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GEOLOGY AND GEOCHEMISTRY OF THE BOA VISTA NICKEL SULFIDE DEPOSIT, CRIXÁS GREENSTONE BELT, CENTRAL BRAZIL.

CARLOS N. COSTA JR. , CESAR F. FERREIRA FILHO , GRANT A. OSBORNE SYLVIA M. ARAUJO* & RENAN O. LOPES*

RESUMO *GEOLOGIA E GEOQUIMICA DO DEPOSITO DE NIQUEL SULFETADO DE BOA VISTA, GREENSTONE BELT DE CRIXÁS, GOIÁS* O deposito de sulfeto de níquel de Boa Vista está localizado na extremidade noroeste do *greenstone belt* de Crixás. O depósito está associado a uma estreita sequência de rochas metavulcânicas máficas e ultramáficas com 7 km de extensão e direção geral E-W. Embora essa sequência de rochas vulcânicas tenha sido submetida à deformação e metamorfismo regional, feições primárias estão ainda preservadas em *low-strain zones.* Dois tipos de derrames ultramáficos são reconhecidos (derrames com textura *spinifex* e derrames não diferenciados). As rochas ultramáficas apresentam feições texturais e geoquímicas diagnósticas de derrames komatiíticos. O teor de MgO (22,1 a 28,7 % peso) em derrames com textura spinifex e derrames não diferenciados é característico de komatiitos peridotíticos. Variações geoquímicas entre os elementos maiores indicam a importância da cristalização fracionada de olivina. A dispersão dos dados geoquímicos sugere alterações na composição química primária durante o metamorfismo regional.
A mineralização sulfetada está restrita a base de uma sequência metavulcânica ultramáfica sobreposta à uma sequência metavulcânica máfica. A espessura do horizonte mineralizado é variável mas geralmente nao ultrapassa alguns metros. Quatro tipos de minério são reconhecidos no depósito de Boa Vista. Esses tipos compreendem, em ordem decrescente de abundância, minério venulado, minério disseminado, minério maciço e minério silicate ocluso. A mineralogia do minério sulfetado e característica de sulfetos magmáticos associados à komatiitos. O minério consiste essencialmente de pirrotita (70 % do volume) associada a pentlandita e calcopirita e com magnetita e esfalerita como acessórios. O minério sulfetado de Boa Vista tem teores de Fe-Ni-S compatível com uma origem magmática. Análises geoquímicas do minério sulfetado recalculadas para 100% de sulfeto têm composição no campo da *monosulfide solid solution à* elevadas temperaturas. A razão Ni/Cu do minério sulfetado e elevada (± 10) e comparável com a maioria dos depósitos de sulfeto associados a komatiitos do arqueano.
O depósito de Boa Vista representa a primeira oportunidade de estudo do ambiente formador de depósitos de níquel sulfetado no greenstone belt de Crixás. Depósitos de sulfeto de níquel associados a komatiitos estão geralmente confinados a unidades ultramáficas específicas nas sequências do tipo *greenstone belt* mineralizadas. Desta forma, estudos geológicos e petrológicos no depósito de Boa Vista podem subsidiar a prospecção mineral nos extensos terrenes do tipo *greenstone belt* do Brasil central.

Palavras-chave: komatiito, níquel, sulfeto, *greenstone belt,* Crixás.

ABSTRACT The Boa Vista nickel-sulfide deposit is located at the NW edge of the late Archean Crixás greenstone belt. The nickel-sulfide deposit is associated with a narrow 7 km-long EW-trending sequence of meta-ultramafic and metabasic rocks. The volcanic sequence was overprinted by regional ductile deformation and associated metamorphism but primary volcanic structures and textures are preserved within low-strain zones. Two types of ultramafic flows are recognized in these zones (spinifex-textured flows and unsettled flows). The ultramafic rocks exhibit some of the classical geochemical and textural features that become the main criterion for the recognition of komatiitic lavas. The MgO content (from 22.1 to 28.7 wt. %) on spinifex-textured and unsettled flows is typical for peridotitic komatiites. Geochemical variations of major elements indicate the importance of olivine fractional crystallization. Scattering of the data suggests that regional metamorphism has chemically modified the ultramafic rocks.
The sulfide mineralization is always present at the lowest part of an ultramafic sequence overlying a mafic sequence. The thickness of the mineralized horizon is variable but it is usually less than few-meters thick. Four types of ore are recognized in the Boa Vista deposit. In order of decreasing abundance they are: stringer ore, disseminated ore, massive ore and matrix ore. The sulfide ore mineralogy is typical of magmatic sulfides associated with ultramafic komatiites. It consists mainly of pyrrhotite (70 vol. %) associated with pentlandite and chalcopyrite and minor magnetite and sphalerite. The Fe-Ni-S variation of the ore is consistent with a primary magmatic origin for the nickel mineralization. Analyses of sulfide ore recalculated to 100 % sulfides plot within the field of the monosulfide solid solution at high temperature. The Ni/Cu ratio of the ore is high (± 10) and comparable to most Archean KHNS deposits. The Boa Vista deposit provided the first opportunity to study nickel-sulfide mineralization processes in the Crixás greenstone belt. Considering that KHNS deposits occuring in greenstone belts worldwide tend to be restricted to specific ultramafic units, geological and petrological studies of the Boa Vista deposit provide important clues for future nickel-sulfide exploration work in the extensive greenstone belt terranes of central Brazil.

