UNIVERSIDADE DE BRASÍLIA – UnB
INSTITUTO DE GEOCIÊNCIAS – IG

O depósito de classe mundial Serra do Tapa e Vale dos Sonhos: mineralização de níquel laterítico associada a complexos ofiolíticos Pré Cambrianos da Faixa de Dobramentos Araguaia - Pará, Brasil.

Dissertação de Mestrado Nº 298

Área de Concentração: Geologia Econômica e Prospecção
Candidato: Fábio Carvalho de Mendonça
Orientadores: Prof. Dr. Elton Luiz Dantas
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2012

Dedico este trabalho a minha família.

A Deus, toda honra e toda glória.

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Agradecimento especial à minha família, por me apoiar sempre.

Também agradeço aos colegas que trabalharam na avaliação da Serra do Tapa pelo companheirismo e dedicação.

"Eu vi a manhã pousada em cima de uma pedra
Isso não muda a feição da natureza?"
Manoel de Barros

RESUMO

A Serra do Tapa e o Vale dos Sonhos é um depósito de níquel laterítico de classe mundial (100Mt @ 1.5% Ni) e localiza-se no sudeste do estado do Pará, Brasil, aproximadamente 200 km SW de Marabá. O desenvolvimento de espessos intervalos mineralizados com mais de 100 m foi comdicinada pela associação dos fatores críticos que controlam a mineralização, que incluem a natureza do protolito, grau de serpentinização, arcabouço estrutural, clima, relevo, sistema de drenagens e história geomorfológica. O silexito é um importante controle da mineralização pois aprisiona a água meteórica e preserva o perfil mineralizado da erosão. A caracterização das facies é fundamental para definir os contatos minério-estéril e para estimar visualmente o teor em frentes de lavra. O perfil de alteração apresenta as características típicas deste tipo de mineralização e é composto por cinco horizontes geoquímicos definidos pela variação dos teores de ferro e magnésio (laterítico, limonítico, saprolítico superior e inferior, e bedrock). O perfil mineralizado compreende 14 facies que apresentam características mecânicas, e texturais, bem como cor e mineralogia singulares, mas que partilham tendências geoquímicas. O depósito é relacionado a um complexo ofiolítico de idade pré-cambriana, e desta forma indica um novo ambiente geotectônico para hospedar depósitos de níquel laterítico de classe mundial, mostrando que complexos ofiolíticos associados a faixas móveis pré-cambrianas são áreas prospectivas.

ABSTRACT

The Serra do Tapa and Vale dos Sonhos is a world class nickel laterite deposit (100Mt @ 1.5% Ni) located at the southeast of Pará state, Brazil, approximately 200 km SW of Marabá. The development of thick mineralized intervals with more than 100 m is conditioned by the association of the critical elements that control the mineralization, which include the protholite nature, degree of serpentinization, structural framework, climate, drainage system and geomorphologic history. The metachert appears as an important control over the mineralization as it traps the meteoric water and preserves the mineralied profile from erosion. The characterization of the facies is important to define ore-waste contacts and estimate visually the grades. A total of 14 facies occur within the profile are distinguished by their mechanic characteristics, texture, color and mineralogy. The facies are grouped in five geochemical horizons defined by the iron and magnesium variation along the weathered profile (from top: lateritic, limonitic upper saprolite, lower saprolite and bedrock). The deposit is related to an ophiolite complex of Precambrian age, and therefore indicates a new geotectonic environment to host nickel laterite deposits, showing that ophiolitic complexes associated to Precambrian mobile belts are prospective areas.

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SUMÁRIO (Artigo)

LISTA DE FIGURAS (Artigo)

1. Introdução

Esta dissertação apresenta o depósito de níquel laterítico Serra do Tapa e Vale dos Sonhos, localizado na Faixa de Dobramentos Araguaia, no Brasil Central. O depósito foi investigado durante o período 2004/2008 e avaliado pela Xstrata Nickel como sendo de categoria classe mundial (100 Mt @ 1.5% Ni).

No âmbito da geologia regional o depósito é associado a corpos de rochas máficas e ultramáficas de caráter ofiolítico dentro da Faixa de Dobramentos Araguaia. (Hasui et al., 1977; Kotschoubey & Hieronymus, 1996; Teixeira, 1996; Osborne, 2001; Paixão & Nilson, 2002). Os maiores corpos ofiolíticos da Faixa Araguaia são alongados preferencialmente na direção N-S, sendo os mais expressivos o Complexo Quatipuru e a Serra do Tapa. As rochas ultramáficas compreendem peridotitos serpentinizados (metaharzburgitos) e, em menor proporção dunitos serpentinizados, que representam o substrato ou "Bedrock" do perfil intempérico, a fonte primária de níquel.

A evolução da Faixa Araguaia é relacionada ao evento Brasiliano, no limite do Neoproterozóico e Paleozóico Inferior, fato este indicado por datações radiométricas disponíveis, em especial, na porção setentrional da faixa. A Serra do Quatipuru, localizada na porção sul da Faixa Araguaia, tem idade Sm-Nd de 757 Ma +- 49 Ma segundo estudos realizados por Paixão et al (2008).

O perfil de alteração no depósito ST e VDS apresenta características típicas de mineralizações de níquel do tipo supergênico, provenientes da concentração residual. A variação dos teores de ferro e magnésio dentro do perfil define zonas geoquímicas compostas por diferentes tipos de facies.

A dissertação é composta por duas partes. A primeira faz uma revisão sobre a mineralização de níquel laterítico, aborda aspectos gerais da região do depósito e contextualiza o depósito no âmbito regional, atendo a evolução geotectônica da Faixa Araguaia e a presença de corpos ofiolíticos neoproterozóicos. Também discorre sobre os aspectos relevantes da geologia do depósito e do perfil de intemperismo. A segunda parte da dissertação é o artigo científico que será submetido para publicação em periódico da revista Society of Economic Geologists (S.E.G.), internacionalmente reconhecida e especializada em geologia econômica.

A introdução do artigo revê as características que definem os corpos ofiolíticos e os fatores que controlam a mineralização de níquel laterítico. Em seguida, apresenta a Serra do Tapa e Vale dos Sonhos como um depósito atípico de níquel laterítico, considerando que em outros complexos ofiolíticos pré-cambrianos ainda não foram identificadas reservas de grande volume (classe mundial).

O artigo comenta a descoberta do depósito e expõe suscintamente os trabalhos desenvolvidos na caracterização do depósito.

Em seguida o depósito é inserido no contexto geológico regional da Faixa de Dobramentos Araguaia e ressalta a importância do arcabouço tectônico e da geomorfologia da região da Serra do Tapa e Vale dos Sonhos como fatores que controlaram a mineralização. Os resultados de datações obtidos por outros autores ao longo da Faixa Araguaia são relatados e comprova a idade neoproterozóica dos ofiolitos da Faixa Araguaia.

Posteriormente aborda a geologia dos depósitos e do perfil intempérico associado. A princípio é mostrada a localização e aspectos geomorfológicos da região. Em seguida, é apresentada a geologia local da área e de cada corpo, a distribuição, dimensões dos corpos, espessura dos perfis de alteração e os aspectos geológicos relevantes da mineralização. Em seguida, são apresentadas as características principais do perfil mineralizado e as facies que o compõem. Nesta abordagem, as facies são agrupadas em zonas geoquímicas, típicas de depósitos de níquel laterítico.

A seguir caracteriza as fácies quanto às propriedades físicas e geoquímicas das fácies mineralizadas. O enriquecimento de níquel e a variação dos teores ao longo das zonas são mostrados em gráficos lito-geoquímicos. A associação entre as características químicas e as propriedades físicas também são abordadas.

O artigo é concluído com uma discussão sobre por que a mineralização de níquel laterítico em outros complexos ofiolitos pré-cambrianos não apresenta reservas significantes. A evolução tectônica e geocronológica de complexos ofiolitos, assim como o grau de influência dos elementos que condicionam a mineralização é avaliada do ponto de vista prospectivo.

Os dados publicados neste trabalho são inéditos para a comunidade científica e apresentam uma compilação de dados não sensitivos obtidos durante a investigação do depósito. A Xstrata Níquel gentilmente concedeu o uso e a divulgação de um rico acervo de dados, além de resultados químicos de 1400 amostras. O autor principal participou da descoberta, caracterização e da avaliação do depósito.

1.1 Objetivo

O objetivo é revisar os dados de trabalhos acadêmicos e industriais da Serra do Tapa e Vale dos Sonhos e compará-lo com outros depósitos de níquel laterítico.

O trabalho é focado na caracterização do perfil de alteração e das fácies que o compõem. Por outro lado, busca discutir a evolução geotectônica global e a idade neoproterozóica de outros complexos ofiolíticos de mesma idade, para discutir a existência de outras possíveis ocorrências de mineralizações de grande volume.

1.2 Métodos

O trabalho desenvolvido seguiu as seguintes etapas:

- Revisão bibliográfica;

A revisão bibliográfica compreendeu o levantamento de um acervo de dados que inclui mapas geológicos, imagens geofísicas, imagens de satélite, estudos petrográficos, relatórios internos da Xstrata, relatórios de pesquisa destinados ao DNPM, relatórios de auditoria interna e externa, apresentações PowerPoint, *Press releases*. A revisão bibliográfica também incluiu o levantamento e estudo de artigos científicos que tratam da evolução da Faixa Araguaia, da caracterização de corpos ofiolíticos e da mineralização de níquel laterítico.

- Seleção de análises químicas;

No depósito são individualizadas 22 fácies, das quais 14 têm representatividade no perfil mineralizado.

Admitiu-se que uma população de 100 análises químicas de cada uma das 14 fácies presente no perfil de intemperismo fosse suficiente para conferir representatividade geoestatística. Assim, foram selecionadas 700 análises químicas de cada corpo mineralizado, que totalizam 1400 análises.

A seleção obedeceu aos seguintes critérios:

(i) Rejeição das análises com teores de ferro e magnésio anômalos à média da fácies. Este critério recusa anomalias geoquímicas para serem interpretadas;
(ii) Distribuição geográfica na área dos corpos;
(iii) Recuperação da sondagem. Amostras com menos de 50% de recuperação foram excluídas;
(iv) Quantidade de amostras restantes;

- Compilação e tratamento dos dados

A compilação dos dados teve como premissa resgatar as principais informações de cada referência pesquisada com o objetivo de unificar, em um único volume, os dados da evolução geotectônica e da mineralização dos corpos ofiolíticos da Faixa Araguaia.

Os resultados das amostras selecionadas foram plotados em gráficos geoquímicos MgO(%) versus Fe(%) para classificar as fácies e zonas que compõem o perfil de alteração. A distribuição do Ni, SiO_2, Fe e MgO (%) ao longo das zonas geoquímicas também é mostrada graficamente.

- Apresentação e discussão dos dados

O trabalho será apresentado à banca examinadora composta por estudiosos dos temas abordados.

2. Revisão sobre mineralização de níquel laterítico

Os principais controles do enriquecimento supergênico de níquel são a natureza do protolito (composição e estrutura), contexto tectônico, clima, topografia e história geomorfológica. Naturalmente, cada depósito exibe características peculiares em função da importância de cada controle supracitado.

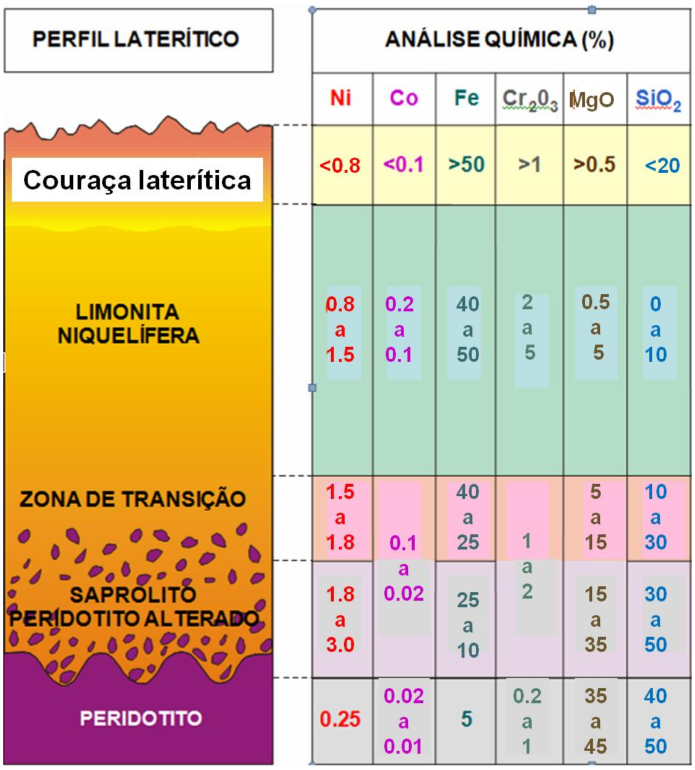
Lateritas niquelíferas são formadas pelo intemperismo de rochas ultramáficas, principalmente peridotitos e serpentinitos (Golightly, 1981).

O processo de intemperismo inicia-se com hidratação, oxidação e hidrólise dos minerais na zona de oxidação, onde há circulação intensa de água meteórica, o pH é neutro a ácido e o Eh é neutro a oxidante. Os silicatos são em parte solubilizados e as substâncias solúveis são carreadas para fora do sistema. As substâncias insolúveis permanecem e passam a se concentrar residualmente. A continuação desse processo gera, após um longo período de atividade, os depósitos residuais.

O intemperismo químico é mais ativo em regiões quentes e úmidas, onde a ação de chuvas com CO2 e a formação de ácidos orgânicos pelas plantas e animais representam uma contribuição efetiva ao ataque das rochas. As reações principais seriam a hidratação pela ação das águas, oxidação, reações com ácido carbônico e com outros ácidos resultantes da decomposição de sulfetos.

Nas rochas ultramáficas, o processo de intemperismo consiste numa lixiviação progressiva do Si e do Mg, enquanto outros elementos como o Fe permanecem no perfil de alteração. Assim, como o passar do tempo, a concentração relativa dos elementos remanescentes (Ni e Co) aumenta (Fig1).

Os perfis lateríticos apresentam uma zonação vertical que mostra uma correlação entre as fácies e a geoquímica. Em geral, o perfil é composto do topo para a base por: crosta hematítica (laterita), zona limonítica, zona de transição, zona saprolítica e substrato rochoso (bedrock), que é geralmente uma rocha ultramáfica serpentinizada.



PERFIL LATERÍTICO	ANÁLISE QUÍMICA (%)					
	Ni	Co	Fe	Cr_20_3	MgO	SiO_2
Couraça laterítica	<0.8	<0.1	>50	>1	>0.5	<20
LIMONITA NIQUELÍFERA	0.8 a 1.5	0.2 a 0.1	40 a 50	2 a 5	0.5 a 5	0 a 10
ZONA DE TRANSIÇÃO	1.5 a 1.8	0.1 a 0.02	40 a 25	1 a 2	5 a 15	10 a 30
SAPROLITO PERIDOTITO ALTERADO	1.8 a 3.0		25 a 10		15 a 35	30 a 50
PERIDOTITO	0.25	0.02 a 0.01	5	0.2 a 1	35 a 45	40 a 50

Figura 1 – Perfil laterítico idealizado a partir de protólito untramáfico (modified from Elias, 2002 and Golightly, 1981).

O material saprolítico derivado do intemperismo do substrato rochoso exibe uma substituição intensa ou completa dos minerais primários de Fe e Mg (olivina e piroxênio). Os minerais enriquecidos em níquel são uma mistura de silicatos hidratados e óxidos e hidróxidos de Fe e/ou Mg, além de componentes amorfos (garnieritas). Em geral, apresenta textura reliquiar.

A zona de transição nem sempre é observada nos perfis de alteração e quimicamente corresponde a uma mistura do material limonítico e saprolítico.

A zona limonítica é formada após considerável lixiviação do Si e Mg do material saprolítico.

Como o intemperismo é uma forma de alteração isovolumétrica, o material resultante é extremamente poroso. Consequentemente, os valores de densidade são baixos (1.4 a 1.0 t/m3) em relação à rocha mãe, exceto onde ocorrem *boulders* (até 2,0 t/m3) (Porto, 2006).

As espessuras do perfil de intemperismo variam de poucos metros a, excepcionalmente, mais de 50 m. Nos grandes depósitos, a espessura do perfil de alteração varia entre 10 e 20 m. As dimensões das lateritas niquelíferas dependem da continuidade do substrato rochoso do qual derivam e, tipicamente se estendem por quilômetros.

Os maiores depósitos de níquel laterítico ocorrem na Nova Caledônia, Indonésia, Venezuela, Colômbia, República Dominicana, Brasil, Cuba e EUA.

A maior parte e os mais importantes depósitos de níquel no Brasil são associados a esse tipo de mineralização (residual), à exceção de Americano do Brasil, Mirabela e Fortaleza de Minas (tipo sulfeto). Os principais depósitos e projetos de níquel laterítrico no Brasil são: Niquelândia (GO), Barro Alto (GO), Vermelho (PA), Morro do Níquel (MG), Morro do Engenho (GO), São João do Piauí (PI), Onça Puma (PA), Jacaré e Jacarezinho (PA), Jacupiranga (SP), Serra do Tapa e Vale dos Sonhos (PA), Serra do Quatipuru (TO), Lontra (TO) e Vila Oito (TO).

3. Aspectos gerais

3.1 Localização e acesso

A área está localizada no município de Sapucaia, Estado do Pará - Brasil.

A área pode ser acessada partindo-se da cidade de Araguaína/TO pela da rodovia estadual TO-222 até o vilarejo do Pontão/TO (130 km), localizado na margem direita do Rio Araguaia. O rio representa a divisa entre os estados do Tocantins e Pará. A travessia do rio é feita por meio de balsa até a Vila São José, Município de Xinguara/PA, de onde se segue por cerca de 40 km em estrada não pavimentada até a área do depósito (Fig2).

