids that modified the chemical content of the primary sedimentary rocks resulting in high potassium and locally high phosphate zones.

As all the regional siltstones are potassium rich, the gammaespectrometry anomalies are not the best tool to individualize the Verdete, but it is still possible to verify the stronger red tones next and surrounding the main occurrences. The stronger the red tones, the richer in K the rocks. It is important to notice that in these locations there is no thick soil cover, so that the anomalies are directly related to the rock outcrops.

The analysis of the gammaespectrometry map (Fig. 9) still permit to interpret three intrusions bodies at depth, what is understood as the intrusion cores. Two of them are rich in the three nuclides K, U and Th, and the central smaller body demonstrates the same content of the three radionuclides.

Fig. 10 shows a schematic model to explain the metasomatic hypothesis of the Verdete siltstone origin, which includes the following processes:

i) Deposition and lithification of the siltstone of the upper portion of the Bambuí Group at the Neoproterozoic or even in the Cambrian. The burring of the sedimentary succession was not expressive, due to the low deformational aspect and anchimetamorphic grade of the siltstone;

ii) Intrusion of alkaline potassium rich magma at depth in the Upper Cretaceous. The intrusive bodies were not, up to now, exhumed, once no outcrop is observed in the whole study area;

iii) Percolation of potassic metasomatic fluids in the host rocks. This fluid migration was facilitated by the strong fractured pattern and by the sparse cleavage of the country rocks;

iv) Interaction of the fluids with the preexisting rocks and substitution of illite by glauconite, crystallization of dawsonite and local crystallization of phosphate minerals.

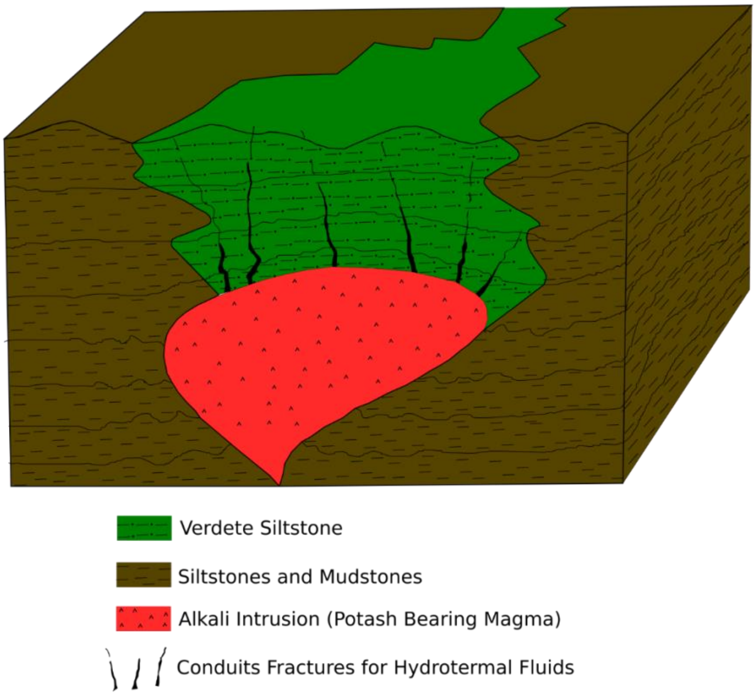


**Fig. 10.** Schematic model to the Verdete siltstone origin. The alkaline intrusions are the source of hydrothermal fluids that percolates into fracture and cleavage planes to shallow crustal portions.

This interpretation is supported by several data that corroborate the hydrothermal genetic model. First, the geophysical data shows that the Verdete main occurrences are very close to the intrusive bodies' anomalies. The most expressive outcrops are right above and in the immediately fringes of the anomalies that represent intrusions in depth. Furthermore, the presence of dawsonite, which is a hydrothermal mineral index, upholds the influence of heat and fluids to modify the chemical compositional of the primary sedimentary minerals of the Serra da Saudade Formation.

It is important to point out that the anomalies observed in the study area are similar to those ones related to the main regional alkaline rocks outcropping in Goiás and Minas Gerais States.

The chemical data, due to the potassium, magnesium, vanadium, cerium and cobalt content also are not common in the Serra da Saudade Formation sediments and indicate post depositional changes in the composition due to hydrothermal fluids. Another observation that is important to the proposed model is the presence of brecciated facies with a strong hydrothermal aspect. These rocks, nonetheless, the textural features, are phosphate rich, what is not expected to common marine siltstone, suggesting once more the influence of alkali fluids to the formation process.

Also, the lateral discontinuity of the Verdete beds is an argument to the hydrothermal origin, otherwise, it would be more common keeping the sedimentary original features and the Verdete would be observed in different areas related to the Serra da Saudade Formation.