Keywords: komatiite, nickel, sulfide, greenstone belt, Crixás.

INTRODUCTION Since the discovery of the Kambalda nickel deposit in 1966, komatiite hosted nickel sulfide (KHNS) deposits have received recognition as a distinct class of deposit. This type of nickel-sulfide mineralization has been discovered in greenstone belt terranes worldwide and is now recognized as a major source of nickel (Naldrett 1989; Duke 1990).

The Boa Vista KHNS deposit (Osborne & Costa Jr. 1996), located 13 km NW of Crixás (Goias State), was discovery in 1994 by Australian-based Western Mining Corporation Limited (WMC) during a multi-disciplinary exploration program. The Boa Vista deposit is the first KHNS deposit discovered in the Goias-Tocantins greenstone belts. Extensive drilling at the deposit area permitted access to the mineralized volcanic succession, leading to ongoing detailed studies by the authors. Several greenstone belt terranes of central Brazil are characterized by extensive ultramafic units (Jost & Oliveira 1991). The Boa Vista deposit thus represents the first opportunity to

Institute de Geociências, Universidade de Brasília, CEP 70.910-900, Brasília-DF
WMC Mineração LTDA., Estrada da Barra da Tijuca, 1636, Bl. B, Loja A, CEP 22.641-001, Rio de Janeiro-RJ
The deposit is being studied as part of the "Projeto Caracterização de Minérios e Rejeitos de Depósitos Minerais Brasileiros" - Con vênio PADCT/FINEP/DNPM n° 65.94.0158.

study the nickel-sulfide metallogenetic environment of a large region with favourable geological potential for KHNS deposits.

The main objective of this paper is to describe the geology, mineralogy and geochemistry of the sulfide ore and host rocks of the Boa Vista deposit. This study suggests a magmatic model for the primary mineralization and discusses its relevance to exploration for KHNS deposits in the region.

The Boa Vista deposit -discovery history The Boa Vista deposit area was previously explored by Billiton Metais Ltda. (SHELL group, 1979-1983) and Mineragao Anaconda Brasil Ltda. (1984-1986) prior to being claimed by Mineração Wesminas Ltda. (WMC group) in 1993.

Exploration by Billiton Ltda. used ground geophysics (magnetics, IP and EM) allied to soil geochemistry, pitting and diamond drilling (5 holes) to partially test the western end of the Boa Vista segment, but failed to locate base metal mineralization. Exploration by Anaconda, using dominantly geological mapping and soil geochemistry, reworked the area covered by Billiton and extended it further east, and whilst noting the potential for nickel sulfides the company was specifically interested in gold.

Mineração Wesminas Ltda. developed a staged exploration campaign beginning with stream sediment sampling, gossan search, and soil sampling. Once the grid was established, ground magnetics and SIROTEM provided targeting criteria. Combined geophysical and geochemical anomalies (Ni and Cu in soil sampling) together with true Ni gossans enabled early drilling successes. Mineragao Wesminas Ltda. claim block includes a 7 km-long anomalous (geophysical and geochemical anomalies) ultramafic sequence with several gossans.