Outra opção é a partir de Marabá, seguindo-se em direção a Eldorado dos Carajás pela PA-150. Em seguida continua-se até próximo ao Município de Sapucaia, num total de 195 km, virando à esquerda para acesso à Fazenda Rio Vermelho, numa estrada não pavimentada, por 70 km, até a Vila São José/PA.

A região apresenta boa logística de transporte e infraestrutura, incluindo ferrovias e sistema de transmissão de energia. A área está próxima de outros depósitos de níquel laterítico, incluindo Onça-Puma e Vermelho, ambos no distrito de Carajás.

Figura 2 – Localização e acesso da área em estudo.

3.2 Geomorfologia e fisiografia

O clima da área insere-se na categoria de equatorial super-úmido, tipo Am, segundo a classificação de Köeppen, próximo à zona de transição para o clima Aw. O clima apresenta duas estações muito bem definidas. O período chuvoso (inverno) ocorre notadamente de novembro a maio, e o mais seco (verão) de junho a outubro. A temperatura média anual elevada é 26°C, apresentando a mínima em torno de 23°C. A umidade relativa é elevada, apresentando a média anual de 78%.

A geomorfologia da região apresenta serras alongadas com direção norte-sul, com altitudes de até 500 m e que se destaca na região.

Estão presentes em maior extensão o solo Vermelho-Amarelo e lateritas ricas em sílica associado aos meta sedimentos do embasamento regional. As rochas máficas e ultramáficas formam manchas contínuas de solo pisolítico vermelho escuro e lateritas fortemente magnéticas com pouca sílica. Solos aluviais também configuram o cenário.

A vegetação da região é representada, em sua maior parte, pela Floresta Equatorial Latifoliada. Grandes clareiras na floresta foram abertas para a implantação de pastagens destinadas à atividade pecuária (Falconbridge, 2006).

4. Geologia regional

4.1 Faixa de Dobramentos Araguaia

A Faixa de Dobramentos Araguaia (Fig3) se estende segundo a direção norte-sul com mais de 1.000 km de comprimento e 150 km de largura, desenvolvendo-se geograficamente nos Estados de Goiás, Tocantins e Pará, desaparecendo a sul e a norte, sob os sedimentos das bacias do Paraná e Amazonas, respectivamente.

A Faixa de Dobramentos Araguaia representa um marcante elemento tectônico de importância regional na região central do Brasil, fazendo parte da Província Estrutural do Tocantins, e que vem sendo alvo de estudos realizados por Almeida (1966), Danni & Fuck (1981), Danni et al. (1982), Marini et al. (1978, 1984), Almeida & Hasui (1984), Hasui et al. (1984), Shobbenhaus et al. (1984), Herz et al. (1989), Hasui & Costa (1990), Abreu et al. (1994), Alvarenga et al. (2000),.

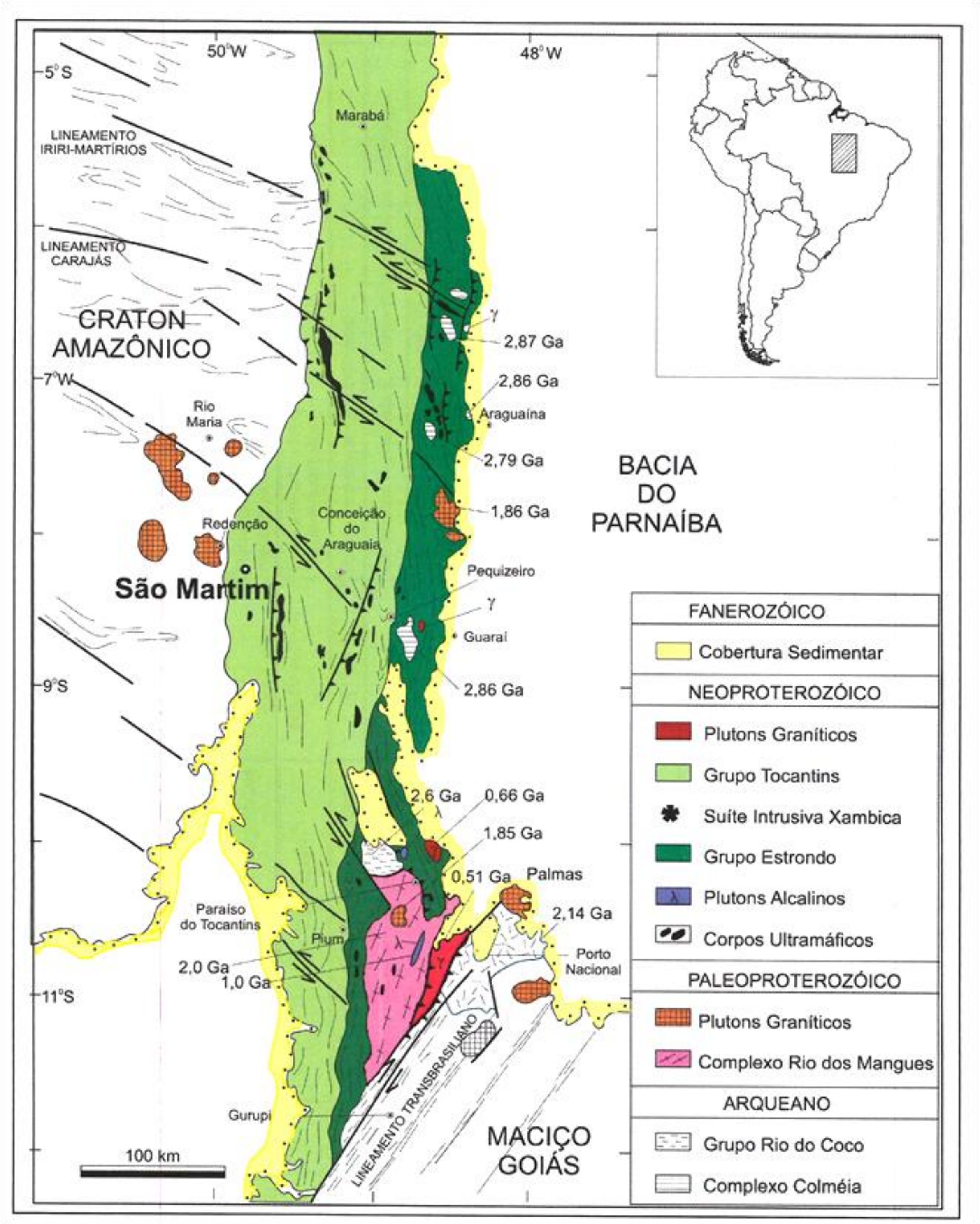


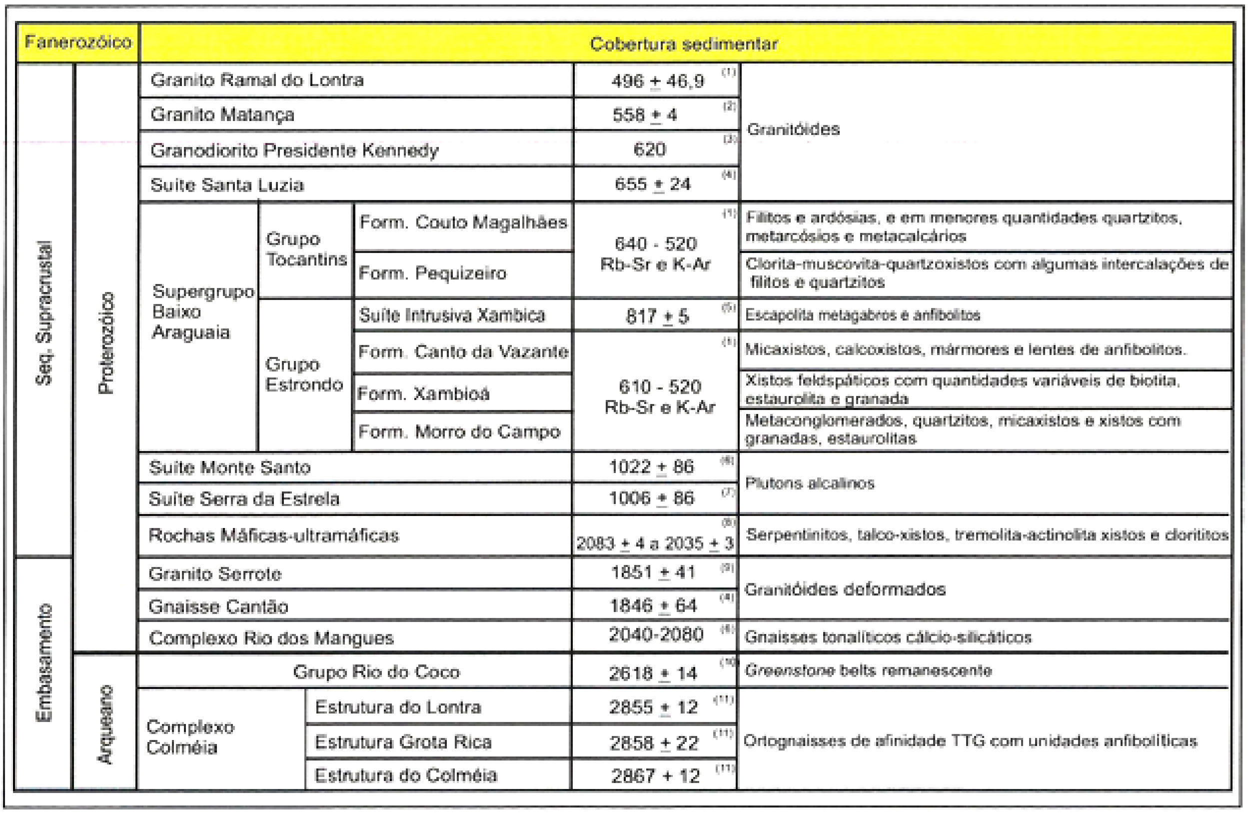
Figura 3 – Mapa geológico da Faixa Araguaia (Alvarenga et al., 2000)

A Faixa de Dobramentos Araguaia agrega os Grupos Estrondo e Tocantins no Supergrupo Baixo Araguaia (Fig4).

Abreu (1978) sugere que o Grupo Estrondo é representado pela Formação Morro do Campo (quartzitos, muscovita +- cianita +- magnetita quartzitos e quartzitos conglomeráticos) e pela Formação Xambioá (diversos tipos de xistos e rochas magmáticas).

Ainda segundo o referido autor, o Grupo Tocantins compreende a Formação Pequizeiro (rochas de baixo grau metamórfico e corpos máfico-ultramáficos) e a Formação Couto Magalhães (metassedimentos detríticos e químicos e rochas máficas).

As rochas do Grupo Tocantins enquadram-se na fácies xisto-verde, sendo que Abreu (1978) aponta uma queda sensível no grau metamórfico para oeste. Almeida (1976) e Hasui (et al, 1975) sugerem uma transição gradual do Grupo Tocantins para o Grupo Estrondo, mas ainda persiste a dúvida sobre a existência ou não de uma discordância.



Fanerozóico		Cobertura sedimentar				
Seq. Supracrustal	Proterozóico	Granito Ramal do Lontra			496 ± 46,9 (1)	Granitóides
		Granito Matança			558 ± 4 (2)	
		Granodiorito Presidente Kennedy			620 (3)	
		Suíte Santa Luzia			655 ± 24 (4)	
		Supergrupo Baixo Araguaia	Grupo Tocantins	Form. Couto Magalhães	640 - 520 Rb-Sr e K-Ar (1)	Filitos e ardósias, e em menores quantidades quartzitos, metarcósios e metacalcários
				Form. Pequizeiro		Clorita-muscovita-quartzoxistos com algumas intercalações de filitos e quartzitos
			Grupo Estrondo	Suíte Intrusiva Xambica	817 ± 5 (5)	Escapolita metagabros e anfibolitos
				Form. Canto da Vazante	610 - 520 Rb-Sr e K-Ar (1)	Micaxistos, calcoxistos, mármores e lentes de anfibolitos.
				Form. Xambioá		Xistos feldspáticos com quantidades variáveis de biotita, estaurolita e granada
				Form. Morro do Campo		Metaconglomerados, quartzitos, micaxistos e xistos com granadas, estaurolitas
		Suíte Monte Santo			1022 ± 86 (6)	Plutons alcalinos
		Suíte Serra da Estrela			1006 ± 86 (7)	
		Rochas Máficas-ultramáficas			2083 ± 4 a 2035 ± 3 (8)	Serpentinitos, talco-xistos, tremolita-actinolita xistos e cloritito
Embasamento		Granito Serrote			1851 ± 41 (9)	Granitóides deformados
		Gnaisse Cantão			1846 ± 64 (4)	
		Complexo Rio dos Mangues			2040-2080 (6)	Gnaisses tonalíticos cálcio-silicáticos
	Arqueano	Grupo Rio do Coco			2618 ± 14 (10)	*Greenstone* belts remanescente
		Complexo Colméia	Estrutura do Lontra		2855 ± 12 (11)	Ortognaisses de afinidade TTG com unidades anfibolíticas
			Estrutura Grota Rica		2858 ± 22 (11)	
			Estrutura do Colméia		2867 + 12 (11)	

Figura 4 - Coluna estratigráfica proposta por Alvarenga et al (2000) com a síntese de alguns dados geocronológicos (em Ma) das rochas da Faixa Araguaia. (1) Macambira, 1983; (2) Gorayeb et al., 2001b; (3) Moacir Macambira (comunicação verbal); (4) Moura & Gaudette, 1993a; (5) Gorayeb et al., 2004; (6) Arcanjo et al., 2001; (7) Arcanjo & Moura, 2000; (8) Gorayeb et al., 2001a; (9) Sousa & Moura, 1995; (10) Arcanjo et al., 2000; e (11) Moura & Gaudette, 1993b.

Costa et al (1988) dividem a Faixa Araguaia em dois domínios: Zona Interna e Zona Externa (Fig5).

A Zona Interna é formada pelo Grupo Estrondo que, por sua vez, é representado por uma seqüência basal denominada Formação Morro do Campo (essencialmente ortoquartzitos e quartzitos micáceos), e uma parte superior, denominada Formação Xambioá (micaxistos variados).

Abreu (1978) assinala que no Grupo Estrondo são frequentes a presença de anfibólio-xistos e anfibolitos, concordantes ou discordantes da seqüência metassedimentar superior. Este autor também aponta serpentinitos, talco-xistos, tremolita-xistos e antofilita-xistos como rochas pertencentes a esta unidade. Ao leste e a norte as rochas do Grupo Estrondo estão recobertas, em discordância angular e erosional, pelos sedimentos da Bacia do Parnaíba.

A Zona Externa é representada pelo Grupo Tocantins, constituído por uma Formação basal denominada Pequizeiro, e uma de topo denominada Formação Couto Magalhães.

A Formação Couto Magalhães compreende rochas metassedimentares, principalmente filitos amarelos, ardósias roxas e localmente lentes arenosas metamorfisadas em fácies xisto-verde baixo. A Formação Pequizeiro é uma seqüência de micaxistos quartzosos com clorita e menores expressões de quartzitos, calcixistos e filitos.

A estruturação da Faixa Araguaia é marcada por cinturões de dobras e falhas e imbricamento tectônico dirigido para oeste, com desenvolvimento de superfícies de deslocamentos. Essas superfícies configuram rampas frontais de direção N-S e rampas laterais NW-SE e NE-SW. O grau metamórfico aumenta para leste.

4.2 Corpos Ultramáficos da Faixa Araguaia

Os primeiros trabalhos que descrevem as rochas máficas e ultramáficas da Faixa Araguaia caracterizavam tais corpos como associados a fraturas profundas (Almeida, 1974; Cordeiro & McCandless, 1976). A descrição desses corpos como ofiolitos foi primeiramente feita por Hasui et al., 1977; Kotschoubey & Hieronymus, 1996; Teixeira, 1996; Osborne, 2001; Paixão & Nilson, 2002).

Vários corpos de rochas ultramáficas e subordinadamente máficas estão associados principalmente a rochas do Grupo Tocantins, ocorrendo na margem oeste da Faixa Araguaia. Os tipos litológicos presentes são peridotitos e dunitos serpentinizados, cromititos e metaultramafitos diversos, tais como tremolita-actinolita xistos, esteatitos, talco xistos e cloritítos. Localmente ocorrem serpentinitos miloníticos e cherts.

Os serpentinitos exibem coloração verde-clara, granulação fina, textura fanerítica fina e estrutura predominantemente maciça, sendo constituídos por um denso intercrescimento de minerais verdes fibrosos e lamelares, micáceos (serpentina, clorita). A mineralogia consta predominantemente de serpentina (antigorita e crisotila), clorita, antofilita, ou tremolita como varietais, e ocorrem acessoriamente o talco, magnetita e carbonato.

Os corpos ultramáficos são comumente estreitos e alongados, estruturados segundo direções N-S, NNE ou NNW, alguns com dimensões expressivas representadas principalmente pela Serra do Tapa e Serra do Quatipuru. Conforme as indicações de suas feições de contato, os corpos ultramáficos são alóctones.

Os contatos das rochas ultramáficas com as encaixantes são geralmente bruscos, não se encontrando, no entanto, qualquer indício de contatos de natureza magmática, notando-se uma rápida passagem de rochas ultramáficas para as encaixantes metassedimentares.

Associados a esses corpos podem ocorrer basaltos com estruturas “pillow lava”.

5. Contexto geotectônico da Faixa Araguaia

A evolução da Faixa Araguaia é relacionada ao evento Brasiliano, no limite do neoproterozóico e paleozóico inferior, fato este indicado por datações radiométricas disponíveis, em especial, na porção setentrional da faixa. Os modelos de evolução são dicutidos por Alvarenga et al. (2000) e por Moura & Gandette (1993).