Finally, all the observations presented in this work were based on surface data, geophysical products, and outcrops, however Moreira *et al*. (2016) describes 4 drill holes and their stratigraphic relationship. Those holes are located in the neighborhood or in the immediately boundary of the magnetometric anomalies and the Verdete siltstone occur in these places as discontinuous vertical intervals that suggest a lenticular form for the deposit, corroborating once more a zone of high concentration generated from the percolation of hydrothermal fluids.

**5. Conclusions**

The new data and observations of the Verdete rocks of the Bambuí Group point to a robust metasomatic metalogenetic process induced by circulation of potassic fluids that is responsible for the accumulation of anomalous quantities of potassium, not commonly found in sedimentary rocks. The mineralogical, chemical, geophysical data and geological observations support that high K rocks are product of a low temperature metassomatism from deep alkali intrusions of the Mata da Corda Group that did not change the structure, but just the chemical composition of the primary sedimentary rocks.

Thus, the great majority of the Serra da Saudade rocks are described as ordinary siltstone facies and the Verdete are rare and isolated occurrences that tend to appear next to the Mata da Corda Group or related to potential intrusions in depth.

If the Verdete were connected to sedimentary processes much more occurrences widespread into the basin area would be expected. Other small occurrences of the Verdete must be related to the same hydrothermal origin, like the one reported in the literature in the Patos de Minas, Lagoa Formosa, São Gotardo and Boassara regions, all located in the central portion of Minas Gerais State.

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# CAPÍTULO 5 - DISCUSSÕES INTEGRADAS

## 5.1 Rochas Potenciais Fontes de Agrominerais na Faixa Brasília

No contexto geológico da Faixa Brasília são reconhecidas inúmeras rochas com eficiente capacidade de utilização como remineralizadoras de solo, como é o caso das vulcânicas e plutônicas alcaninas neocretáceas do Grupo Mata da Corda, que comprovadamente por Loureiro *et al.* (2010), Faroutine (2018), Ferreira (2021) entre outros, mostram resultados promissores no desenvolvimento vegetal após a sua aplicação. Entretanto, como o cerne da discussão da tese é voltado para os depósitos sedimentares, foram consideradas apenas as sequências associadas as bacias proterozoicas/cambrianas.

Dentro dessa perspectiva, as áreas mineralizadas apresentam potencial para suprir tanto os macronutrientes Ca/Mg, $P_2O_5$ e K como também, micronutrientes (Zn, Cu, B, Mn, Mo, Fe, Ni e etc) dependendo das fontes adotadas e formas de utilização.

Para os macronutrinetes Ca/Mg, as unidades carbonáticas amplamente descritas e pesquisadas desde o início da definição das grandes unidades sedimentares da porção externa da faixa são as principais fontes, em especial os dolomitos. Essas rochas são fundamentais para o desenvolvimento da agricultura em regiões de climas tropicais e subtropicais. A aplicação do material pulverizado como corretor de solos possui função de elevação do pH para impedir a mobilidade do alumínio trocável, que em latossolos funciona como substância tóxica às lavouras.

Além da elevação do pH e controle da mobilidade do alumínio estas rochas são as principais fontes dos dois macronutrientes do complexo sortivo. Na Faixa Brasília as rochas dolomíticas ocorrem na forma de lentes e não de camadas contínuas, sendo sempre encontradas em volumes restritos quando comparado às fácies de calcários puros. Duas unidades são particularmente importantes para as ocorrências de lentes de dolomitos: a Formação Sete Lagoas e as unidades carbonáticas da seção intermediária do Grupo Vazante. Ao contráro do Grupo Bambuí, onde as sequências de calcários sobrepõem o volume dolomítico, a transição entre o médio e topo do Grupo Vazante é marcado por uma espessa sucessão de dolomitos, que mantêm o abastecimento deste insumo para as áreas de cultivo do Brasil Central.

O $P_2O_5$ da mesma forma que o Ca e Mg, em termos de viabilidade exploratória, está diretamente associado a um conjunto de rochas específicas presentes da faixa: os fosforitos e siltitos fosfatados hospedados na base e porção medianasda estratigrafia do Grupo Vazante, na base do Grupo Bambuí e restritamente no topo do Grupo Bambuí. Excluindo os depósitos de classe mundial da Formação Rocinha e as ocorrências do topo do Grupo Bambuí, que ainda não possuem volume economicamente expressivo, todos os outros contextos foram amplamente abordados e discutidos nos capítulos de resultados dessa tese.

Finamente, o K está presente nos siltitos da Formação Serra da Saudade no topo do Grupo Bambuí. Em adição a extrema necessidade e escassez de outros depósitos nacionais desse elemento, os teores e o grande volume tornam esse depósito de potencialidade ímpar. Entretanto, para que ocorra a viabilidade de exploração é necessária a evolução das técnicas de beneficiamento ou adaptação de infraestrutura que reduzam o custo de extração do elemento da estrutura cristalina silicática.