Tectonic Setting Figure 1 shows the main tectonic units of central Brazil. The granite-greenstone terranes are located within Proterozoic fold belts exposed between two major cratonic regions (Amazonian and São Francisco cratons). The area outlined in Figure IB was deformed during the Brasiliano erogenic Cycle (circa 650 Ma) and exhibits a tectonic and metamorphic vergence toward the São Francisco Craton (Marini *et al.* 1984). For an updated review of this area the reader is referred to Fuck *et al.* (1994). The main units present in the area are:

1) Archean granite-greenstone terranes: They consist of older basement rocks that are variably affected by the Brasiliano Cycle deformation and metamorphism. The geology and stratigraphy of the granite-greenstone terranes of central Brazil were revised by lost & Oliveira (1991).

2) Layered intrusions: The three major Proterozoic layered intrusions (Barro Alto, Niquelandia and Cana Brava) are deformed, high-grade metamorphic complexes (Danni *et al.* 1982, Ferreira Filho *et al.* 1992, 1997). U-Pb isotopic data for the Niquelândia Complex (Ferreira Filho *et al.* 1994) suggest a Mesoproterozoic age (1560-1600 Ma) for magmatic emplacement and set a Neoproterozoic age for the metamorphism (770-795 Ma). A major Mesoproterozoic continental rift is suggested for the 350 km-long belt of layered intrusions in the region, whereas the high-grade metamorphism and associated deformation are correlated with a Neoproterozoic continental collision (Ferreira Filho & Naldrett 1993). U-Pb isotopic dating of the Barro Alto Complex (Suita *et al.* 1994) indicates the regional extension of the 770-795 Ma metamorphic event. However, older primary magmatic ages (circa 2000 Ma) are suggested by Rb-Sr and Sm-Nd dating of the Cana Brava Complex (Correia 1994); as well as by U-Pb (SHRIMP) and Re-Os dating of the Niquelândia Complex (Correia *et al.* 1996).

3) Volcanic-sedimentary sequences: These sequences form an elongated northeast-trending volcano-sedimentary belt almost 300 km in length. It consists of three members (Palmeiropolis, Indaianopolis, and Juscelandia) that are located in the western border of the large mafic-ultramafic complexes (Cana Brava, Niquelândia, and Barro Alto, respectively) of central Brazil. Pb-Pb dating of galena from the Palmeiropolis Zn-Cu-Pb massive sulfide deposit suggests an age in the range 1170 to 1270 Ma (Araujo *et al.* 1996).

4) Brasilia Belt: The belt borders the western margin of the São Francisco craton. The Paranoá Group is part of the external zone of the Brasília Belt. It consists of continental margin shelf-like sediments submitted to low grade metamorphism (anquimetamorphism to greenschist facies). The Araxá Group represents the internal zone of the Brasília Belt. It consists of turbiditic sediments and minor volcanics and ophiolite fragments (mèlange) submitted to higher grades of metamorphism (greenschist to amphibolite facies).

5) Serra da Mesa and Araí Group: They are considered to be Paleoproterozoic folded cover terranes. The Arai Group is a continental sedimentary sequence with a thick rhyolitic unit at the base (Marini *et al.* 1984). U-Pb zircon ages of 1770 Ma are reported for both rhyolitic volcanism and associated tin-bearing granites (Pimentel *et al.* 1991), indicating a magmatic-sedimentary activity in an extensional intracratonic tectonic setting.

6) Goiás Magmatic Arc: The arc includes Neoproterozoic (900 to 600 Ma) volcano-sedimentary sequences and tonalite gneisses (Pimentel & Fuck 1992, Pimentel *et al.* 1996).

The Crixás greenstone belt The Crixás Greenstone Belt (Saboia 1979, lost & Oliveira 1991) is a 30 km-long and 2 to 6 km-wide supracrustal sequence. The greenstone belt forms a N-S synformal structure surrounded by granite-gneiss terranes (Fig. 2). To the north, the greenstone belt is covered by younger metasedimentary units (Mara Rosa Sequence). The Crixás greenstone belt shows a complex tectonic evolution including Archean structures overprinted by Neoproterozoic (Brasiliano Cycle) tectonism (Queiroz *et al.* 1995). Both supracrustal rocks and granite-gneiss terranes yield Archean ages close to 2700 Ma. (Montalvão 1986, Arndt *et al.* 1989). The belt is divided in three units (lost & Oliveira 1991):

a) The Lower Ultramafic Unit (Corrego Alagadinho Formation) consists of komatiitic flows with minor banded iron formation and metabasalt. Estimated thickness is 500 meters.

b) The Intermediate Mafic Unit (Rio Vermelho Formation) consists of metabasalt with minor banded iron formation. Estimated thickness is 350 meters.

c) The Upper Sedimentary Unit (Ribeirao das Antas Formation) consists of metapelite, metadolomite. Estimated thickness is 700 meters.