Almeida (1974) interpreta as rochas ultramáficas como produtos do manto ao longo de profundas geossuturas, paralelas aos rios Tocantins-Araguaia, idéia também compartilhada por Silva et al (1974) que as associam a uma zona de falha.

Almeida (1974) considera que os corpos máficos e ultramáficos representariam o aporte de material do manto ao longo de fraturas profundas da Geossutura Tocantins-Araguaia. Gorayeb (1981) concluiu que os corpos de serpentinitos são de natureza pré-tectônica, dispostos em zonas de falha e que as composições químicas e mineralógicas evidenciam sua natureza ultramáfica. Concluiu, também, que os serpentinitos originaram-se a partir de magma de composição dunítica, colocados tectonicamente como massas cristalinas ou semicristalinas com feições gerais do tipo alpino, representando corpos ofiolíticos.

Atualmente, uma idade Mesoproterozóica é admitida para o Grupo Estrondo, tendo em vista a idade de 1.050 Ma obtida através de diagrama isocrônico em xistos desse grupo (Hasui et al., 1980). Esses autores interpretam esse valor como representativo do metamorfismo regional que afetou as rochas do Grupo Estrondo, comprovando assim, um registro ao menos de idade Uruaçuana, afetada posteriormente pelos eventos brasilianos.

A Serra do Quatipuru, localizada na porção sul da Faixa Araguaia, tem idade de 757 Ma +- 49 Ma segundo estudos realizados por Paixão et al (2008).

Atualmente, os modelos evolutivos propostos tem relação com: 1) megaestrutura ensiálica, 2) produto de estágio avançado de colisão continental, e 3) bacia que evoluiu de um rift continental para uma bacia proto-oceânica, que experimentou inversão, intensa compressão e metamorfismo.

6. Depósito de níquel laterítico Serra do Tapa e Vale dos Sonhos

6.1 Introdução

Na região do depósito são identificadas rochas metassedimentares da Formação Couto Magalhães e rochas máficas e ultramáficas do Grupo Tocantins (Supergrupo Baixo Araguaia). As unidades geológicas presentes estão tectonicamente imbricadas para oeste por falhas de empurrão regionais e formam uma faixa de serras com mais de 40 km alinhadas N-S. As rochas metassedimentares possuem pouca expressão topográfica, enquanto que o silexito e as rochas ultramáficas estão relacionados ao terreno acidentado da área.

6.2 Unidades Litológicas

A seguir são descritas sumariamente as principais rochas encontradas na área:

- Rochas metassedimentares da Formação Couto Magalhães.

Inclui ardósias e filitos em sua essência, com variações de quartzitos e metacherts. São rochas de dureza baixa, com foliação S0/S1 e S2 incipiente, que mergulham para E-SE e E-NE. O mergulho é geralmente em torno de 30º, mas pode atingir 70º quando próximo à zona de contato com rochas ultramáficas ou com o silexito.

- Rochas Ultramáficas do Grupo Tocantins:

Compreende principalmente peridotitos serpentinizados (metaharzburgitos) e subordinadamente dunitos serpentinizados. O metaharzburgito é formado por uma massa verde a verde escura de serpentina, de granulação fina a média, e por cristais pseudomorfos provenientes da alteração do ortopiroxênio. Exibe magnetismo moderado a forte e normalmente apresenta vênulas, falhas e fraturas preenchidas por serpentina verde claro, talco e, em menor quantidade, carbonato.

O perfil de alteração desenvolvido sobre o harzburgito é formado por uma variedade de facies e dividido quimicamente em cinco zonas ou horizontes: laterítica, limonítica, saprolítica superior, saprolítica inferior e substrato ultramáfico (“bedrock”).

- Silexito:

O silexito é silicoso-hematítico e apresenta intensa venulação de sílica. Possui dureza alta e cor que varia de branca a vinho e marrom. A granulação é fina a afanítica e com textura brechóide ou milonitizada quando próxima a zonas de falha. Geralmente possui magnetismo fraco e apresenta baixo teor de níquel (<0.2%).

Os aspectos texturais e a correlação com os outros litotipos indicam que os silexitos têm origem tectônica. Nos poucos afloramentos “in situ”, esta unidade acompanha o trend regional de vergência para W, com ângulo alto de mergulho (> 50º). Devido a sua dureza alta, o silexito forma serras com variação topográfica superior a 100 metros, e que são fundamentais para o desenvolvimento de espesso perfil laterítico nas rochas ultramáficas.

- Cloritites

Os cloritites ocorrem localmente na porção oeste (corpo Pau Preto) da área e geralmente estão associados a zonas de contato com as rochas sedimentares.

- Formação Ferrífera Bandada

A Formação ferrífera bandada ocorre a oeste da Serra do Tapa e apresenta feições típicas deste tipo de rocha.

6.3 Geologia Estrutural e Metamorfismo

O arcabouço tectônico da área é representado por uma seqüência de empurrões do tipo duplex onde o embasamento é formado por rochas sedimentares metamorfisadas em fácies xisto verde baixo (predominantemente filitos e ardósias da Formação Couto Magalhães) e os empurrões são formados por lascas ofiolíticas de mesmo grau metamórfico (meta-harzburgitos do Grupo Tocantins). A zona de contato é formada por silexitos de espessura variável.

A vergência regional é para W, sendo que próximo às zonas de contato, o mergulho varia entre 50º e 70º. Localmente, os empurrões apresentam vergência para NW ou SW, provavelmente em função de anteparos estruturais.

As rampas laterais dos empurrões também são estruturas marcantes na área e possuem direção preferencial WSW-ENE, com pares conjugados de menor expressão de direção ENE-WSW. Estas estruturas, além de atuarem como rampas laterais dos empurrões regionais, podem ter facilitado o desenvolvimento de falhas normais e inversas sin-pós laterização, observadas no perfil de alteração.

Esta estruturação tectônica é fundamental para o desenvolvimento do perfil intempérico observado na área. O silexito atua como um envelope ou bordas de bacia do pacote de rochas ultramáficas. Esta estruturação aprisiona a água meteórica e diminui o transporte de material durante o processo erosivo. Conseqüentemente, o intemperismo químico das rochas ultramáficas se torna mais eficiente. Além disso, a zona de falha entre o silexito e o metaharzburgito tem grande expressão em profundidade e facilita ainda mais a percolação de água meteórica, permitindo o desenvolvimento de perfis mineralizados com mais de 100 metros.

Exceto em locais de topografia suave, onde existe material transportado, o contato é geralmente brusco e apresenta fortes indícios de cisalhamento. Contatos recobertos por material transportado podem ser inferidos com auxílio de imagens geofísicas.

A paragênese mineral observada nas rochas máfico-ultramáficas caracteriza um metamorfismo regional de baixo grau da fácies xisto-verde.

7. Conclusões

A compilação dos dados obtidos durante a avaliação do depósito e de artigos científicos permitiu a caracterização da Serra do Tapa e Vale dos Sonhos como um depósito de níquel laterítico de classe mundial associado a complexo ofiolítico neoproterozóico.

O perfil de alteração da Serra do Tapa e Vale dos Sonhos mostra o zoneamento químico típico de depósitos de níquel laterítico (laterítico, limonítico, saprolítico superior, saprolítico inferior e “bedrock)”, no qual o baixo valor de ferro e alto valor de magnésio do substrato ultramáfico progressivamente se transforma num horizonte limonítico com alto valor de ferro de baixo magnésio.

O perfil de alteração apresenta características singulares do depósito. O grande número de facies que compõem cada horizonte ressalta já que muitos depósitos os horizontes químicos não apresentam grande variação faciológica. Dentro de um mesmo horizonte, a correlação negativa entre ferro e magnésio também é observada entre as fácies. Essa variação é interpretada como determinante nas propriedades mecânicas, texturais, na cor dos facies.

A caracterização das fácies que compõem o perfil de alteração é importante paras as operações de lavra, no momento em que se definem os contatos minério-estéril.

Outro aspecto peculiar da Serra do Tapa é o desenvolvimento de perfil de alteração com mais de 100 metros de espessura. Esta característica está associada aos controles da mineralização, em especial ao arcabouço estrutural e a presença de silexito, que exercem grande influência sobre a topografia, o sistema de drenagem, a taxa de erosão e na variação do lençol freático.

O silexito atua como um envelope ou bordas de bacia do pacote de rochas ultramáficas. Esta estruturação aprisiona a água meteórica e diminui o transporte de material durante o processo erosivo. Consequentemente, o intemperismo químico das rochas ultramáficas se torna mais eficiente.

O trabalho também conclui que a Serra do Tapa e o Vale dos Sonhos indica um novo ambiente geotectônico para hospedar depósitos de níquel laterítico de classe mundial, mostrando que complexos ofiolíticos associados a faixas móveis pré-cambrianas são áreas prospectivas. Neste sentido, o estudo dos fatores condicionantes para a mineralização de níquel laterítico em outros complexos ofiolíticos de idade pré-cambriana deve ser conduzido no intuito de descobrir novos depósitos.

Serra do Tapa and Vale dos Sonhos world class deposit: Ni-laterite mineralization associated to a Precambrian ophiolitic complex of the Araguaia Fold Belt – Pará state, Brazil.

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ABSTRACT

The Serra do Tapa and Vale dos Sonhos is a world class nickel laterite deposit (100Mt @ 1.5% Ni) located at the southeast of Pará state, Brazil, approximately 200km SW of Marabá. The development of thick mineralized intervals with more than 100 m is conditioned by the association of the critical elements that control the mineralization, which include the protholite nature, degree of serpentinization, structural framework, climate, drainage system and geomorphologic history. The metachert appears as an important control over the mineralization as it traps the meteoric water and preserves the mineralied profile from erosion. The characterization of the facies is important to define ore-waste contacts and estimate visually the grades. A total of 14 facies occur within the profile are distinguished by their mechanic characteristics, texture, color and mineralogy. The facies are grouped in five geochemical horizons defined by the iron and magnesium variation along the weathered profile (from top: lateritic, limonitic upper saprolite, lower saprolite and bedrock). The deposit is related to an ophiolite complex of Precambrian age, and therefore indicates a new geotectonic environment to host nickel laterite deposits, showing that ophiolitic complexes associated to Precambrian mobile belts are prospective areas.

Keywords: Nickel laterite deposit, Precambrian, ophiolites

1. Introduction

Production of nickel comes from two types of deposits: magmatic sulfide and laterite. This second is a chiefly Ni-only deposit with some deposits hosting Co as a recoverable by-product. Laterite deposits stand for 72% of worldwide known contained nickel resources and about half of current primary production of nickel (Porto, 2006). Nickel laterite deposits can develop over ultramafic rocks originated in different tectonic settings, mainly associated with Phanerozoic ophiolitic complexes, Archean greenstone belts and Precambrian layered mafic-ultramafic intrusions in cratons (Brand et al, 1998).

Ophiolites are a distinctive association of rocks interpreted to form in a variety of plate tectonic settings, including oceanic spreading centers, back-arc basins, forearcs, arcs, and other extensional magmatic settings including those in association with plumes (Moores, 1982, 2002; Lippard et al., 1986; Nicolas, 1989; Peters et al., 1991; de Wit and Ashwal, 1997; Dilek et al., 2000).

Many ophiolites are altered to serpentine-, chlorite-, albite-, and epidote-rich rocks, possibly by hydrothermal sea floor metamorphism. In the 1960s and 1970s much research was aimed at defining a type ophiolite succession, which became known as the Penrose-type of ophiolite. More recent research has revealed that the variations between individual ophiolites are as significant as any broad similarities between them (Moores, 2002; Karson, 2002; Dilek, 2003).

The ophiolitic complexes represent a record of the Wilson cycle opening, narrowing and closing of ocean basins. A global survey of sutures predating formation of the supercontinent Rodinia (e.g. older than 0.9–1.0 Ga), has yielded evidence for at least 35 described ophiolitic complexes that appear to cluster at times of 1.0-1.5 Ga, 1.8-2.3 Ga, c. 2.5-2.7 Ga and c. 3.4 Ga (Moores, 2002). The record of Archean, Paleoproterozoic and Mesoproterozoic ophiolites is poorly documented because the obliteration of key characteristics, deformation and metamorphism over time.

The existence of Neoproterozoic ophiolites in Afro-Arabia and South America is associated with the evolution of several Pan-African-Brazilide ocean basins (e.g. Mozambique Ocean) in the aftermath of the break-up of the supercontinent Rodinia and during the assembly of West Gondwana. These Pan-African-Brasilian ophiolites are fragments of Proterozoic oceanic crust, juvenile island arcs and oceanic plateau that were amalgamated during the evolution of both collisional- and accretionary-type orogens.

None of the Precambrian ophiolite complexes host significant nickel laterite mineralization in order to categorize them as a world-class deposits (>100Mt). This paper presents the world class Serra do Tapa (ST) and Vale dos Sonhos (VDS) nickel laterite deposits, which is associated to Precambrian ophiolitic complexes of the Araguaia Fold Belt, in Central Brazil. Combined resources for ST, VDS and closely associated satellite ore bodies are greater than 100Mt@1.3%Ni (AMEC, 2007), promoting the deposit as the largest nickel resource associated with Precambrian ophiolitic complex in the world.

A description of the geology, morphology, mineralogy and geochemistry of the deposit, mainly based upon extensive exploration data provided by Falconbridge Ltd. and Xstrata Nickel is presented in this study. These data include geological maps and sections, petrographic studies, as well as 1,400 geochemical analyses of samples from diamond drill holes. Results are used to discuss the key features leading to the development of the ST and VDS deposits, and to compare them with other nickel laterite deposits in the world.

2. Exploration Review

Nickel occurrence at the Araguaia Fold Belt (AFB) was identified in the 1970´s by CPRM (Brazilian Geological Survey) during nickel sulphide exploration programs. From 2002 to 2008, prospecting and exploration of laterite deposits was carried out by many junior and major mining companies along the ophiolites of the AFB.

In 2004, Falconbridge Brazil Ltd. (now Xstrata Nickel) performed geological mapping with geochemical sampling, photo interpretation and 500 m spaced E-W oriented airborne magnetometric and gamma-spectrometric surveys in several areas along the AFB (Falconbridge, 2006). The presence of limonitic/ferricrete crusts on surface, high magnetometric and low radiometric anomalies led to more than 10 potential targets along the AFB.

The VDS was discovered in July 2004 following field investigations in a low plateau located to the east of the main ridge. The ST was discovered shortly after in one of the prominent ultramafic ridges in the region. Other smaller ore bodies (Pau Preto, Escalada, Indiaporã and Tapa West) were also identified. Following the discovery in 2004, an extensive program was developed for the evaluation on nickel resources, including 55,334 meter of diamond drill hole and 46,006 assays, leading to indicated resources for the ST and VDS of 79Mt at 1.37% Ni using a 1.0% cutoff (AMEC, 2007).

3. Regional Geology

3.1 Araguaia Fold Belt

The tectonic evolution of the AFB has been target of discussion by many authors: Almeida (1966, 1968), Danni & Fuck (1981), Danni et al. (1982), Marini et al. (1978, 1984), Almeida & Hasui (1984), Hasui et al. (1984), Shobbenhaus et al. (1984), Hasui e Costa (1990), Hasui et al. (1994), Abreu et al. (1994), Gorayeb, (1989); Paixão et al (2008), Moura et al (2008), Alvarenga et al (2000) Teixeira (1996), Koutschoubey et al (1996) and many others.

The AFB represents a regional tectonic element within the central region of Brazil, being part of the Tocantins Province. The AFB outlines over 1,000 km along N-S direction and crosses the Tocantins and Pará states. The southward portion of the AFB makes limit with the Brasília Fold Belt and the northeastern portion limits the Parnaíba Basin and Phanerozoic sedimentary rocks. To the northwest the AFB limits the Amazon Craton (Fig.1).

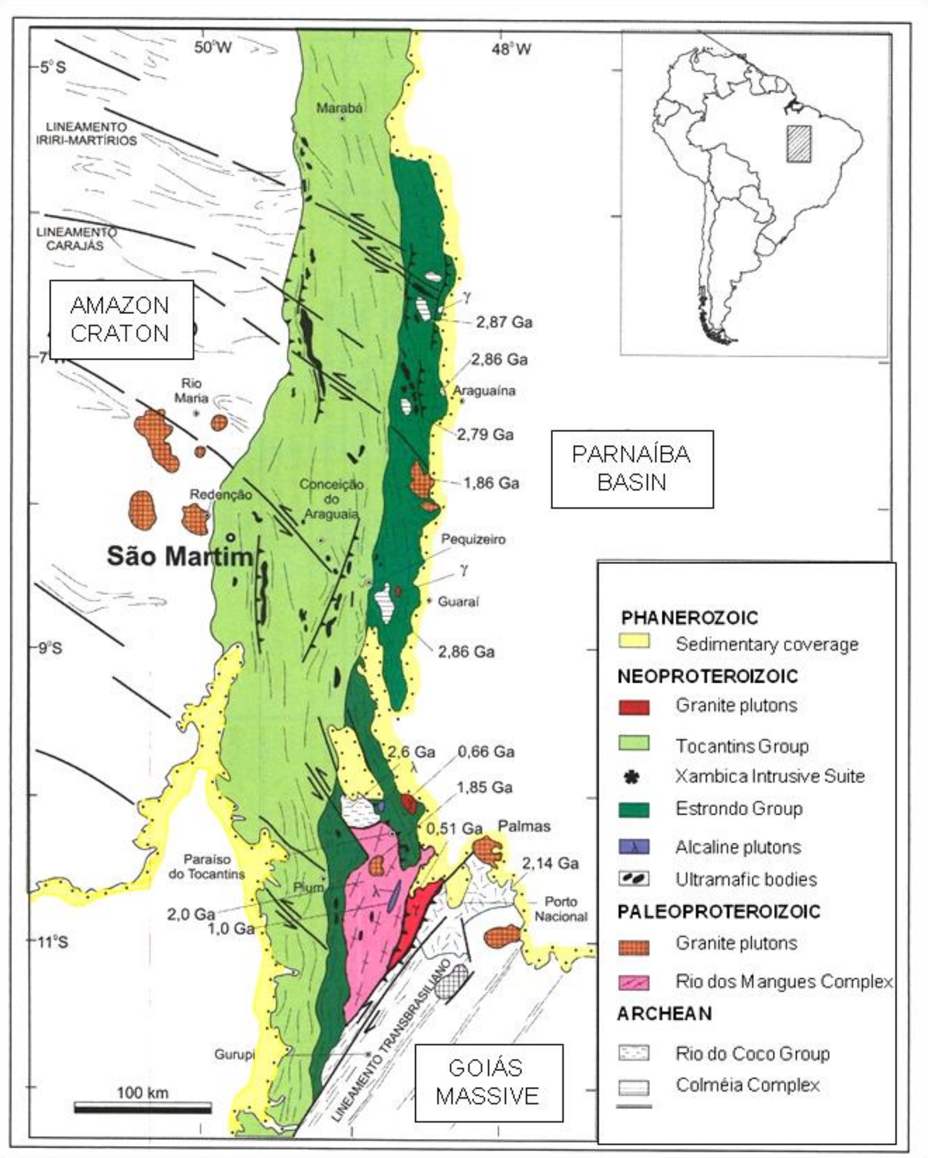

Figure 1 – Geologic map of the Araguaia Fold Belt (modified after Alvarenga et al., 2000).