Tendo em vista o real potencial e os desafios que devem ser superados para a inserção desses depósitos no mercado interno, podem ser citadas duas diferentes formas de utilização dos insumos fosfatados: i) após beneficiamento industrial para produção de fertilizantes químicos solúveis ou ii) diretamente na forma de rocha moída no modelo de remineralizadores de solos.

Como discutido anteriormente, para a produção de fertilizantes químicos solúveis, os processos são mais complexos e dispendiosos, porém acrescentam valor agregado aos produtos, o que reflete no preço final de venda. Dessa forma, a utilização direta tem se destacado e se tornado cada vez mais atrativa. A simples aplicação de técnicas de pulverização e mistura, em quantidades que podem ser inclusive personalizadas para cada tipo de cliente, resultam em um produto com preço e benefício competitivos. Essa metodologia conhecida por rochagem surge como forte aliada para a viabilidade dos depósitos e confirma o potencial da Faixa Brasília como fonte produtora de agrominerais.

## 5.2 Vetores Exploratórios para Agrominerais na Faixa Brasília

O desenvolvimento de metodologia exploratória para fosfato, cálcio/magnésio e potássio de origem sedimentar tem o objetivo de maximizar a eficiência dos programas prospectivos dessas *commodities*, principalmente no contexto geotectônico da Zona Externa da Faixa Brasília.

Os guias ou vetores exploratórios são evidências e registros de processos geológicos que estão associados a depósitos, jazimentos ou ocorrências minerais e que exercem a função de importante ferramenta nas etapas de identificação de áreas alvos e fases iniciais de *follow up*. A subdivisão de classes ou de processos naturais é puramente arbitrária e conta com o objetivo de compartimentalizar o conhecimento para facilitar o desenvolvimento na integração dos dados do ponto de vista geoespacial. Tendo em vista que os fenômenos naturais não ocorrem dissociados e muito menos compartimentados do ponto de vista do raciocínio geocientífico.

Dentro do tema abordado pela presente tese, o método proposto segue a seguinte lógica: parte-se de pressupostos e fatos geológicos conhecidos, a partir do estado da arte do conhecimento geológico dos depósitos, ocorrências existentes e de áreas potencialmente importantes do ponto de vista de economicidade de projetos, além de áreas com moderada a baixa potencialidade. A partir daí se inclui áreas com menor potencial para avaliação do ”*background* geológico”. Assim é possível definir os limites geológicos das áreas potenciais e compreender o conhecimento para organização dos dados e informações disponíveis.

A metalogenia dos agrominerais (fosfato, cálcio/magnésio e potássio) sedimentares e hidrotermais é basicamente controlada por processos genéticos e processos transformadores/modificadores. Por um lado, os processos genéticos são deposicionais, biogênicos e hidrotermais, que fornecem as características gerais dos depósitos desses remineralizadores. Por outro lado, os processos transformadores são aqueles tardiamente superimpostos que podem ser representados por movimentação tectônica, silicificação, retrabalhamento erosivo, enriquecimento pedogênico, dentre outros. Este conjunto de processos marca as características individuais das mineralizações de $P_2O_5$, Ca/Mg e K sedimentares, ou seja, as feições individuais e específicas de cada um dos depósitos.

Destacam os aspectos tectônicos, estratigráficos, sedimentológicos, paleoambientais, geocronológicos, biogênicos, como temas que resultam em caráter genético comum aos depósitos. Os processos pós-deposicionais ou deformacionais, além de processos supergênicos associados a formação ou modificação das fases primárias, podem alterar a potencialidade e economicidade do prospecto.

Finalmente, a determinação de novos alvos potenciais deve considerar as informações já armarradas e conhecidas, juntamente com as novas informações geológicas e geofísicas.

### 5.3 Controles Geológicos dos Depósitos

Levando em consideração a necessidade de se entender os modelos metalogenéticos para a aplicação da metodologia de exploração prosposta no tópico anterior, a Tabela 1 traz a síntese dos aspectos mais importantes que devem ser considerados para a busca de novos prospectos, mesmo em áreas consideradas *brownfield* para depósitos sedimentares.

Ressalta-se que os verdetes são conhecidos como fonte potencial de potássio, contudo sua origem sempre foi considerada como sedimentar diagenética. Recentemente, Teles *et al.* (2022) propuseram uma origem alternativa para estas rochas. Com a mudança do processo genético, abre-se nova possibilidade de se encontrar novos depósitos a partir dos novos paradigmas: associação de anomalias geofísicas (gamaespectrometria e magnetometria) e locais cartografados como Formação Serra da Saudade do Grupo Bambuí.