The ultramafic rocks in the northern part of the greenstone belt (Fig. 2) are considered to be part of a separate unit (Mina Inglesa Sequence) by Kuyumjian & Dardenne (1982). The Mina Inglesa Sequence consists of basal ultramafic metavolcanics (mostly serpentinite and talc-chlorite schist), followed mostly by metachert and banded iron formations, and felsic metavolcanics in the upper part of the sequence. Intrusive granitic and gabbroic rocks cross-cut the sequence.

Although igneous structures and textures are well preserved in many outcrops, thus permitting detailed study of their morphology, almost all igneous minerals have been replaced during metamorphism. Metamorphic mineral assemblages indicate mainly greenschist facies conditions for the supracrustal rocks. Amphibolite facies assemblages are locally described and no major progressive metamorphic trend is reported for the belt.

The field and the petrographic characteristics of the ultramafic and mafic komatiitic flows were described in detail

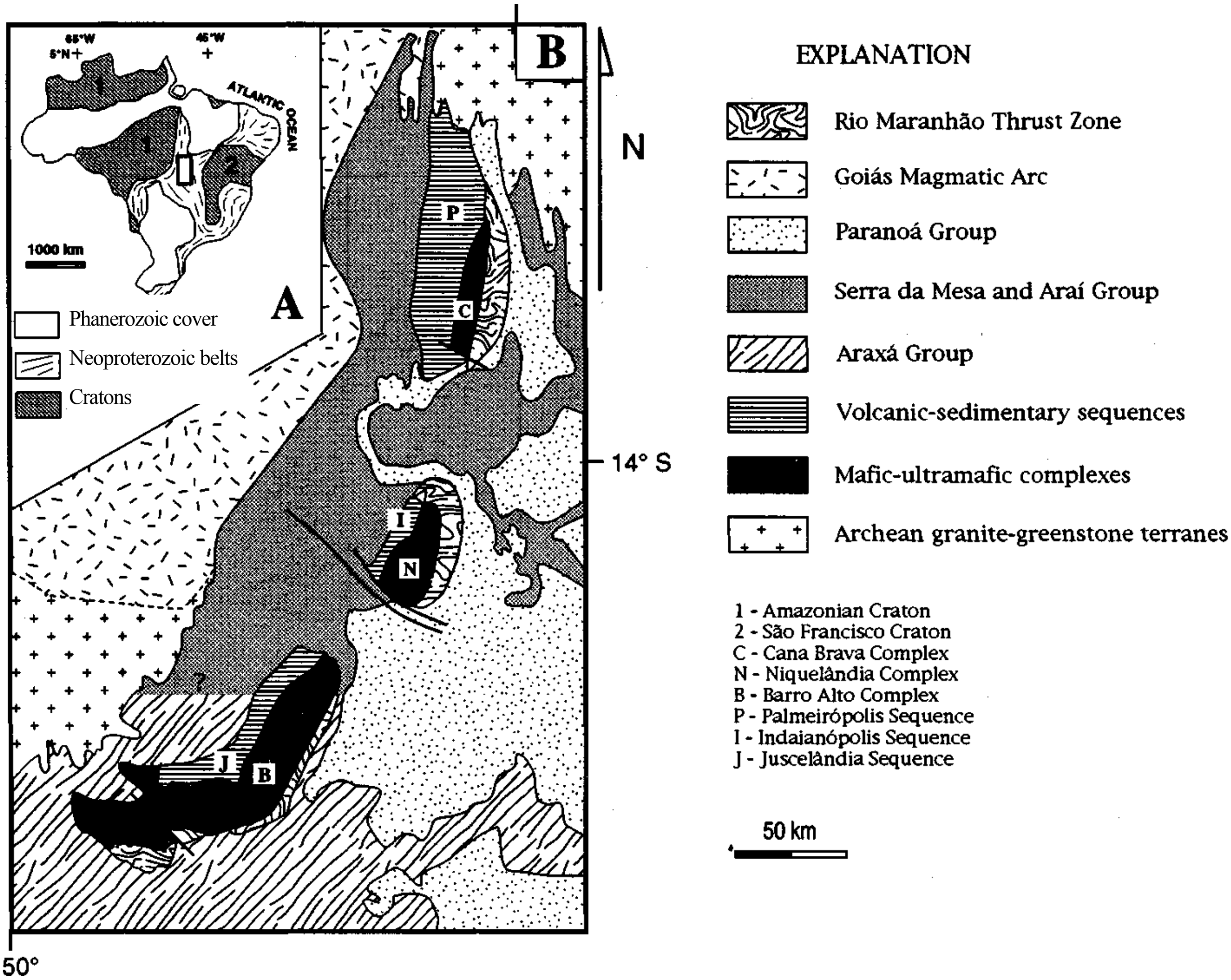

Figure 1 - A) Main geotectonic units in Brazil. The outlined area is detailed in B. B) Geological sketch map of central Brazil. Based on Danni et al. (1982), Marini et al (1984), and Fuck et al. (1994).
Figura 1 - A) Principais unidades geotectônicas do Brasil. A área delimitada está detalhada em B. B) Mapa geológico simplificado do Brasil central. Modificado de Danni *et al. (*1982), Marini *et al. (*1984) e Fuck *et al. (*1994).

by Saboia & Teixeira (1980) and Teixeira *et al.* (1981). The Crixás greenstone belt komatiites are similar to Archean mafic-ultramafic volcanic rocks described in other areas (like Munro Township in Canada). In general terms the ultramafic komatiites of Crixás are geochemically similar to typical Archean ultramafic volcanics (Saboia & Teixeira 1980, Kuyumjian & Dardenne 1982). They have high MgO contejit (20 wt. % on anhydrous basis), low TiO_2 content (0.9 wt. %), and average CaO/Al_2O_3 values close to 1. Arndt *et al.