The stratigraphic proposal of Abreu (1978) for the AFB assemblages the Estrondo and Tocantins Groups into the Baixo Araguaia Supergroup (Fig.2).

Abreu (1978) proposed that the Estrondo Group is represented by the Morro do Campo Formation (quartzites, muscovite +- cyanite +- magnetite quartzites and conglomeratic quartzites) and by the Xambioá Formation (various types of schists and granitic rocks).

Also according to the referred author, the Tocantins Group is represented by the Pequizeiro Formation (low grade metamorphic rocks of various nature, mafic and ultramafic bodies) and by the Couto Magalhães Formations (granular and chemical sedimentary rocks, mafic rocks associated).

Phanerozoic		Sedimentary coverage			
Supracrustal Sequence	Proterozoic	Ramal do Lontra Granite			496 +- 46.9 (1)
		Matança Granite			558 +- 4 (2)
		Presidente Kennedy Grandiorite			620 (3)
		Santa Luzia Suite			655 +- 24 (4)
		Baixo Araguaia Supergroup	Tocantins Group	Couto Magalhães Fm.	640 -520 (1) Rb-Sr and K-Ar
				Pequizeiro Fm.	
			Estrondo Group	Xambica Intrusive Suite	817 +- 5 (5)
				Canto da Vazante Fm.	640 -520 (1) Rb-Sr and K-Ar
				Xambioá Fm.	
				Morro do Campo Fm.	
		Monte Santo Suite			1022 +- 86 (6)
		Serra da Estrela Suite			1006 +- 86 (7)
		Mafic - Ultramafic rocks			2083 +- 4 (8) to 2035 +- 3
Basement rock		Serrote Granite			1851 +- 41 (9)
		Cantão Gneiss			1846 +- 64 (4)
		Rio dos Mangues Complex			2040 - 2080 (6)
	Archean	Rio do Coco Group			2618 +- 14 (10)
		Colméia Complex	Lontra		2855 +- 12 (11)
			Grota Rica		2858 +- 22 (11)
			Colméia		2867 +- 12 (11)

Figure 2 - Stratigraphic column proposed by Alvarenga et al (2000) with some geochronologic data (in Million years) of the rocks of the AFB. (1) Macambira, 1983; (2) Gorayeb et al., 2001b; (3) Moacir Macambira (comunicação verbal); (4) Moura & Gaudette, 1993a; (5) Gorayeb et al., 2004; (6) Arcanjo et al., 2001; (7) Arcanjo & Moura, 2000; (8) Gorayeb et al., 2001a; (9) Sousa & Moura, 1995; (10) Arcanjo et al., 2000; e (11) Moura & Gaudette, 1993b.

The ultramafic rocks of the Pequizeiro and Couto Magalhães Formations act an important role in the economy of the region. The supergene enrichment in nickel over ultramafic rocks is widespread in the AFB, sometimes hosting significant deposits like ST and VDS. Some bodies also display cobalt as a sub-product.

Besides the ST and VDS, another mineralized body associated to the AFB and that is well studied is the Serra do Quatipuru (Paixão, 2009), located 350 km to south (Fig.1).

Costa et al (1988) divided the AFB in two domains: External and Internal Zones. The External Zone is correlated to the Tocantins Group (Couto Magalhães and Pequizeiro Formations) and is in contact with the Amazon Craton.

3.2 Tectonic framework

The tectonic framework of the AFB is marked by the presence of regional folds and thrust faults moving towards west. The imbrications obey a duplex thrust fault system that is notable especially in the region of the ST and VDS.

The frontal ramps of the major thrust fault display an N-S direction. The lateral ramps are preferentially NE-SW oriented and behave as transcurrent faults. Regionally the metamorphism increases to east in the AFB.

Within the AFB, the mafic and ultramafic bodies are encountered within a 700 N-S by an E-W 200km area. Figure 4 is a magnetometric product of the ST and VDS region and it shows the N-S orientation of the frontal ramps. The magnetic contrast between the meta-sedimentary and mafic-ultramafic rocks is outstanding. Same feature is observed with the N-S oriented mafic dykes (Fig.3).

The meta-sedimentary rocks of the Baixo Araguaia Supergroup exhibit S0/S1 foliation and incipient S2 structures dipping ESE to ENE usually around 30º. On the contact with the ultramafic bodies the foliation averages 50º.

The red contrast of the magnetometric product is related to the mafic and ultramafic rocks. Regional N-S dykes also are evidenced.

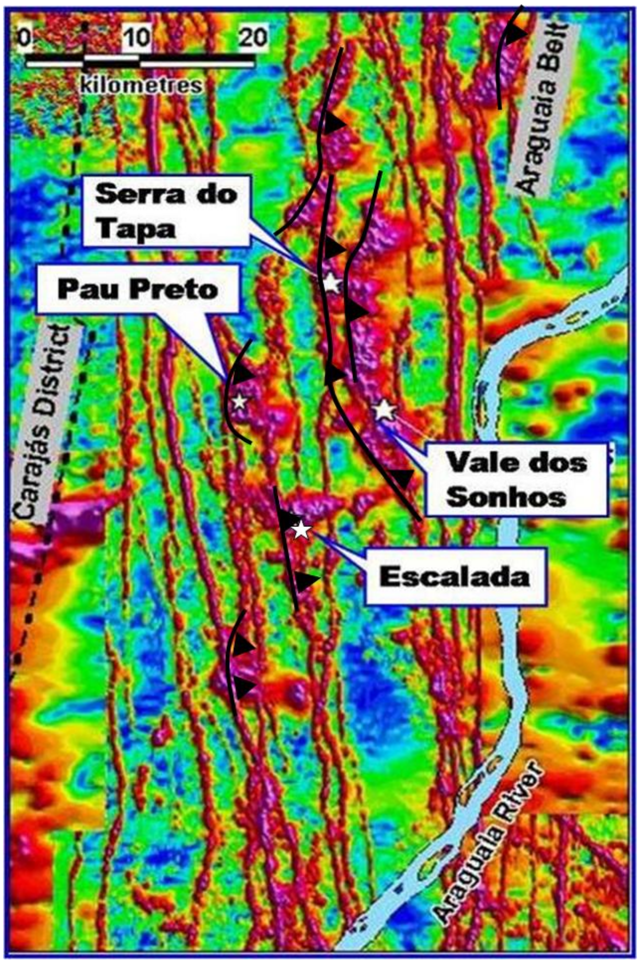

Figure 3 - Magnetometric airborne product of the ST and VDS region.

3.3 Ultramafic bodies of the Araguaia Fold Belt: ophiolitic nature and geochronology

The existence of an ophiolite assemblage within the AFB has been suggested since the early 1970s (Almeida, 1974; Silva et al, 1974; Cordeiro and McCandless, 1976), and has been discussed more recently by several authors (Gorayeb, 1989; Hasui and Costa, 1990; Alvarenga et al., 2000; Moura & Gandette, 1993; and others). This suggestion is now supported by detailed descriptions of closely associated ultramafic complexes, mafic pillow lavas and siliceous exhalative rocks (Teixeira, 1996; Koutschoubey et al, 1996). Most authors note that whilst the ophiolite assemblages possess basal ultramafic complexes and upper mafic pillow lavas associated with pelagic, hemi-pelagic or volcanogenic sediments, they lack the middle sheeted dyke and massive gabbro sections of ideal ophiolite sequences (Moores, 2002). The lack of intermediate segments in the AFB ophiolites, contrasting with remarkably well preserved pillowed basalts and extensive peridotite complexes, is interpreted as tectonic dismemberment (Osborne, 2001).

Paixão et al (2008) concluded that the AFB represents an accretion of Neoproterozoic terrains developed during the amalgamation of West Gondwana and contains remnants of oceanic arcs and ophiolite complexes, formed in a time interval between 880 and 650 Ma, with final collisional event at approximately 530 Ma.

The age of 757± 49 Ma (Sm-Nd whole-rock isochron) for the ophiolite remnants in the AFB, along with geochronological data for the tectonic evolution of this orogeny (e. g. last granitic intrusion from 530 to 510 Ma) render comparisons with other Neoproterozoic orogens in South America, such as the Brasília Fold Belt in Central Brazil, suggesting a common evolution during the Neoproterozoic–Early Cambrian assembly of West Gondwana (Paixão et al., 2008).

According to the study performed by Moura et al. (2008), which is focused on discussing the provenance of metasedimentary rocks of the Baixo Araguaia Supergroup of the Brasiliano Araguaia Belt, the zircon evaporation ages for detrital zircons from quartzites concentrated around 1000–1200 Ma and 2800–2900 Ma (207Pb/206Pb method); Sm–Nd TDM model ages of schists and phyllites scatter around 1600–1700 Ma. Facies analysis of low-grade metasedimentary rocks suggests a sedimentary environment of basin floor and lower- to upper-slope turbidites. Nearby sources are indicated by the textural and mineralogical immaturity; together with structural geological data indicating tectonic transport of the supracrustal pile towards the NW, this suggests probable provenance from the southeastern portion of the Araguaia Belt and not from the Amazonian Craton as usually believed. The Goias Massif and the São Francisco Craton are considered to be the best candidates. They may have formed a larger continental mass during West Gondwana amalgamation, prior to their collision with the Amazonian Craton to form the Araguaia Belt. Final timing of this collision is constrained by c. 550 Ma syntectonic granites.

4. Serra do Tapa and Vale dos Sonhos Deposit

4.1 General Aspects

The ST and VDS deposits are located approximately 22 km west of Sao José (Pará State), a village located at the margin of the Araguaia River. The area of the deposits has a good trasportation system, including highways and a major railroad, being located at 120 km west of Araguaína city (Tocantins State) and 1,000 km north of Brasilia, the capital of Brazil. The deposit is in the vicinity of other large Ni-laterite deposits, including Onça-Puma and Vermelho in the Carajás District (Fig.4). Mining and nickel production of ferronickel in the world-class Onça-Puma deposit (www.vale.com) started in 2011, with installed capacity to produce 52 kt of nickel.

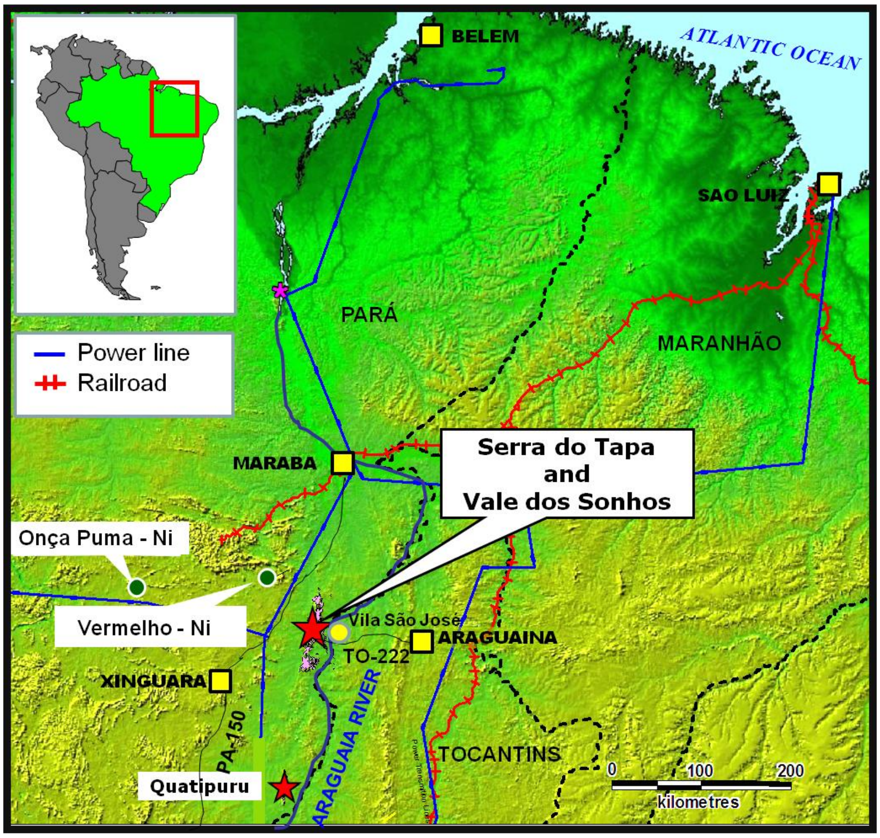

Figure 4 - Location of the Serra do Tapa and Vale dos Sonhos deposits.

The regional topography is nearly flat where meta-sedimentary rocks occur, with altitude varying from 170 m to 220 m. This topographic pattern is crossed by occasional, elongated, north-south oriented crests of ultramafic rocks that reach up to 500 m elevation. At ST the elevations range from 280 to 500 m in which complex topography dominates over plateau areas. As opposed to Serra do Tapa, Vale dos Sonhos is located in a relatively flat plateau, with altitudes ranging from 200 m to 290 m (Fig.5)

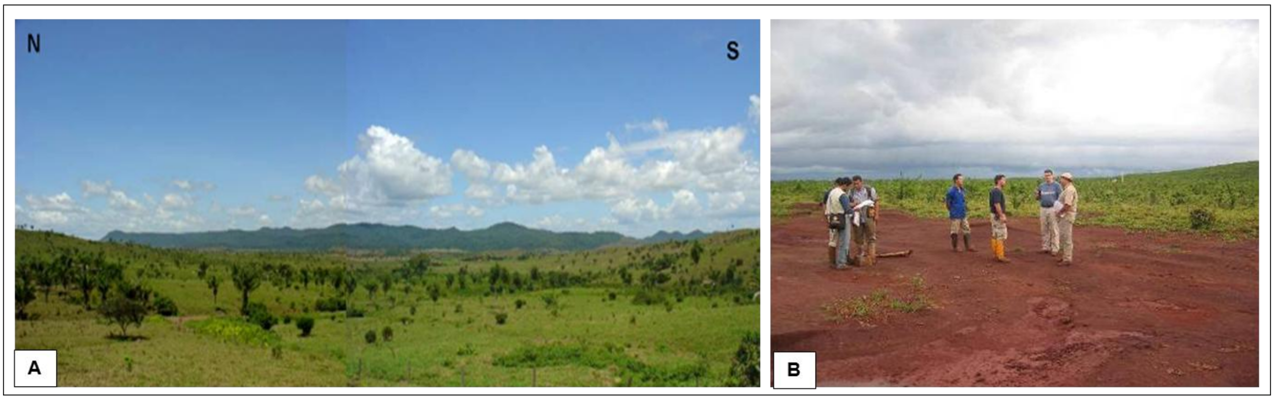

Figure 5 – (A) View of Serra do Tapa from west to east showing a NS orientation of the ridges; (B) Vale dos Sonhos plateau with gramineuos vegetation.

4.2 Geology

A detailed geological map of the ST and VDS resulted from extensive exploration developed in this area by Xstrata Nickel. Figure 6 is a simplified map that shows the main rock types (except regional mafic dykes), the N-S direction of main thrust faults and preferential NE-SW lateral ramps. The schematic geological section (Fig.6) shows the metachert associated with duplex fault systems and that it is an important control of the mineralization.

At the area of the deposit the rocks types are (Fig.7A to D):

- Meta-sedimentary rocks that are generally siltic to clayey and display low grade metamorphism. This rock type represents the regional metasedimentary sequence of the Araguaia Fold Belt (Couto Magalhães Formation);
- Epidothized basalts with preserved pillow lava structure that represents the volcanic portion of the ophiolitic complex. The texture is well preserved and the metric-size pillow lavas are mined for dimension stones;
- Serpentinized ultramafic rock (metaharzburgite) that represents the basal portion of the ophiolitic complex. Presence of pisolites is a strong evidence of weathered profile.
- Metachert displaying variable degree of shearing and brecciation.
- Gabbroic dykes with no metamorphism associated.

The tectonic framework observed in the region was essential for the development of deep weathering profiles over the ultramafic subtract. Tectonic imbrications obey a duplex thrust fault system that is evident in the region of the deposit. NE-SW transcurrent faults limit the ultramafic bodies along the NS direction and form an efficient structural control for the development of deep weathered profiles. These faults not only limit ultramafic bodies, but also cross cut them, displacing vertical blocks by several kilometers.

The contact between the ultramafic and enclosing rocks (meta-sediments and metachert) is usually abrupt and shows no indications of thermal metamorphism.