**Tabela 1** - Principais características diagnósticas dos depósitos de agrominerais existentes na porção externa da Faixa Brasília.

| | DEPÓSITOS TIPOS | | | |
|---|---|---|---|---|
| **Feições Diagnósticas** | **Lagamar-Rocinha** | **Coromandel** | **Campos Belos-Arraias** | **Cedro do Abaeté** |
| Idade da gênese do depósito | Meso/Neoproterozoico | Meso/Neoproterozoico | Neoproterozoico | Neocretáceo |
| Estratigrafia/Correlações | Formação Rocinha, Grupo Vazante | Formação Retiro, Grupo Vazante | Base da Formação Sete Lagoas, Grupo Bambuí | Formação Serra da Saudade, Grupo Bambuí |
| Fácies de Minérios | Fosfarenito e fosfolutio | Fosfolutito e fosfarenito fino | Fosforitos brechados, fosforitos laminados e siltitos fosfatados | Fosforitos brechados, e siltitos ricos em ilita |
| Processo Metalogenético | Sedimentar - ressurgências marinhas | Sedimentar - a partir de fonte continental | Sedimentar - a partir de fonte continental local | Hidrotermal em associação com intrusões alcalinas |
| Relação Fosforito/Siltito fosfatado | Muito alta | Moderada | Muito baixa | Muito Baixa |
| Relação com Glaciação Continental | Não | Sim | Sim | Não |
| Proximidade com o Embasamento | Ausente | Sem informações | Presente | Ausente |
| Controle da Paleogeografia da Bacia | Ausente | Presente | Muito Forte | Ausente |
| Ambiente Deposicional | Plataformal raso | Plataformal | Lagunar | Plataformal |
| Fonte de $P_2O_5$ | Marinha Profunda | Sem informações | Continental | Continental |
| Processos Modificadores | Erosão, Dobramento e falhamento | Erosão, Dobramento | Erosão e Silificicação | Erosão |
| Potencial para Novos Depósitos de $P_2O_5$ | Muito Baixo | Alto | Muito Alto | Baixo |
| Potencial para outros Depósitos | - | - | Dolomito | Potássio |
| Assinatura Geofísica | Forte Anomalia K/U/Th | Sem informações | Sem anomalia gamaespectrométrica | Anomalia Magnetométrica |

Embora ocorram em áreas geograficamente próximas, os depósitos de Rocinha e Lagamar são geneticamente distintos do depósito Tipo Coromandel. A deposição da faixa estreita rica em rochas fosfatadas situada entre as localidades de Rocinha e sudeste da cidade de Lagamar é considerada como a materialização do modelo de Kazakov.

Neste contexto, se considera a atuação de correntes ressurgentes oriundas de águas profundas (associadas à deposição da Formação Serra do Garrote) que se acumulam em condições de águas plataformais rasas vinculadas à deposição da Formação Rocinha, incluindo pelitos, ritmitos psamo-pelíticos.

O enquadramento da deposição dos sedimentos fosfatados nesta faixa no modelo proposto por Kazakov é corroborado pelos seguintes argumentos:

- Acúmulo de grandes volumes de fosfato sedimentar exclusivamente em uma estreita faixa, o que requer controles deposicionais específicos;
- Presença de ambientes de águas profundas (Formação Serra do Garrote) em situação adjacente a depósitos de águas rasas (formações Rocinha e Lagamar);
- Faciologia interna no interior da faixa fosfatada, com depósitos de águas rasas, com retrabalhamento por ondas (fosfarenitos e raros fosforuditos) e depósitos de águas plataformais abaixo da atuação de ondas de tempo bom (fosfolutitos);
- A não repetição do modelo deposicional em outros níveis estratigráficos na mesma unidade gerológica, o que indica a exaustão da fonte de $P_2O_5$ dissolvida proveniente do reservatório profundo.

## 5.4 Assinaturas Geofísicas dos Depósitos

O estudo geológico da superfície de um terreno e sua relação no espaço e no tempo é de importância indiscutível para o entendimento das rochas em subsuperfície e para a localização de áreas de interesse. No entanto, nem sempre as rochas estão disponíveis sob a forma de afloramentos ou permitem inferências seguras sobre o que ocorre em profundidade. Dessa forma, as informações geofísicas são ferramentas que auxiliam e complementam o estudo em superfície. Todavia, pode não ser suficiente a coleta de dados e a simples representação espacial da propriedade física ou química. Técnicas estatísticas ou determinísticas como operações matemáticas, filtragens, modelamentos, interpolações, integrações ou a combinação de duas ou mais dessas técnicas podem ser bastante úteis na interpretação.

Portanto, os métodos geofísicos são ferramentas essenciais ao mapeamento geológico e outras investigações geológicas em regiões de clima úmido e áreas com espessa cobertura vegetal, já que por muitas vezes as rochas encontram-se intemperizadas, apenas com regolito ou sem rochas aflorantes. Ainda são técnicas fundamentais para depósitos cuja gênese passa por processos precursores em profundidade, como calor e fluídos oriundos de intrusões.