* (1989) point out the unusual geochemistry of komatiites from Crixás. The authors speculate that most elements (including REE) were mobile during hydrothermal alteration or metamorphism. Trace element data (including REE) of komatiitic metabasalts of the Intermediate Mafic Unit (Kuyumjian & Araujo Filho 1991) indicate lower REE abundances and lower Ti/Zr ratios relative to komatiitic basalts from Munro Township and Barberton. The authors suggest a less depleted mantle source for the komatiitic magmatism of Crixás.

THE BOA VISTA DEPOSIT Geology of the Boa Vista deposit The Boa Vista deposit is located at the NW edge of the Crixás greenstone belt (Fig. 2). The nickel-sulfide deposit is associated with a sequence of meta-ultramafic and metabasic rocks. Figure 3 shows the main geological features of the narrow E-W-trending supracrustal sequence that hosts the nickel-sulfide mineralization. The supracrustal rocks are surrounded by poorly exposed tonalitic gneiss. The ultramafic rocks are mainly talc-chlorite-serpentine schist (± serpentinite, ± talc schist, ± talc-serpentine schist, ± tremolite-chlorite schist) with tectonic fabric. Primary volcanic structures and textures, described in a following section, are restricted to low-strain zones intercepted during drilling. Interlayered metasediments (metamorphosed banded iron formation, metachert, sulfide-bearing graphite schist) consist of thin (less than one meter-thick) layers intercepted by few drill cores. The mafic rocks are greenschists consisting of actinolite + albite ± chlorite with accessory epidote, quartz, biotite, titanite, magnetite, and sulfides. Biotite- and quartz-rich actinolite-albite schists are associated with typical greenschists. The former is interpreted to be subaqueos mafic tuffs with a pelitic component. The later one has tourmaline as an ubiquitous accessory mineral (± chlorite, ± titanite, ± zircon, ± epidote, ± sulfides). Archean metasediments are restricted to the southern and eastern part of the mapped area (Fig. 3). They consist of quartz-sericite-chlorite schist and metachert. Small