The metachert appears as sheets of variable thickness and occurs as an envelope to the ultramafic rocks. It is characterized by mylonitic or brecciated silicious-hematitic rocks with intense silica veining, suggesting a tectonic origin.

The metachert occurs in high topographic level and has an important role in the geomorphology of the region. Because the metachert traps the meteoric water in higher level, acting like a cup, it controls the weathering process over the ultramafic rocks. Consequently, the metachert influences the geomorphology, topography and drainage system.

The gabbroic dykes cut meta-sedimentary and ultramafic rocks. They are mainly medium-size rocks with no evidence of metamorphism.

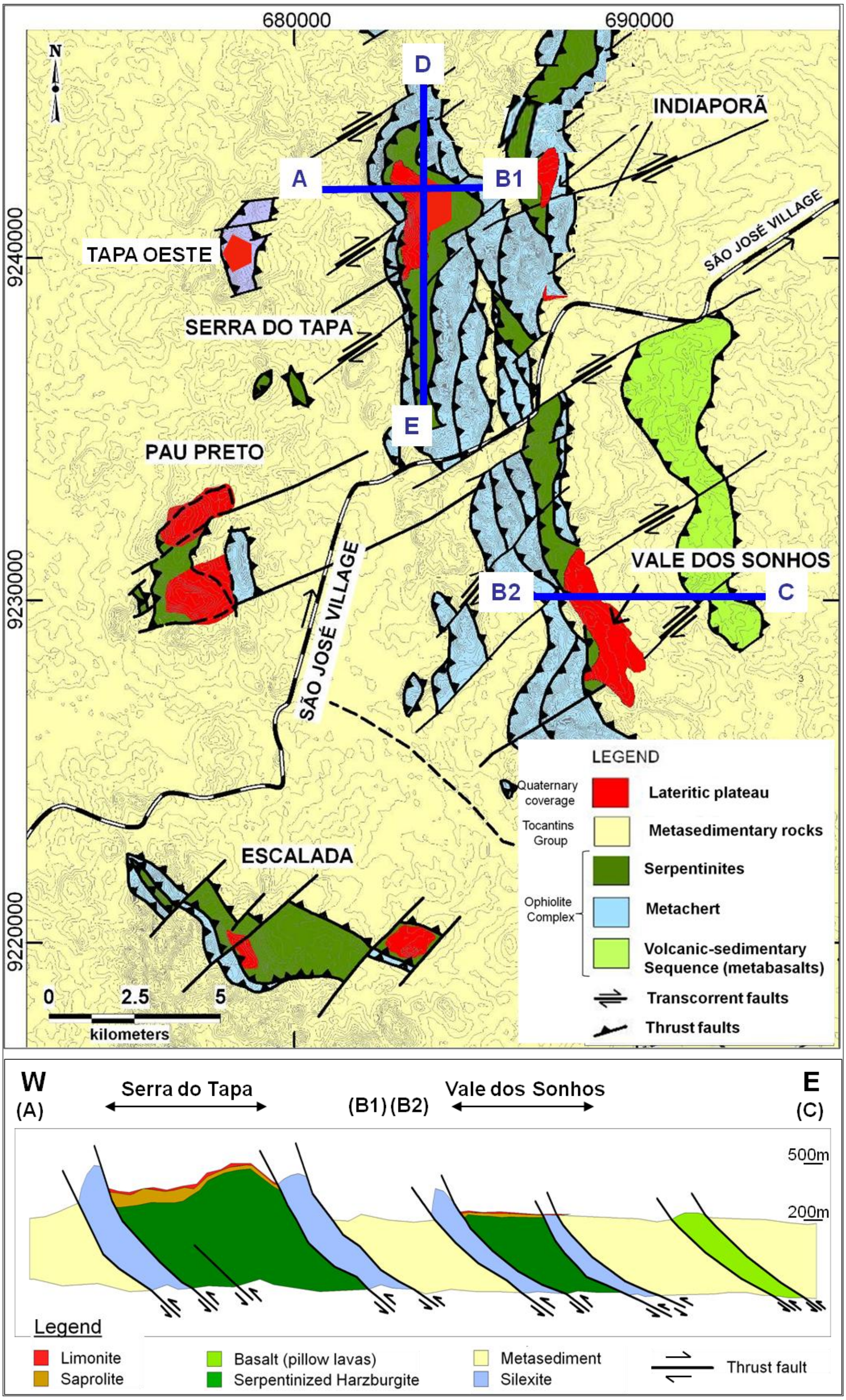

Figure 6 – Geology and schematic geological section of the area showing the duplex fault system. Modified from Xstrata NIckel internal reports.

The original ultramafic rock (bedrock) was probably a serpentinized harzburgite. In this rock olivine was altered to serpentine and minor talc, and orthopyroxene was replaced by a mixture of talc, serpentine and carbonate. Relicts from the primary texture are indicated by coarse-grained olivine and orthopyroxene pseudomorphs, but the primary mineralogy was pervasively replaced during serpentinization. The serpentinite consists mainly of serpentine (antigorite and lizardite) with associated chlorite, carbonate, talc and Fe-oxides (Fig.7E and F).

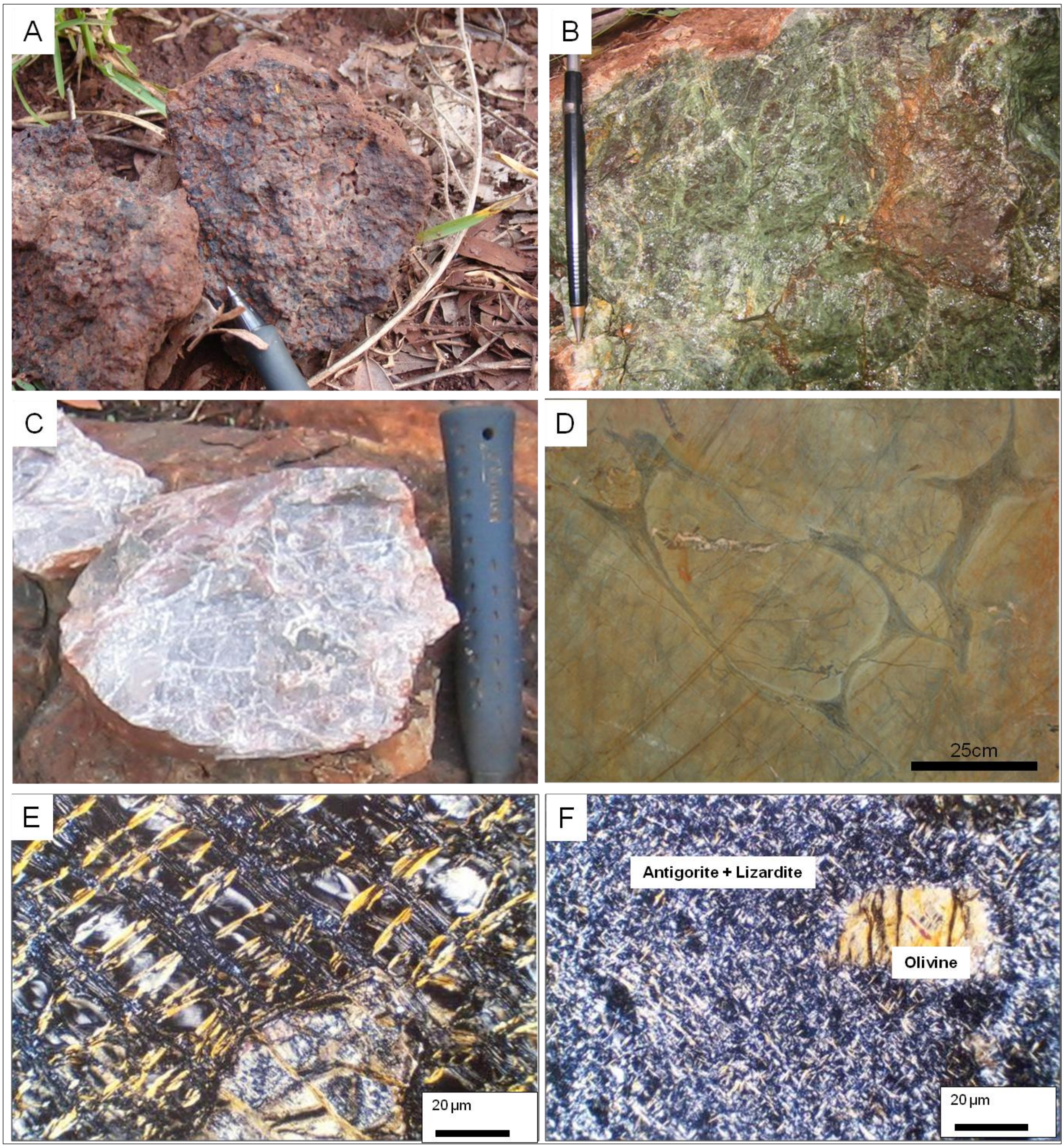

Figure 7 – (A) Laterite; (B) Serpentinized harzburgite; (C) Metachert; (D) Metabasalt with pillow lava structure; (E and F) General aspect of the serpentinized harzburgite in thin section.

Serra do Tapa

The ST deposit has a sigmoid shape with the associated ultramafic body extending roughly 10 km along N-S direction (Fig.6). The mineralization extends nearly 5 km of the ultramafic rocks from the central portion to its north limit. Maximum width of the mineralized portion is 900 m.

The mineralization is restricted to 5 km at the northern part of the ultramafic body due to the presence of NE-SW transcurrent faults (lateral ramps). Normal faults coincident with these lateral ramps divide the ST deposit into blocks (Fig.8). These blocks show significant difference in the weathering profile, estimated by the distance between the topographic surface and bedrock. To the south of the ST deposit the weathered profile is absent and becomes deeper towards the north, reaching depth of more than 100 m (Figs.9 and 12B)

The control promoted by the metachert ridges is more evident at ST than at VDS. Because the ultramafic rock in the ST deposit is totally enclosed by the metachert ridge, the meteoric water flow to lower topographic levels is largely reduced. Besides facilitating the development of deep weathering profiles, this aspect standardizes the geomorphologic characteristic of the ST (irregular terrain).

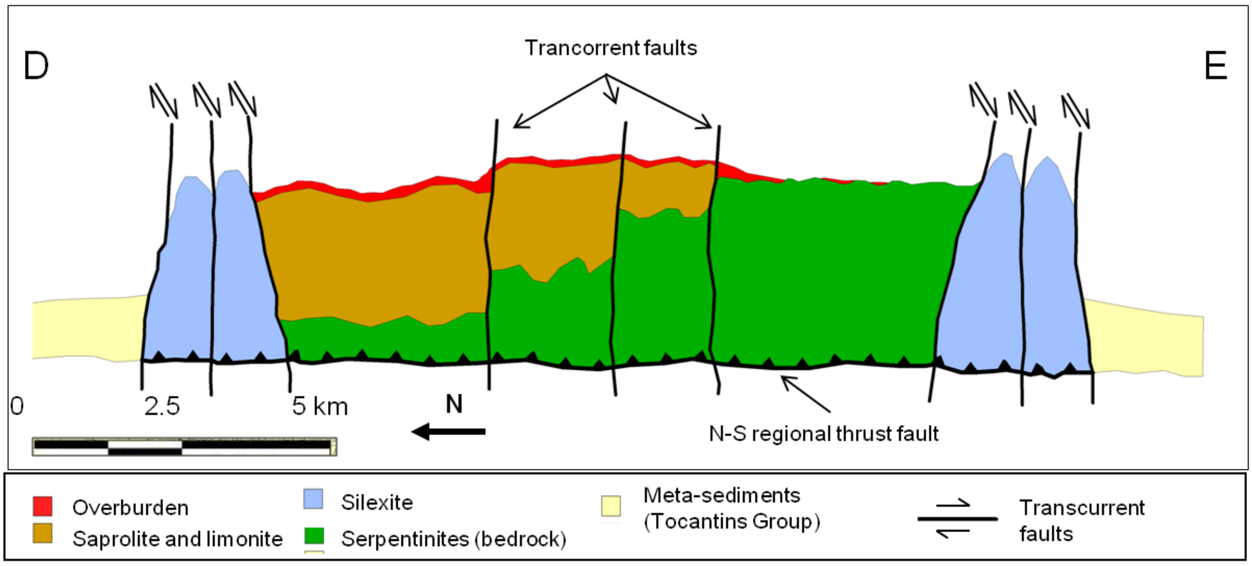

Figure 8 – Geological section (D-E in figure 6) at the ST deposit showing block compartments due to normal faults.

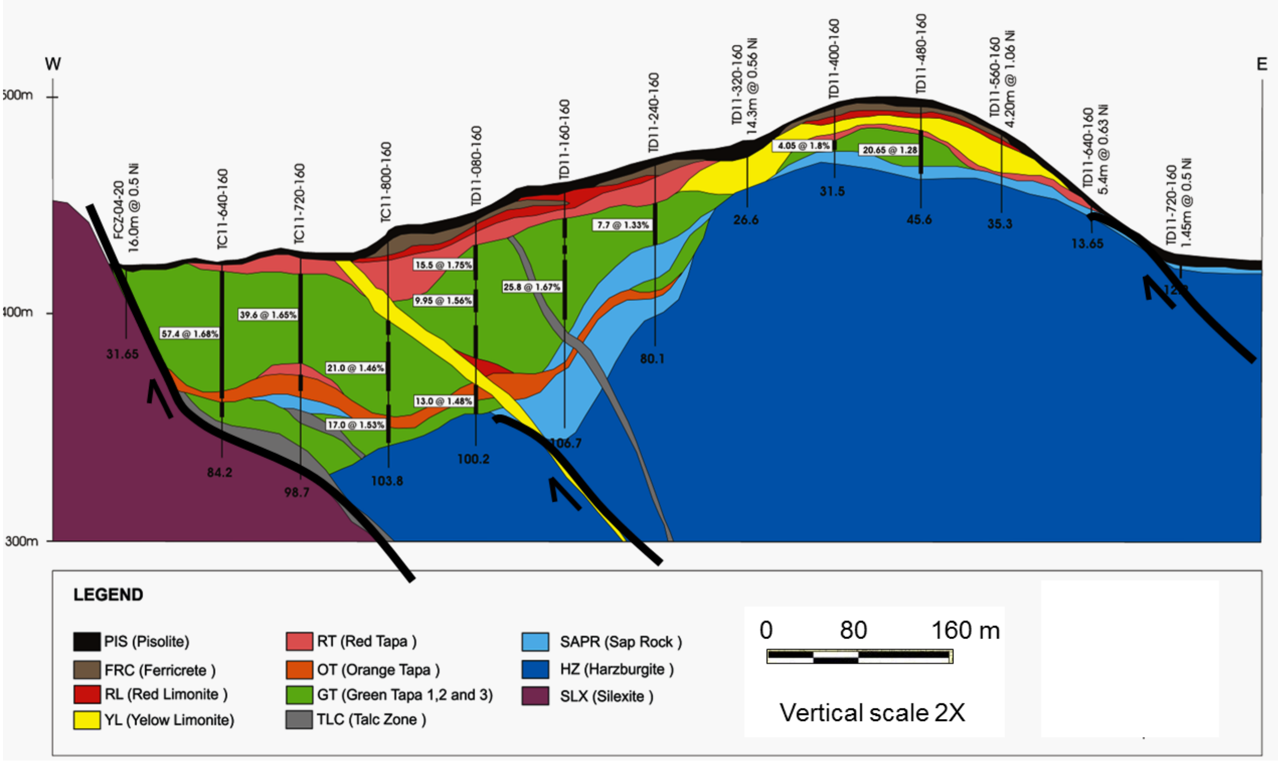

Figure 9 – Geological section (A-B1 in figure 6) at the Serra do Tapa. In this section the weathering profile reaches almost 100 meters (Xstrata, 2009).

<u>Vale dos Sonhos</u>

At VDS the NE-SW oriented lineaments display a smaller control over the mineralization. The area with developed profile is located between two of these faults, permitting the formation of a weathering profile with lateral continuity and consistent average depth. Pinacles of weathered meta harzburgite (WHZ facies) is common.

In addition, the terrain is flat at VDS. The presence of metachert at the east contact of the VDS is restricted and physical weathering was more efficient promoting a plateau characteristic (Fig.10).

The mineralization is outlined by a pisolitic laterite crust on surface that extends nearly 4,000 in NNW-SSE direction, with 800 m average width.

At the east contact with the metasedimentary rocks, a false laterite plateau is present due to the transportation of limonitic material by erosion process The deposits that host transported mineralized material are rare. The material usually displays uneconomic nickel content and the profile is shallow.

The contact with meta-sedimentary rocks is abrupt. Metabasalts show best exposures to the east of VDS.