Para os tipos de depósitos em questão, os levantamentos de geofísica são grandes aliados tendo em vista que as respostas manipuladas ao longo do trabalho apresentaram resultados bastante satisfatórios.

A natureza dos dados também implica em diferentes tipos de respostas e diferentes tipos de influências (Tabela 2).

**Tabela 2 -** Avaliação de parâmetros geofísicos para aplicações em estudos de exploração mineral.

| Método | Parâmetro Físico | Influência Vertical | Tipo de Resposta |
|---|---|---|---|
| Magnetometria | Campo magnético | Alta | Profunda - influência da topografia |
| Gamaespectrometria | Emissão de radiação gama | Baixa | Superficial - influência do intemperismo |
| Gravimetria | Densidade | Muito Alta | Profunda - influência do tamanho dos corpos |

Para ressaltar a aplicação dessa importante ferramenta, todos os depósitos pesquisados possuem relação intrínseca com respostas geofísicas, em especial a gamaespectrometria. No caso do fosfato, devido as similaridades de raio iônico e carga, potencialmente pode ocorrer a substituição do fósforo por urânio nos sítios aniônicos, sendo que são relatados valores que variam de 50 a 200 ppm de urânio em depósitos sedimentares (Baturin & Kochenov, 2001). Dessa forma, os levantamentos gamaespectrométricos dessas áreas resultam em anomalias positivas de U que se destacam em meio aos elevados teores de potássio das rochas sedimentares encaixantes.

Como exemplo da potencialidade de tal técnica, Teles *et al*. (2020) propõem a utilização de classificação superfisionada voltada ao objeto, baseada na manipulação entre os dados de modelo digital de elevação (MDE) e produto cartográfico temático de gamaespectrometria como planos de informação primários. A partir da classificação, as áreas fosfatadas indicadas pelo modelo tiveram uma correlação de 82% com a verdade terrestre determinada em campo, corroborando com a eficiência da ferramenta que pode ser amplamente aplicada em outros depósitos com gênese similar.

Para os depósitos de Ca/Mg, a relação é semelhante, sendo os dados gamaespectrométricos os de maior relevância. No entanto, ao contrário dos fosfatos, os carbonatos tendem a possuir médias respostas no canal do potássio e baixas respostas nos canais do urânio e tório e dessa forma, são principalmente identificados por anomalias de coloração magenta associadas a baixos magnéticos que também se destacam, na maioria dos casos, em meio as outras rochas adjacentes. Por mais que representem importantes elementos dentro do cenário agrícola, os depósitos de Ca/Mg foram menos abordados nesta tese, pois se tratam de níveis estratigráficos chave dentro do contexto evolutivo da faixa e sendo assim possuem um variado leque de trabalhos que já caracterizam e descrevem em detalhe essas unidades carbonáticas.

Finalmente, no caso do K, os depósitos sedimentares da Formação Serra da Saudade não são tão bem diferenciados na gamaespectrometria, uma vez que boa parte dos siltitos estéreis também respondem alto no canal do potássio e podem ser identificadas apenas algumas feições mais avermelhadas que sugerem o enriquecimento potássico. No entanto, os núcleos das áreas hidrotermalizadas pelas intrusões respondem alto nos 3 canais, o que resulta em zonas circulares de tonalidade esbranquiçada (na imagem ternária) e em anomalias fortemente marcadas na magnetometria. Essas intrusões mais profundas em associação com os sedimentos pelíticos compõem o principal vetor exploratório dessa unidade e que novamente pode ser identificado com eficiência pela utilização dos métodos geofísicos.

### 5.5 Potencial para Novos Depósitos

Dentro do conhecimento atual em adição as novas informações, pode-se inferir sobre o potencial para a descoberta de novos depósitos nas áreas alvos e adjacentes da pesquisa. A proposição dos novos modelos resulta em novos vetores exploratórios que antes ainda não eram observados e, portanto, aumenta-se o grau de detalhamento da observação, favorecendo novas descobertas ou ampliação das áreas conhecidas.

No depósito fosfático do tipo Coromandel ainda há a possibilidade da existência de ocorrências na porção sul que marca o fechamento da Faixa Vazante. Esse extremo sul é caracterizado pelos grandes contatos tectônicos com o Grupo Canastra e foi pouco explorado. O contraste entre as baixadas, dissecadas pelo Rio Santo Antônio do Bonito, relacionadas ao Grupo Vazante e o relevo proeminente e movimentado do Grupo Canastra delimitam as áreas alvos. Adicionalemnte, a presença de afloramentos de diamictitos e arenitos conglomeráticos sugerem possíveis acumulações de fosfato nas arredeondezas.