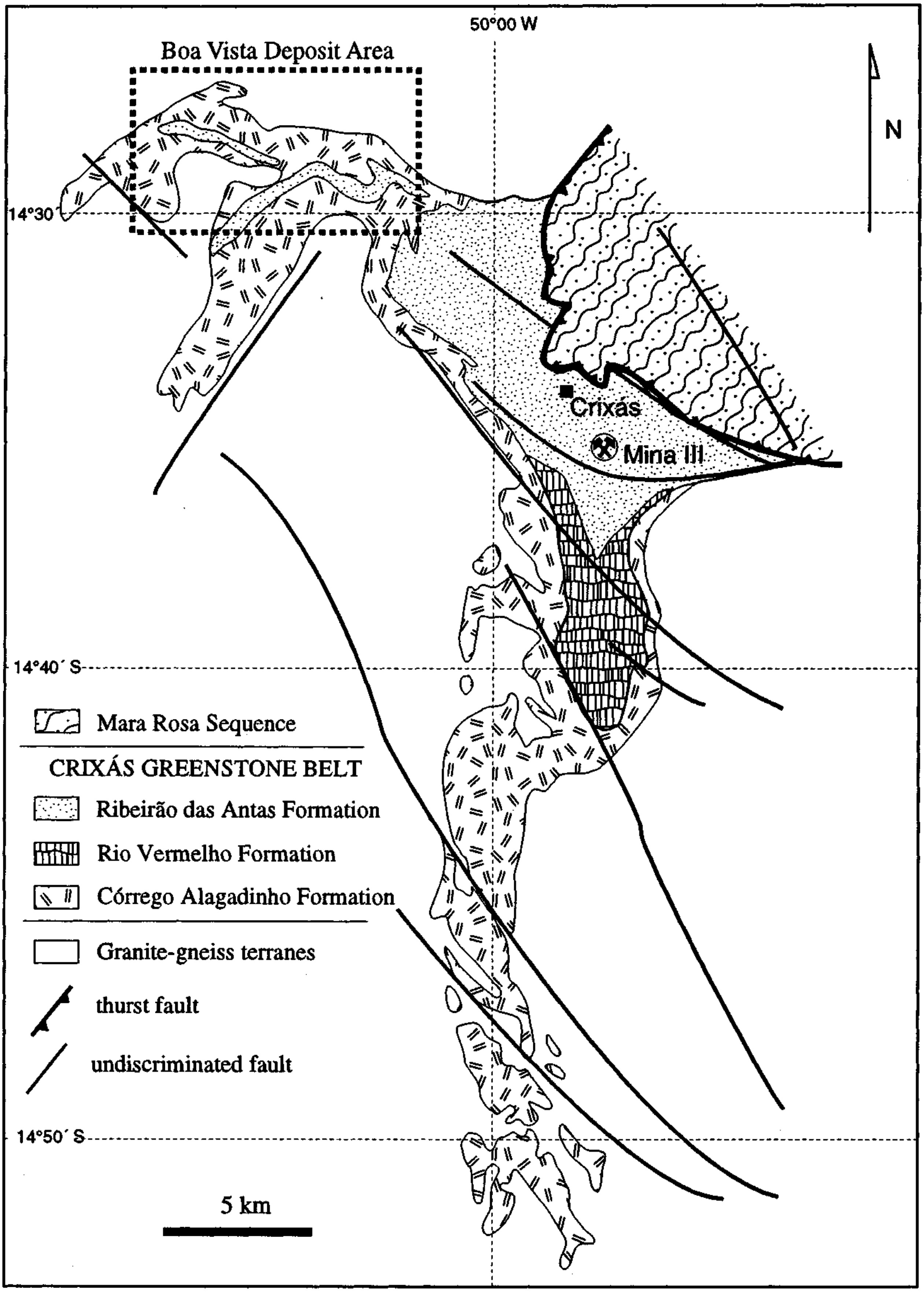

Figure 2 - Geology of the Crixás greenstone belt. Modified from Sabóia (1979) and Jost & Oliveira (1981).
Figura 2 - Geologia do greenstone belt de Crixás. Modificado de Sabóia (1979) e Jost & Oliveira (1981).