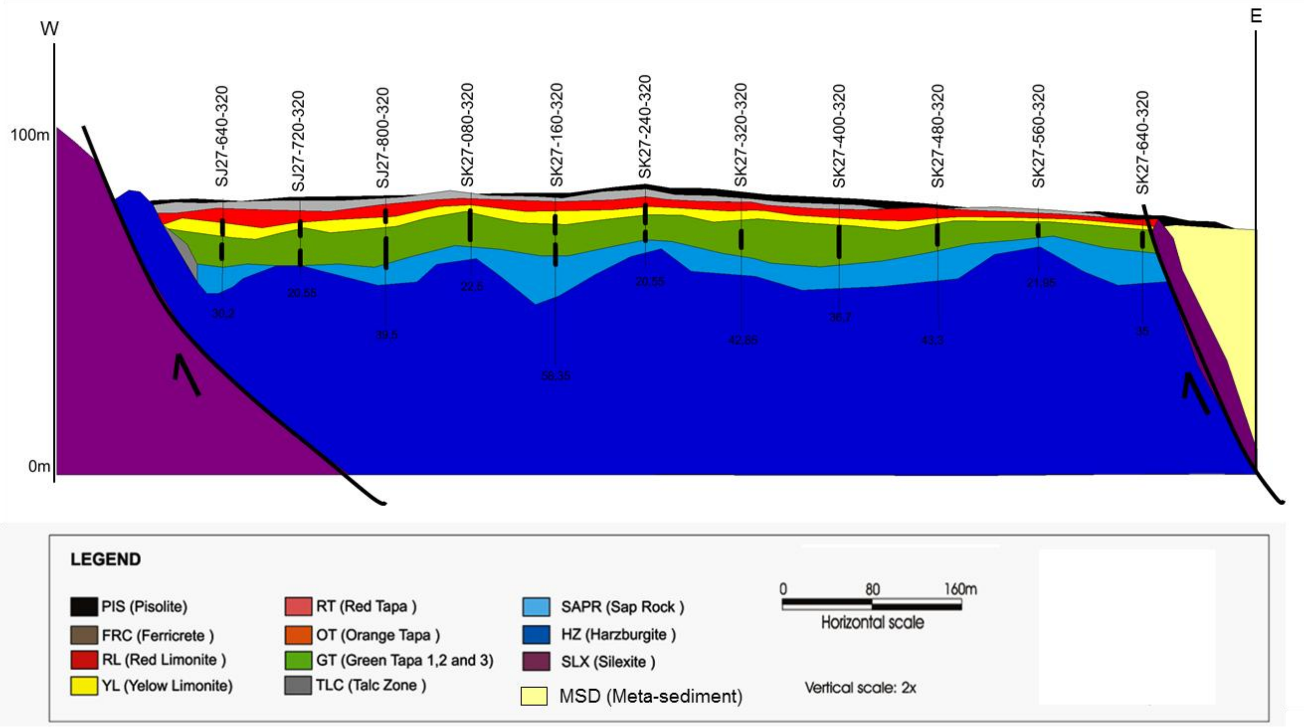

Figure 10 – Geological section (B2-C in figure 6) at the Vale dos Sonhos (Xstrata, 2009).

<u>Other deposits</u>

Besides the ST and VDS, other three areas show significant mineralized profiles: Pau Preto, Escalada and Tapa West. All of them are within an area of 25 by 15 km.

The Pau Preto deposit is an ultramafic body of 4km long in an N-S direction with approximately 2 km width. The ultramafic body is cut by a main WSW-ENE transcurrent fault in two lateritic plateaus. Elevations at Pau Preto range from 160 m to 320 m.

The Escalada deposit is represented by an ultramafic body elongated in the N45ºW direction dipping between 35º and 40º to NE. Transcurrent faults have general direction NE fragmenting the ultramafic body into separated blocks. Deeper profiles are located near the contact with the metachert ridge in central portion of ultramafic body. Escalada has a complex topography with elevation ranging between 170-520 m.

The Tapa West is a minor deposit, as far nickel resources are considered, characterized by a mineralized weathered profile up to 5 m. It is the highest topographic elevation at the west of ST and also confirms the duplex faulting system.

At Indiaporã the weathering profile is shallow (1-2 meters) and great part of the lateritic plateau consists of transported limonitic material over a metasedimentary bedrock. This body doesn´t host significant resources concerning volume and nickel and cobalt content.

4.3 Weathering profile

The weathering profiles of ST and VDS present typical characteristics of supergene enrichment mineralization derived from the residual concentration by laterization process. This topic presents broad features of the weathering profile for ST and VDS deposits. A complete description of the weathering profile, including physical and chemical characteristics, is provided in the following section.

The main field indicators of mineralization are the dark red to purple laterites and the dark red pisolitic soil coverage. Both exhibit strong magnetism. The laterites and pisolitic soil coverage is developed on top of approximately 50% of the area where the bedrock is ultramafic.

The weathering profile is formed from the top to bottom by an overburden horizon, limonitic horizon, saprolitic horizon (upper and lower) and finally by a bedrock. These horizons are formed by a specific group of facies that share similar geochemical signature, although different physical properties may occur.

There are twenty two (22) facies that compose the weathering profile, in which fourteen (14) facies have relevant importance considering the mineralization profile (Fig.11):

- Overburden Horizon: Soil, Pisolitic and Ferricrete facies (SOIL, PIS and FRC respectively);
- Limonitic Horizon: Yellow Limonite, Red Limonite, Red Tapa and Orange Tapa (YL, RL, RT and OT respectively);
- Upper and Lower Saprolitic Horizon: Green Tapa 1, Green Tapa 2, Green Tapa 3, Rocky Saprolite, Transitional 1, Transitional 2 (GT-1, GT-2, GT-3, SAPR, TZ-1 and TZ-2 respectively);
- Bedrock Horizon: Metaharzburgite and weathered metaharzburgite (HZ and WHZ respectively).

In general the mineralization is approximately tabular and the contacts mimic surface topography.

The contact between the overburden horizon and the limonitic is usually abrupt, although the red limonite can have pisolites displaying a transitional characteristic.

The contact of the limonitic and saprolitic horizons is generally abrupt and marked by presence of green clay. The Orange Tapa facies may show considerable amount of green clay and can behave chemically as a saprolite.

The saprolitic horizon is divided chemically in upper and lower saprolite. The contact is usually gradational. The saprolitic horizon is formed by six facies and represents the majority of the mineralized material.

Within the horizons it is common to have gradational contacts among facies (mixed facies). For example, the main difference between the Green Tapa facies (GT-1, 2 and 3) is the amount of green clay. The color is also decisive to differentiate red and yellow limonite facies.

The average thickness of mineralized intervals at the ST is 17.8 meters, reaching more than 100 m at the northern portion of the deposit (Fig.13A). This variation is due to the NE-SW faults that cut the deposit. At VDS the mineralized intervals have average thickness of 10 m.

An uncommon characteristic is the restricted presence of boulders in the weathered profile (Fig.12B), which is a remarkable aspect considering that in many deposits around the world the boulders are abundant and host high nickel grades.

Figure 11 - Visual aspect of the 14 significant facies in the mineralized profile (drill core with HQ diameter).

Figure 12 – (A) Photo of hole TC09-640-080 showing the thickest mineralized interval at Serra do Tapa (83.4m @ 2.06% Ni). The GT-1 facies is dominant on high grade ore. (B) Photo showing one of the rare boulders.

5. Characterization of the mineralized profile of ST and VDS

Twenty two (22) facies compose the weathering profile and are distinguished by mineralogy, texture and physical properties, such as hardness, color, plasticity, malleability and granulation.

Fourteen (14) facies have relevant importance in the mineralized profile. They will be presented in groups according to its geochemical signature (Overburden, Limonitic, Upper and Lower Saprolitic and Bedrock horizons).

The geochemical characterization used a total of 1400 samples, being 700 for ST and 700 for VDS. There are 100 samples for each of the 14 facies relevant to the characterization of the profile. The selection of samples used for geochemical characterization obeyed the following criteria:

(v) Rejection of samples with anomalous Fe and Mg analysis. This criterion eliminates anomalous trends and samples that are a mixture of facies;

(vi) Geographic distribution within the deposits. This criterion minimizes the chances of geochemical anomalies;

(vii) Drilling recovery. Samples with less than 50% of recovery were excluded.

(viii) Number of remaining samples;

5.1 Facies description

The facies is the most basic unit division of the deposit geology at meter-scale. Facies are defined by textural, mineralogical, color and mechanical characteristics. The rigorous definition and understanding of the facies and their composition is important for the location of mineralized and non-mineralized (ore-waste) contacts. It also allows visual selection and separation in the field and during mining of material that may have compositions deleterious to processing (Wright, 2007a).

Overburden Horizon Facies

Ferricrete (FRC), pisolite (PIS) and soil (SOIL) typically overlie the limonitic and saprolitic facies. These facies are normally composed of the end-products of the laterite weathering process and can be mixed with varying amounts of transported material. Magnetism is strong.

Soil (SOIL) is characterized by a mixture of *in situ* and transported material with partially decomposed loam and roots. The presence of angular rock fragments and organic matter is diagnostic of the facies.

Pisolite (PIS) is comprised of >70% disaggregated pisolites (rounded nodules of Fe-oxides and oxyhydroxides) forming a horizon with no cohesion. Limonitic material can be present. The composition of PIS is similar to that of FRC.

Ferricrete (FRC) is a red to wine-red to chocolate-brown solid mass rich in hematite/goethite and comprised of aggregated pisolites. The facies is very hard, magnetic, and commonly porous. At Vale dos Sonhos this facies forms a continuous layer.

Limonitic Horizon Facies

The limonite facies are characterized by the near-total conversion of olivine and serpentine to yellow, brown and red clays and oxides, and the complete destruction of primary harzburgite texture. Magnetism is moderate.

The Red Limonite (RL) is usually dark-brown to reddish brown (indicates presence of hematite/goethite) showing no visible structure or banding (texturally amorphous). The horizon can be loose or compact (cohesive) and may be plastic (malleable). Small proportion (10%) of pisolites and concentrations of orange-yellow material rich in goethite may occur. Black wisps and crusts of Mn-Co oxyhydroxides are common. No green clay or serpentine occurs in this facies.

The Yellow Limonite (YL) is usually yellow-orange, sometimes ochre and orange or spotted (dark-brown with ochre spots). The horizon can be loose or compact (cohesive) and usually plastic (malleable). Rare fragments with relict granular texture may occur. Mn-oxyhydroxides may be disseminated, forming irregular particles up to 0.5 mm in size. It is commonly laminated and without green clay or serpentine. The yellow limonite is rich in goethite and displays lesser amounts of hematite.

The Orange Tapa (OT) is an orange-brown colored material with dominance of goethite over hematite in the oxide phases. It is characterized by nucleus of green serpentine (10-30% of the material) in an orange matrix. The material is generally soft and compact, but not very plastic (friable). It is frequently banded although original harzburgite texture has been obliterated. Free silica is common.

The Red Tapa (RT) is red-brown to reddish purple, usually soft to compact and plastic. The red-brown clay typically forms bands and laminations at centimeter scale but without original harzburgite texture. Green serpentine and serpentine can comprise < 30% and white clay is usually disseminated (5-20%). Black wisps and crusts of Mn-Co oxyhydroxides are common.

Upper Saprolite Horizon Facies

The Upper Saprolite consists of a pervasively altered rock composed of Fe-oxyhydroxides, serpentine and minor to trace of vermiculite, chlorite. Primary rock textures have been obliterated, with only trace amounts of chlorite/vermiculite/serpentine/talc pseudomorphs after primary olivine. The sub-facies are determined by the amount of serpentine (green clay garnierite like), percentage of brown clay layers, hematite/goethite, Mn-oxide and talc. The TZ facies is best developed at Vale dos Sonhos.

The Transitional 1 facies (TZ-1) is orange to brownish orange to yellow-orange colored and has granular rock texture preserved. Granular serpentine is predominant to clay laminations. Concentrations of hematite/goethite, Mn-oxide and talc are common. The material is soft and cohesive.

The Transitional 2 facies (TZ-2) is a light green to brownish green material with granular rock texture eventually preserved (pseudomorphs of Opx). The material may display brown clay layers (5-30%) and disseminations of Mn-oxides, hematite/goethite, talc and rarely chrysotile. The material is soft, cohesive but not very plastic. The TZ-2 facies is the most important mineralized facies at Vale dos Sonhos.

The Green Tapa 1 facies (GT-1) has >90% green to bright dark green clay (garnierite like), may be weakly laminated but has no original rock texture. The material is generally compact and not plastic (friable). Fine brown clay layer (5-10%) may occur. Minor goethite and Mn-oxide may be present.

The Green Tapa 2 facies (GT-2) is a green-brown-orange colored mass with brownish clay laminations (5-60%). The material is generally heterogeneous, soft to compact, quite plastic and shows no primary texture preserved. It is characterized by 30-60% of green clay, and is differentiated from TZ-2 by the near total conversion of serpentine granules to green clay. Goethite and Mn-oxide are usually present.

Lower Saprolite Horizon Facies

The Lower Saprolite facies are the Saprock (SAPR) and Green Tapa 3 (GT-3). These facies are characterized by moderate to complete serpentinization, but without the extensive development of clay or oxides.

The Saprock (SAPR) is light green, strongly fractured, hard but can still be broken by hand. Primary olivine has been completely altered to serpentine, saprolitic chlorite/vermiculite/ nontronite/amorphous silicates and Fe oxyhydroxides. Patches of fresh orthopyroxene and olivine can be present.

The Green Tapa 3 facies (GT-3) is characterized by a light green color and recognizable relic harzburgite texture. It may be compact to quite plastic and friable with >90% serpentine granules and green clay. The remainder of the GT-3 material consists of disseminated talc (5-20%). Trace amounts of chlorite/vermiculite/talc serpentine pseudomorphs and Mn-oxide are also common. Laminations are common.

Bedrock Horizon Facies

The bedrock facies are Harzburgite (HZ) and weathered Harzburgite (WHZ). HZ is the starting point for weathering process and all mineralized saprolite and limonite is underlain by HZ and WHZ.

HZ is hard and competent, weakly fractured, dark green to greyish green and with moderate magnetism. The texture icharacterized by a fine-grained green massive aggregate of serpentine after olivine with coarse-grained prismatic pseudomorphs of orthopyroxene replaced by serpentine. It is poorly fractured and may display tectonic foliation

WHZ is characterized by variable amounts of weathered rock (friable) and blocks of unweathered and not fractured hard rock. Fractures are commonly filled with orange material (clay or Fe-hyroxides) and minor Mn-oxide. Initial enrichment of Ni occurs in WHZ, nickel values are in the range 0.3-0.5%. High weathering can be correlated with the saprolitic facies (SAPR).

Other relevant facies

The Metachert (MCH) is a hard and competent material with variable degree of shearing and breciation. It displays a purple to wine to brownish red color and weathering provides a friable material. Frequently occurs with dots of green magnetic material. White silica is commonly associated.

The Talc (TLC) facies is rich in white to purple talc and commonly displays foliation related to fault zones. Mn-oxides and layers of brownish clay may be present. Traces of serpentine and free silica may occur. The material is usually soft and compact, but not plastic.

5.2 Geochemistry of the weathering profile

Major elements used for chemical characterization of facies are MgO and Fe content (%). The variation diagram Fe (%) vs. MgO (%) shows a negative correlation between these elements (Fig.13). Fresh rock has low iron and high magnesium content leading progressively to a limonite with high iron and low magnesium.

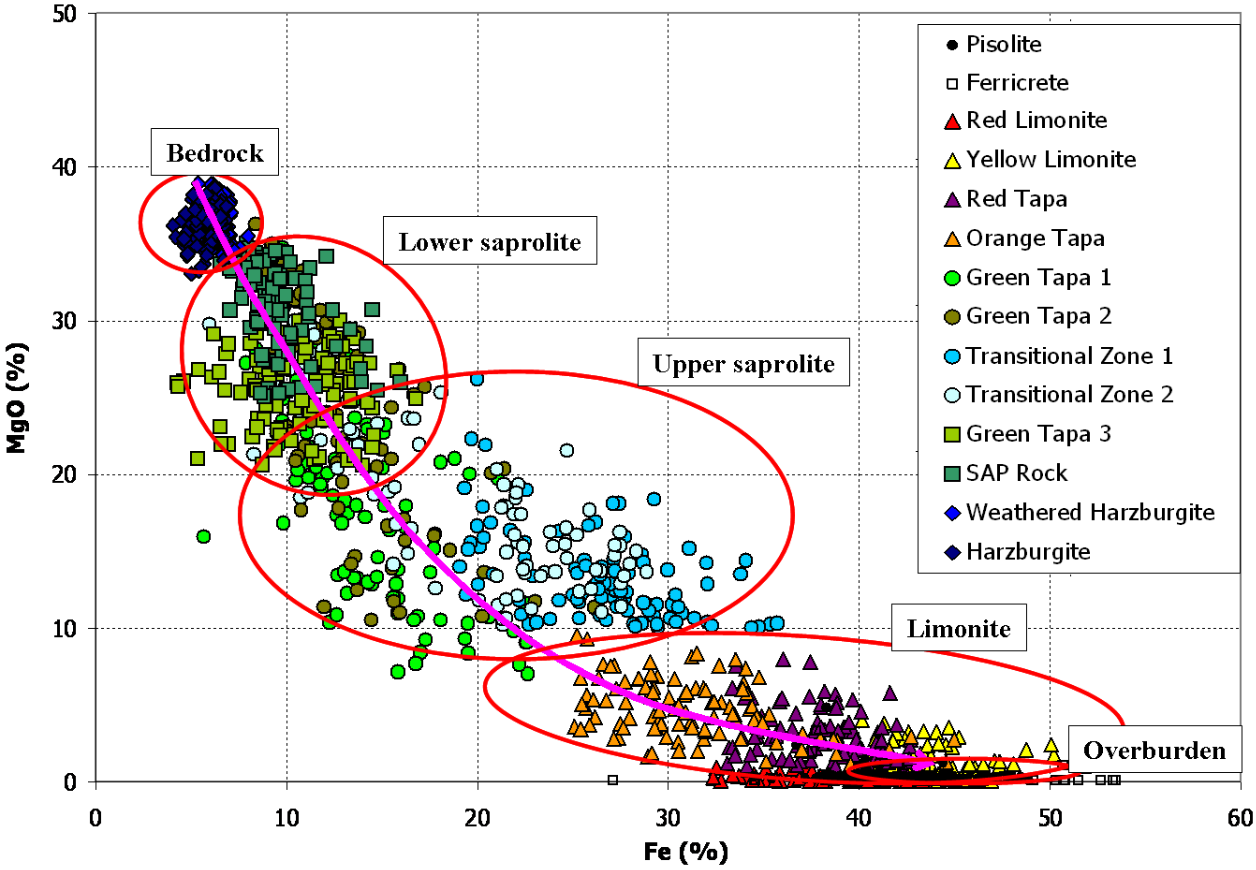

Figure 13 – Fe (%) vs MgO (%) variation diagram for different facies of the weathering profile of the ST and VDS. The diagram has a total of 1400 samples (100 from each facies) (adapted from Wright, 2007b).