Para os depósitos de Lagamar e Rocinha, inseridos na Formação Rocinha, os dados gamaespectométricos sugerem um alinhamento de *trend* NE-SW com forte resposta no canal do urânio, sugerindo a presença contínua de fosforitos. Fora das cavas das minas (Antiga Vale Fertilizantes e Galvani), o retrabalhamento por erosão e dissolução no Vale do Rio Paranaíba é um fator limitante que pode influenciar diretamente na viabilidade dos novos depósitos. Entretanto, em alguns locais ainda é possível encontrar amostras alteradas com forte reação ao molibdato de amônia e tendo em vista a corrente valorização do minério fosfático, a proximidade com infraestruturas já montadas e necessidade do mercado consumidor, mesmo que necessárias intervenções para a exploração desses locais, dentro de pouco tempo serão áreas de importante interesse.

O depósito fosfático do tipo Campos Belos - Arraias, da mesma forma que o do tipo Coromandel ainda apresenta moderado potencial para novas ocorrências. Devido a similaridade entre a rocha minério e os pelitos estéreis, é provável que ainda existam ocorrências não mapeadas. Novamente, a proximidade com as rochas rudáceas e os paleocanais encaixados no embasamento granítico da Suite Aurumina ou arcóseos do topo do Grupo Araí representam os vetores exploratórios mais importantes. Similarmente ao citado para os depósitos anteriores, a supervalorização do minério fosfático e a evolução dos processos de beneficiamento irão futuramente viabilizar ocorrências com valor de corte mais baixos. Atualmente, para ser considerado como minério e passível de flotação, utiliza-se a média de 4% de $P_2O_5$ como valor de corte mínimo, mas o aproveitamento de rochas com teores menores irá favorecer o enquadramento de amplas áreas de siltito como minério e consequentemente ampliação do depósito.

As possibilidades de novas ocorrências fosfáticas na Formação Serra da Saudade em Cedro do Abaeté são baixas. Por mais que os teores sejam relativamente elevados, mesmo as ocorrências conhecidas não possuem expressão volumétrica econômica.

Diferentemente do fosfato e como já citado em tópicos anteriores, os depósitos de Ca/Mg são mais bem conhecidos, definidos e estudados. Basicamente todo o volume da Zona Externa está concentrado nas unidades carbonáticas da porção mediana do Grupo Vazante e base do Grupo Bambuí. Uma questão de importante discussão deve-se ao fato de que as reservas são relativamente suficientes para abastecimento do mercado, entretanto devido a localização geográfica, a distância entre as áreas fontes e os locais de consumo são grandes, o que resulta no encarecimento dos produtos, pelo seu transporte. Uma alternativa seria a viabilização de depósitos mais próximos desses centros consumidores, mesmo de menor volume, para suprir ao menos parte da demanda com melhor custo/benefício e diluir os custos de transporte das áreas fontes mais distais.

Em termos da possibilidade da descoberta de novos alvos e ampliação das reservas, a maioria dos depósitos explorados estão relacionados a ocorrências superficiais e dessa forma, lentes e *mounts* subaflorantes são as melhores oportunidades futuras. Nas áreas de *brownfield*, os setores de exploração já possuem essas continuidades em profundidade mapeadas e cubadas, e o fator limitante é baseado apenas no custo de exploração de pitchs mais profundos. Com a evolução da utilização desses insumos e a não existência de substitutos, é possível que em um curto espaço de tempo, esses depósitos serão viáveis.

Outro aspecto que pode ampliar os teores de corte de depósitos de fosfato sedimentar é a aplicação de técnicas para ampliação de concentrações, a exemplo da flotação. É conhecido que os depósitos tipo Campos Belos respondem bem à flotação, elevando teores originais de 4% para 12% em siltitos. Estudos metalúrgicos devem ser desenvolvidos nos depóstos de Coromandel, visando á redução do teor de corte economicamente viável, e em consequência ampliando o volume das jazidas.

Na última vertente, novos depósitos fosfáticos, associados à Formação Serra da Saudade possuem uma possibilidade restrita de descoberta, tendo em vista que para o modelo proposto, deve existir a associação espacial entre intrusões alcalinas e os sedimentos pelíticos. As duas maiores anomalias magnéticas regionais, que compõem o depósito de Cedro do Abaeté, já foram identificadas e sendo assim, as novas ocorrências estariam relacionadas a corpos menores não mapeados seja em decorrência da escala dos aerolevantamentos existentes ou ainda corpos mais profundos que não são ressaltados nos produtos magnéticos. O levantamento terrestre e a utilização de novas técnicas refinadas de processamento podem ser fortes aliadas ao maior detalhamento e identificação de novas áreas alvos, mesmo que de menor expressão.

Além dos depósitos anteriormente relatados, na porção externa da Faixa Brasília, ainda há a possibilidade de se listar rochas potenciais para produção de remineralizadores de solos, o que tem sido considerado uma possibilidade realista para substituir os fertilizantes solúveis tradicionais. Os remineralizadores são aplicados na forma de pós de rochas no modelo tradicionalmente denominado de "rochagem" (Martins *et al.* 2008 e 2010 e Martins 2013).