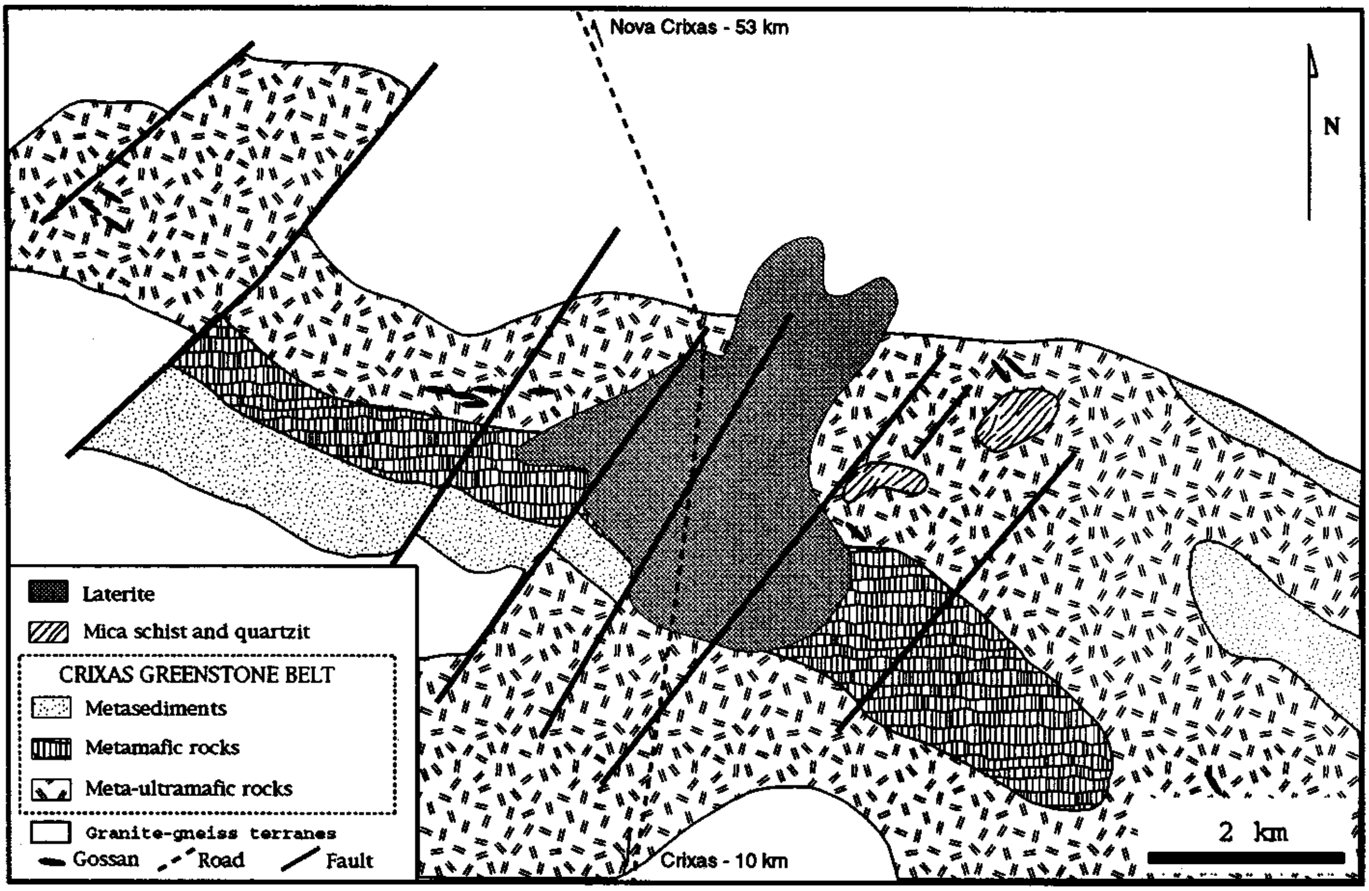

Figure 3 - Geology of the Boa Vista deposit.
Figura 3 - Geologia do depósito de Boa Vista.

hills nearby Boa Vista Farm are interpreted to be tectonic slices of Araxa Group rocks. They consist of quartz-sericite schist, chlorite-quartz schist and quartzite formed under greenschist facies conditions of metamorphism.

Structure and mineralogy of the ultramafic flows

Most of the drill cores of the Boa Vista deposit area consist of completely sheared mafic and ultramafic rocks. Primary structures and textures are restricted to low-strain zones intercepted by few drill cores. The morphology of the volcanic flows can be reconstructed within the low-strain zones, where two types of ultramafic flows are recognized.

The first type consists of thin spinifex-textured komatiitic flows (Fig. 4). The flow-top consists of fine-grained brecciated ultramafic rock. The spinifex-textured zone shows the transition from fine random spinifex texture (Fig. 5A) to coarse plate spinifex texture (Fig. 5B-D). The cumulate zone is characterized by cumulus olivine (completely replaced by serpentine ± talc ± chlorite ± magnetite) within a matrix of serpentine, talc, tremolite, chlorite, carbonate, and magnetite (Fig. 5C). Although primary igneous textures are well preserved within the low-strain zones, primary igneous minerals are not preserved. Metamorphic recrystallization is pervasive and obliterated most of microscopic-scale textures. In spinifex-textured samples, the primary olivine blades are mainly replaced by serpentine (± chlorite, ± talc, ± tremolite) and outlined by fine magnetite grains. Pseudomorphs of cumulus olivine crystals within cumulate zone are mostly oblit-