The main geochemical characteristics of the horizons are:

- Overburden: 38-50% Fe and MgO<1%. Nickel grades are uneconomic and this horizon is normally used as a surface indicator of mineralization. The compositional variability of this facies is small and the horizon represents the ultimate stage of weathering;
- Limonite: 25-50% Fe and MgO<8%. The nickel mineralization has lower grade in this horizon, though Co is still relatively enriched (0.1%). Silica content is low compared to the horizons located below the limonite facies. The red limonite has the lowest MgO content of the limonitic facies. It usually occurs with some pisolitic material associated and therefore may have a geochemical signature similar to the overburden. The yellow limonite has the highest iron content. The Orange and Red Tapa have a wider composition range and may act as a transition facies to the saprolite horizon. The Orange Tapa may store significant amount of green clay and therefore can be interpreted as a transitional facies to the Upper Saprolite Horizon;
- Upper Saprolite: 10-35% Fe and 8-25% MgO. This horizon has the widest compositional Fe and MgO range among the horizons. It also presents the highest nickel grades within the mineralized facies, being the Green Tapa 1 the richest and ranging from 1-2%. The Transitional facies (TZ1 and TZ2) display a more restricted compositional variation compared to the Green Tapa (GT1 and GT2). This second can act as a Lower Saprolite. Transitional facies also have Fe content higher than the Green Tapa facies. The Green Tapa 2 is the most variable of the facies that compose the Upper Saprolite.
- Lower Saprolite: 8-15% Fe and 20-35% MgO. This horizon is characterized by moderate to complete serpentinization, but without the development extensive quantities of clay or oxides. It typically shows an upward in nickel grades, from waste to economically significant mineralization (1% Ni). Compositional ranges are smaller compared to the Upper Saprolite Horizon.

- Bedrock: 5-8% Fe and 33-39% MgO. The Bedrock Horizon is the starting point for weathering process and all mineralized saprolite and limonite. Nickel values are at background levels 0.22-0.3%. Initial enrichment of Ni occurs in WHZ, nickel values are in the range 0.3-0.5%. Occasional enrichment of nickel in fractures results in rare assays up to 1% Ni in WHZ.

The distribution of Ni, SiO_2, Fe and MgO (%) throughout the weathering profile of the ST and VDS is shown in figure 14. Average compositions are indicated in the diagram.

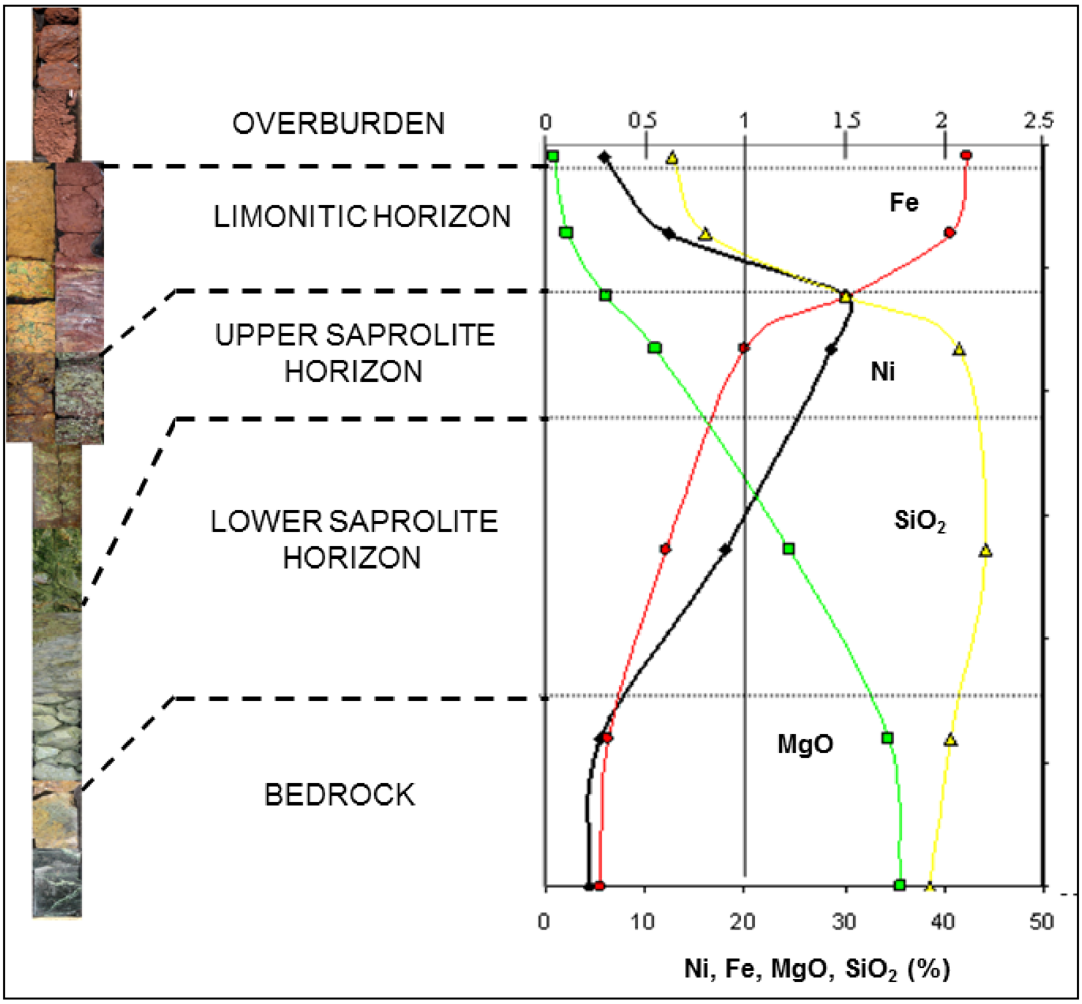

Figure 14 - Distribution of Ni, SiO2, Fe and MgO throughout the weathering profile of the ST and VDS (adapted from Wright, 2007b).

The chart on figure 15 shows the average composition (Ni, Co, Fe, MgO, SiO_2) and specific gravity (wet and dry) of each facies from different horizons of the weathering profile.

Because of the collapse of mineral structures in the saprolite zone the average density (specific gravity) is low compared to the bedrock. The increase of density (SG dry) observed in the limonitic and overburden horizons are related to the enrichment in Fe.

Horizon	Facies	Ni (%)	Co (%)	Fe (%)	MgO (%)	SiO2 (%)	SG Wet	SG Dry
Overburden	PIS	0,38	0,08	41,38	0,32	13,90	2,13	1,65
	FRC	0,43	0,08	42,61	0,26	12,33	2,33	1,98
	Average	**0,40**	**0,08**	**41,99**	**0,29**	**13,12**	**2,23**	**1,81**
Limonite	RL	0,43	0,09	39,62	0,34	16,66	2,06	1,51
	YL	1,07	0,17	44,55	1,13	10,80	1,88	1,26
	RT	1,14	0,14	37,87	3,03	20,99	1,79	1,17
	OT	1,54	0,09	31,27	4,71	29,25	1,94	1,34
	Average	**1,05**	**0,12**	**38,33**	**2,30**	**19,42**	**1,92**	**1,32**
Upper Saprolite	TZ1	1,38	0,08	26,56	13,32	28,52	1,62	1,01
	TZ2	1,29	0,06	18,68	19,05	36,75	1,65	1,04
	GT1	1,53	0,04	14,02	18,42	43,67	1,77	1,19
	GT2	1,25	0,04	12,75	24,60	40,93	1,72	1,16
	Average	**1,36**	**0,05**	**18,00**	**18,85**	**37,47**	**1,69**	**1,10**
Lower Saprolite	GT3	1,02	0,03	10,46	25,45	43,73	1,74	1,25
	SAPR	0,88	0,02	9,48	30,94	40,45	1,77	1,25
	Average	**0,95**	**0,02**	**9,97**	**28,19**	**42,09**	**1,76**	**1,25**
Bedrock	WHZ	0,36	0,01	6,42	36,50	40,32	2,02	1,71
	HZ	0,27	0,01	5,88	36,20	39,02	2,50	2,45
	Average	**0,31**	**0,01**	**6,15**	**36,35**	**39,67**	**2,26**	**2,08**

Figure 15 - Chart showing the average content of major elements of the facies and respective horizon (for ST and VDS); SG = Specific gravity.

The high-grade cobalt mineralization is associated with intervals rich in manganese oxide, which ~~is~~ are common in the Yellow Limonite, Red Limonite and Red Tapa facies. Results from metallurgical tests done by Xstrata are not available, but considering that the majority of the ore is saprolitic, the pyrometallurgical processing (partial reduction and smelting of dried ore) is likely to be the most appropriate method of beneficiation. Because the expected product of pyrometallurgical processing for these ore types is crude ferronickel, cobalt will not be concentrated as a by-product.

6. Discussion

6.1 ST and VDS deposits: An example of world-class Ni-laterite deposit associated with Precambrian Ophiolites

Comparative graph (Fig.16) between nickel laterite deposits and projects concerning nature and age of protholite show that the majority of them are related to Phanerozoic ophiolitic complexes. These deposits, such as Koniambo and Goro (in New Caledonia), host the highest resources and reserves worldwide. Deposits of Achaean and Proterozoic ages are associated to mafic-ultramafic intrusions or komatiites in greenstone belts. The age of 757± 49 Ma (Sm-Nd whole-rock isochron) for ophiolite remnants in the AFB indicates an evolution during the Neoproterozoic (Paixão et al., 2008), and therefore entitles the ST and VDS deposit as a rare example of Precambrian Ni-laterite world-class deposit.

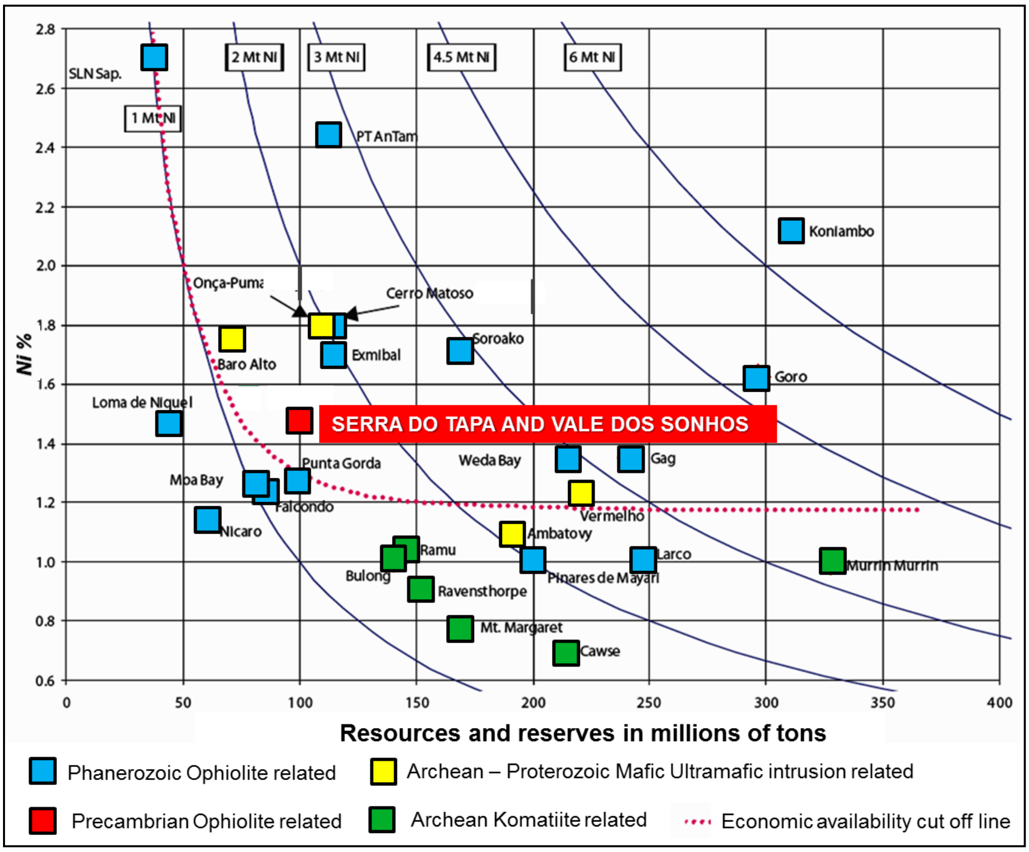

Figure 16 – Graph resources/reserves in millions of tons versus Ni% comparing protholith nature/age of nickel laterite deposits/projects (adapted from Castro et al., 2006).

But why large lateritic mineralization in Precambrian ophiolite complexes is uncommon?

The critical elements required for the development of a nickel laterite deposit include the ultramafic nature of the protholith, degree of serpentinization, climate, structure framework, topography, drainage conditions, erosion rate and geomorphological history.

The deposits associated to Phanerozoic ophiolites are located in regions of converging plates (Caribbean plate and Western Pacific plates) and within a band about 22 degrees of latitude on either side of the Equator. Deposits or occurrences outside this band are mostly fossil profiles and associated to mafic-ultramafc intrusions of komatiites (e.g. Larco, Greece; Kosovo region, former Yugoslavia and Albania; Ukraine; Urals; Riddle, USA; and deposits in the Yilgarn Craton, Australia) (Porto, 2006).

The laterization event of the deposits associated to Phanerozoic ophiolitic complexes occurred in Miocene to present time, which is frequently associated in time to their tectonic emplacement. In the Precambrian laterite deposits, the laterization and tectonic emplacement are not closely associated in time. At the ST and VDS, and other deposits in Brazil (Barro Alto, Onça-Puma, Vermelho etc.), the laterization event is associated to Cretaceous to Early-Mid Tertiary (Fig.17).

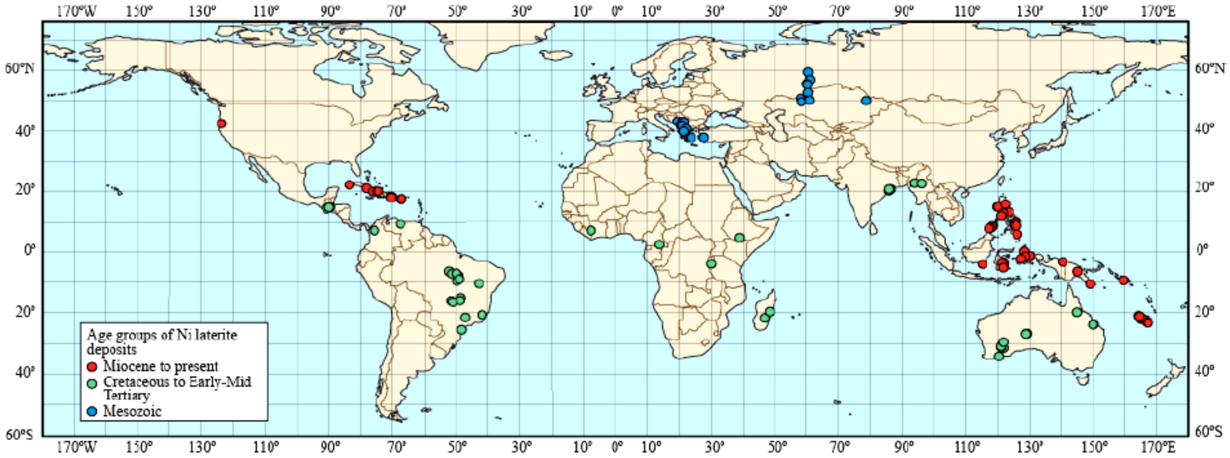

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Figure 17 – Distribution of nickel laterite deposits grouped by the age of the laterization event (USGS, 2011)

The mineralized profile is developed exclusively on top of the ultramafic sequence. The mineralogy of the parent rock type determines susceptibility of rocks to weathering and the elements available for recombination as new minerals (serpentinite). Regional metamorphism, intense deformation, changes in bedrock permeability and reworking of continental crust are common features in Precambrian orogenic belts, and therefore may be decisive to develop weathered profiles and Ni enrichment.

Typically a great landmass is required in order to produce significant nickel laterite resources. The obduction of small slices of Precambrian oceanic crust may restrict economic volumes. Because of dismemberment during obduction, some Precambrian ophiolites only display the volcanic and sedimentary sequences.

Climate is another important factor. Recent laterites are constrained to sub-tropical regions where the high average annual temperatures and rainfall provide the necessary conditions for the profile development. Rainfall determines the amount of water passing through the soil, which influences the intensity of leaching and removal of soluble components. In this sense, the geographic location of Precambrian ophiolites is a control factor since it conditions the climate and rainfall.

Climate together with topography are responsible for drainage conditions. Drainage affects the net water budget available for leaching from the whole landscape. Relief and slope geometry influence drainage, the extent to which water passes into the soil, and water table level.

Tectonic uplift increases erosion of the top of the profile, increases topographic relief and lowers the water table. The tectonic stability of Precambrian ophiolites allows planation of the landscape, slowing groundwater movement.

Clearly many of these climatic and geological factors are closely interrelated, and the characteristics of a profile at any one place can best be described as due to the combined effect of all the individual factors acting over time, rather than being dominated by any single factor.

The combination of the control factors are easily recognized in the Phanerozoic ophiolitic complexes. In this sense, the characterization of the control factors over Precambrian ophiolites is required to verify the potential to host mineralization.

6.2 Mineralized profile

The mineralized profile of ST and VDS is chemically similar to other known deposits. It displays the typical chemical zonation where the low iron and high magnesium content of the protholite leads progressively to a limonitic horizon with high iron and low magnesium.