Neste contexto pode-se listar as seguintes rochas e unidades associadas:

- Siltitos ricos em matéria orgânica com até 1% de $P_2O_5$ da base da Formação Sete Lagoas;
- Rochas vulcânicas intermediárias da Formação Quilombo (Campos *et al.* 2020);
- Rochas vulcânicas básicas da Formação Buracão do Grupo Arraias Tanizaki *et al.* 2015 e Martins-Ferreira *et al.* 2018);
- Calcixistos do Grupo Araxá;
- Calcifilitos do Grupo Canastra.

# CAPÍTULO 6 - CONCLUSÕES E RECOMENDAÇÕES

As ocorrências fosfáticas associadas à Formação Retiro, as quais definem o depósito do Tipo Coromandel, possui fosfogênese fortemente vinculada a glaciação. A descrição petrográfica sistemática e as associações de fácies corroboram com a instalação de um ambiente pró-glacial responsável pelo controle de todas as variáveis físico-químicas necessárias para a precipitação fosfática. As rochas da Unidade Rudácea, caracterizadas por diamictitos matriz suportados maciços e arenitos conglomeráticos maciços, apresentam arcabouço mal selecionado e de composição variável, sendo encontrados até blocos métricos de granitos, que foram arrancados de áreas continentais pela movimentação das massas de gelo.

Os arenitos conglomeráticos foram interpretados como retrabalhamento dos diamictitos a partir da evolução de uma planície de outwash nos limites terminais da geleira. Nesse contexto, a maior parte da matriz pelítica é lavada restando apenas os componentes do arcabouço.

Em contanto direto com as rochas da Unidade Rudácea são encontrados os siltitos fosfatados e fosforitos da Unidade Fosfatada. Os contatos entre essas duas unidades ocorrem de forma direta, sendo que muitas vezes a própria matriz dos diamictitos é fosfatada e apresenta reação ao molibdato de amônia. Essa intrínseca relação sugere e corrobora o forte controle glacial nas etapas fosfogenéticas. As condições físico-químicas, como condições oxirredução intermediárias à ligeiramente mais oxidantes, pH ligeiramente mais elevado (alcalino) e baixas temperaturas que resultam na diminuição da solubilidade do fosfato e sua imediata precipitação em um mecanismo análogo ao encontrado para a deposição dos *cap dolomite*, sugerindo um novo modelo fosfogenético vinculado às unidades glaciais, que foi denominado de deposição de fosforitos de capa ou *cap phosphorite*.

Por fim, o topo da Fomação Retiro é representado pela Unidade Pelítica que marca o final do ambiente glacial em uma plataforma marinha. Em porções pontuais, em meio aos pelitos variados ocorrem finas laminações fosfáticas, como se um excedente transportado ao longo da planície de *outwash* chegasse a porções marinhas e se precipitasse juntamente com a deposição dos terrígenos finos.

De forma similar ao depósito do Tipo Coromandel, o depósito do Tipo Campos Belos, hospedado nas rochas da Formação Sete Lagoas, possui um mecanismo fosfogenético bastante similar aos observados para a deposição dos fosforitos de capa. Todas as condições de contorno favoráveis a precipitação fosfática são diretamente controladas pelo ambiente glacial, porém nesse caso específico, o controle de paleo relevo na forma de canais encaixados no embasamento da Suíte Aurumina ou arcóseos da base do Grupo Araí é extremamente relevante e funciona como condicionante da existência do depósito.

A Unidade Fosfatada foi subdividida nas fácies: Fosforitos Estratificados/Laminados, Fosforitos Brechados, Fosforitos Pedogenéticos e Siltitos Fosfatados. Como características principais dessas fácies destaca-se a composição mineralógica mais simples, basicamente composta por fluorapatita e quartzo e os valores de $P_2O_5$ que variam de 4% até 30%. Como amplamente discutido no capítulo 3, os principais ambientes deposicionais inseridos na formação do depósito estão relacionados a evolução geológica da base da bacia Bambuí, especialmente nas etapas cronológicas sin- a imediatamente posteriores a glaciação responsável pela deposição da Formação Jequitaí e as diferenças de subdivisão das fácies intrinsecamente ligadas a eventos superimpostos, como retrabalhamento nos canais.

A partir da compilação dos dados de aerogeofísica, mineralogia, características de ocorrência e geoquímica, é possível propor um modelo metalogenético robusto para os Verdetes, como são localmente denominados os siltitos verdes da formação Serra da Saudade. O mapa de magnetometria identifica a ocorrência de duas anomalias magnéticas, equivalentes a corpos alcalinos da Formação Mata da Corda (não aflorantes), intrudidos nos pelitos da Formação Serra da Saudade. As principais ocorrências mapeadas apresentam-se como zonas alongadas restritas apenas às porções imediatas das anomalias, sugerindo forte vinculação.