An uncommon characteristic of the deposit is the great number of facies that compose the weathering profile. Within each chemical zone that composes the profile, the iron and magnesium content of the facies also appears to change progressively, determining the mineralogy and physical properties between them. This progression is well represented by mixed facies.

The degree of serpentinization and solubility of mineral phases seem to have been favorable for the development of the weathering profile at ST and VDS. At the Quatipuru complex, Gorayeb (1989) and Paixão (2009) observed an enrichment of nickel on serpentinites when comparing results obtained by Golightly (1981) for harzburgites with low degree of serpentinization.

Another singular feature is the development of mineralized intervals with more than 100m thickness. The metachert envelope is considered to be the critical as it promotes the combination of control factors (erosion rate, drainage conditions, topography, variation of groundwater level and structure).

The restricted presence of boulders and pinnacles with minor expression is also a particular characteristic. The occurrence of these features is usually associated to faults, shears, joints and cleavages. The serpentinite displays pervasive shearing which seems to be favorable for tabular weathering of the bedrock.

At the ST body the high topography is conditioned by the resistance of the metachert to weathering. The flat land area of VDS is associated to poorly developed metachert sheets at the east side of the body, to where the eroded limonitic material is carried to forming a false mineralized plateau (Fig.18).

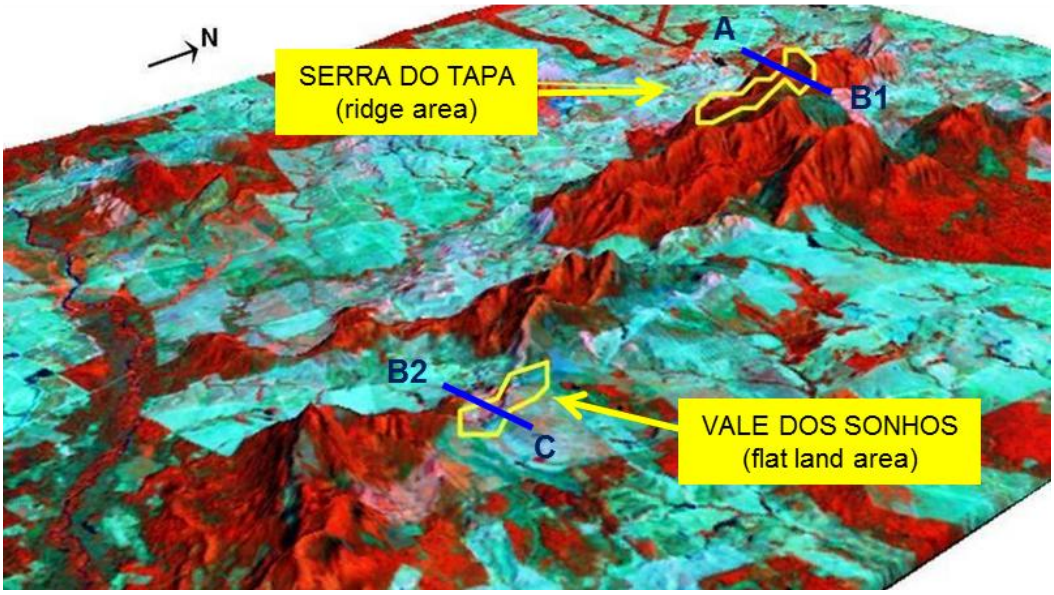


Figure 18 - Landsat image (453 RGB on 3D DEM) showing the different topographic signature of the ST and VDS (A-B1 and B2-C are geological sections in figures 9 and 10).

Twenty one samples were sent for mineralogical characterization at the SGS Lakefield Research Ltd. in Canada. The results obtained were not allowed to be fully presented. The information presented is based on alteration mineral assemblage and chemical analysis. The samples were subdivided in four main ore-types: saprolite ore, intermediate/smectite-clay ore, intermediate/limonite ore and limonite ore.

6.3 Genetic model for the ST and VDS deposit

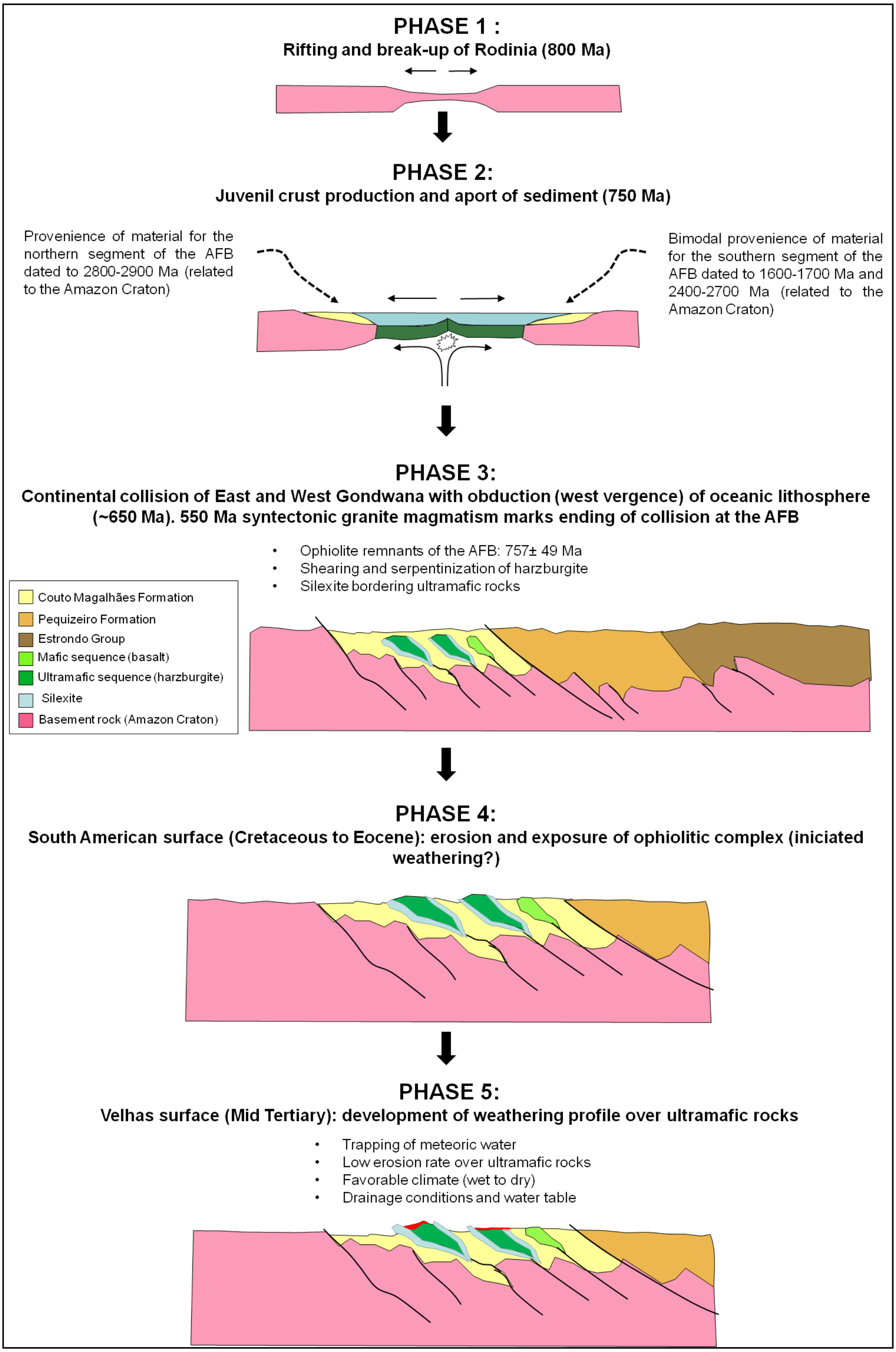
During obduction, the bases of the mafic-ultramafic thrust sheets developed a silica- and talc-rich zone that frequently exhibits a brecciated aspect. Secondary transcurrent faults interpreted as lateral ramps developed at the same time, with minor silicification and brecciation. Sin- to post- tectonic normal faults parallel to these lateral ramps had an important contribution to the formation of thick weathering profiles in the region. Both lateral ramps and sin- to post- tectonic faults define and mark compartments within the deposits, differentiated by thickness of the profile and facies dominance. The primary serpentinization is interpreted to be occurred during the westward thrusting, which took place during the Brazilian tectonic-thermal event, occurring near the Neo-Proterozoic/Lower Paleozoic boundary (AMEC, 2007).

After the obduction of the complex, a series of north-striking, sub-vertical diabase and gabbro dykes cuts the meta-sedimentary and ultramafic rocks. Although the dykes outcrop only locally, they are well marked by its magnetic characteristic on geophysical products.

Since Cretaceous times the ophiolite complex has undergone named South American surface weathering event. Subsequently, at Mid Tertiary, the Ciclo das Velhas surface initiated the development of the weathering profile at the Serra do Tapa and Vale dos Sonhos.

As a result, lateritic profiles with zonation from iron-rich limonitic material, to clay-rich saprolite, to poorly weathered serpentinites, and finally to relatively unweathered serpentinized harzburgite were developed. Moreover, topographic irregularities caused by the outstanding hardness of metachert sheets acted as borders of a basin, retaining meteoric water to make the weathering process more efficient.

A schematic cartoon in figure 19 shows the evolution of the ultramafic rocks and mineralization process.



PHASE 1 :
Rifting and break-up of Rodinia (800 Ma)

PHASE 2:
Juvenil crust production and aport of sediment (750 Ma)

Provenience of material for the northern segment of the AFB dated to 2800-2900 Ma (related to the Amazon Craton)

Bimodal provenience of material for the southern segment of the AFB dated to 1600-1700 Ma and 2400-2700 Ma (related to the Amazon Craton)

PHASE 3:
Continental collision of East and West Gondwana with obduction (west vergence) of oceanic lithosphere (~650 Ma). 550 Ma syntectonic granite magmatism marks ending of collision at the AFB

- Ophiolite remnants of the AFB: 757± 49 Ma
- Shearing and serpentinization of harzburgite
- Silexite bordering ultramafic rocks

PHASE 4:
South American surface (Cretaceous to Eocene): erosion and exposure of ophiolitic complex (iniciated weathering?)

PHASE 5:
Velhas surface (Mid Tertiary): development of weathering profile over ultramafic rocks

- Trapping of meteoric water
- Low erosion rate over ultramafic rocks
- Favorable climate (wet to dry)
- Drainage conditions and water table

Figure 19 – Genetic model for the area of the ST and VDS.

6.4 Implications for exploration of Precambrian Ni-laterite deposits

Exploration boomed until about 1980, with large programs leading to the discovery of most nickel laterites known today. A variety of methods successfully led to discoveries such as prospecting, mapping, gamaespectrometric and magnetometric surveying and stream-sediment geochemical surveys. Air photo interpretation was used to select targets on the basis of topographic signature in large areas of the virgin Amazon rain forest in the early 1970s, leading to the discovery, in quick succession, of the Onça, Puma, Jacare, and the Vermelho laterite deposits.

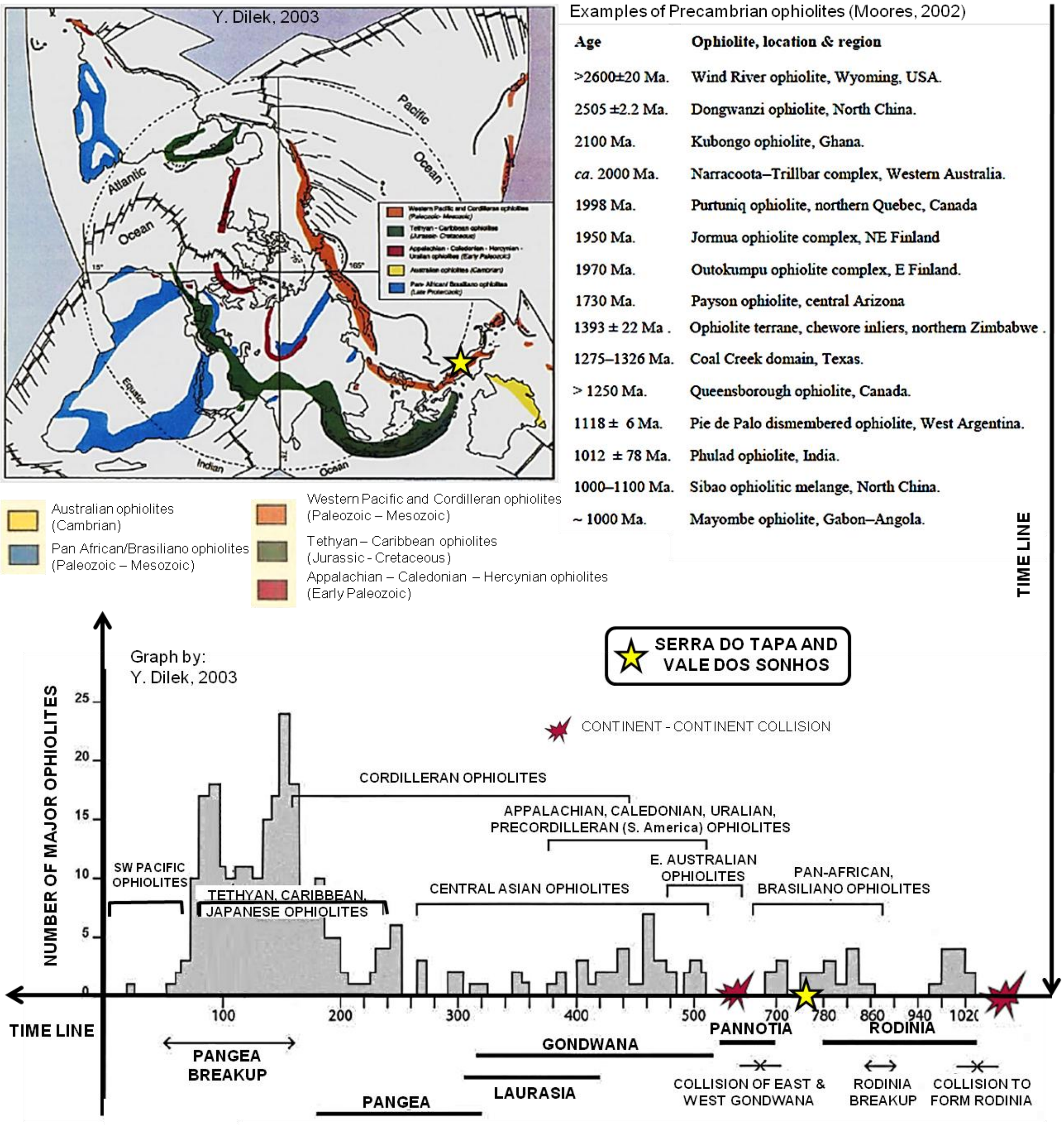
After low levels of activity through the 1980s, much new exploration was carried out in areas of Ni-rich laterites that were identified earlier and at projects that had been suspended during economic crisis in the mineral industry. Most exploration programs concentrated on the major ophiolite complexes where laterite potential had been identified in the previous decades. In many cases, exploration has consisted of raising inferred resources to indicated or measured status.

In the AFB, the renewed activity led to the grassroots discovery of the Serra do Tapa and Vale dos Sonhos deposits. Other grassroots discoveries, such as the Lontra and Vila Oito are still being evaluated and the combined resources added 60Mt @1.22% nickel and 0.55% cobalt (Horizonte Minerals, 2012).

The exploration methods used to identify potential nickel laterite deposits developed over ophiolites, mafic-ultramafic intrusions or komatiites don´t vary significantly. The selection of belts with mantle fragments followed by airborne geophysical surveys and air photo interpretation is usually used in initial phase of regional exploration. In plateau areas, stream sediment survey can also trace mafic-ultramafic rocks by Ni, Cu, Co, Cr anomalies. Presence of dark red magnetic soil, silica cap, pisolite and laterite are strong field evidences of weathering profiles developed over mafic-ultramafic rocks.

Figure 20 shows a time line indicating the occurrence of ophiolitic complexes from Neoarchean to present time. It also shows the tectonic setting of the Neoproterozoic and Phanerozoic ophiolites and their present location in a polar projection view. The ST and VDS deposit provide a new tectonic setting for world-class Ni-laterite deposits, indicating that ophiolite complexes in Precambrian mobile belts are prospective areas for Ni-laterite deposits.

Nickel laterites are an important resource of Ni and should account for more than 50% of the world production in the near future. In this way the characterization and understanding of deposits from Precambrian ophiolitic complexes are important to the academic and industrial sectors.



Examples of Precambrian ophiolites (Moores, 2002)

Age	Ophiolite, location & region
>2600±20 Ma.	Wind River ophiolite, Wyoming, USA.
2505 ±2.2 Ma.	Dongwanzi ophiolite, North China.
2100 Ma.	Kubongo ophiolite, Ghana.
ca. 2000 Ma.	Narracoota–Trillbar complex, Western Australia.
1998 Ma.	Purtuniq ophiolite, northern Quebec, Canada
1950 Ma.	Jormua ophiolite complex, NE Finland
1970 Ma.	Outokumpu ophiolite complex, E Finland.
1730 Ma.	Payson ophiolite, central Arizona
1393 ± 22 Ma .	Ophiolite terrane, chewore inliers, northern Zimbabwe .
1275–1326 Ma.	Coal Creek domain, Texas.
> 1250 Ma.	Queensborough ophiolite, Canada.
1118 ± 6 Ma.	Pie de Palo dismembered ophiolite, West Argentina.
1012 ± 78 Ma.	Phulad ophiolite, India.
1000–1100 Ma.	Sibao ophiolitic melange, North China.
~ 1000 Ma.	Mayombe ophiolite, Gabon–Angola.

Figure 20- Time line showing age, tectonic setting and present location of Precambrian and Phanerozoic ophiolitic complexes around the world.

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