Os difratogramas de Raios-X, obtidos de amostras de Verdetes venulados, identificaram a presença de dawsonita, um carbonato de sódio hidratado e mineral índice de hidrotermalismo de baixa temperatura. Em adição, os dados de geoquímica sugerem que os sedimentos pelíticos da Formação Serra da Saudade apresentam modificação do sistema químico original, com ênfase em um metassomatismo potássico causado pela interação dessas rochas com fluídos prevenientes das intrusões alcalinas.

A forte correlação entre ocorrências de verdetes e magmatismo da Formação Mata da Corda também é observada em outras regiões do Estado de Minas Gerais como Patos de Minas, Lagoa Formosa, São Gotardo e Boassara. Dessa forma, a presença de anomalias magnéticas nas regiões recobertas pelos sedimentos da Formação Serra da Saudade representam um importante vetor exploratório para esse tipo de depósito potássico.

Em termos gerais, a Faixa de Dobramentos Brasília apresenta um grande e expressivo potencial para agrominerais sedimentares e hidrotermais, assim como outras áreas do território nacional. A tendência de exploração dos depósitos ígneos e a omissão de olhares exploratórios para esses tipos de depósitos podem significar o adiamento da autosuficiência, ou ao menos da menor dependência externa dessas *commodities*.

A necessidade de investimento em diferentes rotas de beneficiamento com processos metalúrgicos não convencionais é uma poderosa ferramenta, como por exemplo a aplicação da técnica de biolixiviação, que basea-se na aplicação de bactérias quimilitotróficas para a quebra de estruturas cristalinas e liberação dos elementos de interesse, e que caso seja demonstrada a eficiência poderá viabilizar a exploração do depósito potássico de Cedro do Abaeté e aumentar o custo/benefício dos depósitos fosfáticos sedimentares até mesmo diminuindo os teores de corte, e consequentemente ampliando o volume dos depósitos.

A intalação de infraestruturas como Pequenas Centrais Hidrelétricas e outras fontes de energia de menor custo (solar, eólica e etc.) também são soluções cabíveis. Com a diminuição dos custos com energia elétrica, é possível a fabricação dos termofosfato e termopotássio, obtidos a partir da fusão dos sedimentos mineralizados, extração dos macroelementos da estrutura cristalina dos silicatos e disponibilização em fases amorfas não solúveis em água (mas apenas em ácido acético).

Finalmente, após todas as conclusões relativas à parte de caracterização e de formas de viabilização, ainda existem recomendações de algumas etapas que persistem para a solução de questionamentos em aberto.

É necessária a continuidade dos estudos dos ambientais deposicionais, em especial com a realização de análises isotópicas e geocronológicas para melhor diferenciação entre as glaciações das bases dos grupos Vazante e Bambuí, de forma a inclusive melhor comparar os tipos de depósitos de Coromandel e Campos Belos. A princípio, a diferença marcante apontada pelos estudos dos depósitos sugere que a unidade fosfatada da base do Grupo Vazante apresenta aspectos genéticos do tipo controlado por glaciação ("*Glacio Controlled*"), enquanto a do Grupo Bambuí se enquadra melhor em mecanismos deposicionais influenciados por glaciação ("*Glacio Influenced*"). Uma forma de se melhor explorar essas características seria a determinação dos *proxies* geoquímicos das apatitas para se entender de forma aprofundada as condições ambientais, sendo possível a aplicação dessa metodologia até mesmo como vetor exploratório nas futuras campanhas de prospecção.

O desenvolvimento de técnicas mais apuradas de aquisição e de processamento de dados magnetométricos de alta resolução nas áreas com os vetores exploratórios característicos do depósito potássico de Cedro do Abaeté. De forma mais específica, ressalta-se a importância da aplicação de ferramentas de manipulação de produtos geofísicos, como por exemplo, a determinação das derivadas verticais e posterior aplicação da técnica de deconvolução de Euler para se ter informações numéricas da profundidade de colocação dos corpos e dessa forma, adicionar mais dados aos modelos genéticos.

Por fim, a aplicação e determinação da eficiência da técnica de biolixiviação, em especial nos verdetes, para se determinar a viabilidade exploratória da *commodity*, mesmo estando inserida em estrutura cristalina silicática muito estável. Neste contexto é possível verificar pela análise da literatura, que esta técnica tem sido aplicada com sucesso em diferentes materiais, em especial para o cobre (Schippers *et al*., 2014; Potszy, 2015; Diaz-Tena *et al*., 2016) inclusive em rejeitos de mineração e urbanos como forma de solução de problema ambiental (Lee & Pandey, 2012; Pedroza-Herrera *et al*., 2020).

# CAPÍTULO 7 - REFERÊNCIAS BIBLIOGRÁFICAS


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