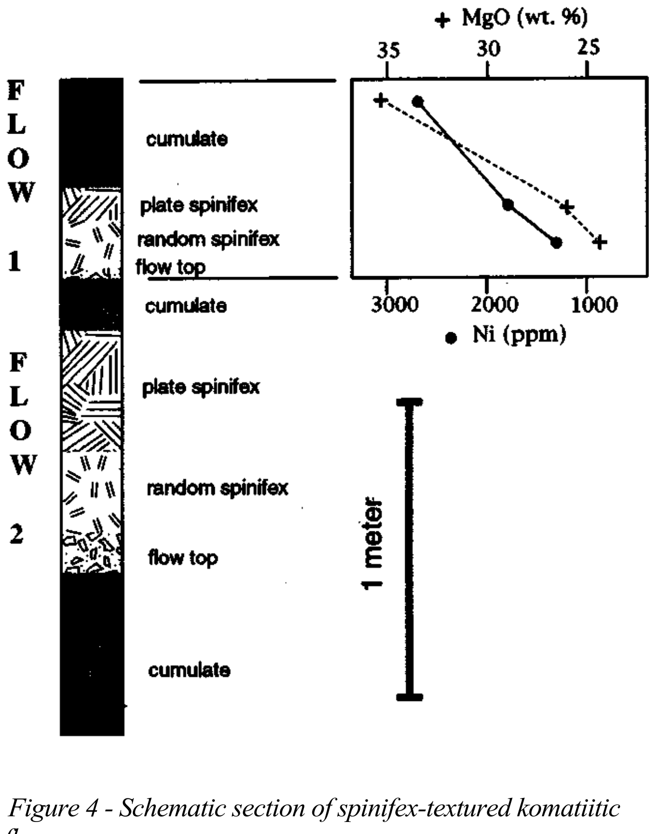

Figure 4 - Schematic section of spinifex-textured komatiitic flows.
Figura 4 - Seção esquemática de derrames komatiíticos com textura spinifex.

crated by the metamorphic growth of serpentine, tremolite, chlorite, talc and magnetite.

The second type consists of few meters-thick unsettled komatiitic flows. The flows have no internal structure other than fine-grained flow tops. This type of flow lacks the characteristic geochemical trends observed on the first type.

It is worth stressing that primary structures are only preserved within few intercepts of low-strain zones. Nevertheless, the primary textures allowed the identication of both normal and inverted sequences of komatiitic flows. The stratigraphic orientation provided by the flow morphology indicates that the nickel-sulfide is concentrated at the base of a sequence of ultramafic flows above a mafic sequence, thus providing a critical datum for the metalogenetic interpretation of the nickel-sulfide mineralization.

Geochemistry of the komatiites Analytical whole-rock major element data for 21 core samples of ultramafic rocks are reported in Table 1. The ultramafic rocks exhibit some of the classical geochemical and textural features which are the main criterion for the recognition of komatiitic lavas (Arndt & Nisbet 1982). The MgO content (recalculated to 100% on anhydrous basis) ranges from 22.1 to 28.7 wt. % on spinifcx-texturcd and unsettled flows what is typical for peridotitic komatiites. Two samples representing cumulate portions ofspinifcx-texturcd flows have higher MgO content (35.5 and 35.8 wt. %). Geochemical variations between cumulate rocks and spinifex-textured and unsettled flows (Fig. 6) indicate the importance of olivine fractional crystallization. Compared to spinifex-textured zone and unsettled flow the cumulate portion of spinifex-textured flows is enriched in MgO and NiO, being depleted in CaO and TiO_2. Scattering of the data (Fig. 6) suggests that regional metamorphism, including serpentinization and talc-carbonatization, has chemically modified the ultramafic rocks. Further petrological considerations of the Boa Vista komatiites are hampered by the suggested metassomatism and the lack of immobile trace-elements data. An evaluation of the metasomatic effect on the primary magmatic chemistry should be done before comparisons with other komatiitic suites (like Barbeton, Kambalda or Munro Township) were considered. It is worth noticing, however, that major-elements whole-rock geochemistry of the Boa Vista deposit komatiites is similar to what has been formerly published (based upon samples from the Corrego Alagadinho creek) about the Crixás komatiites (Arndt *et al.* 1989). This suggests that komatiites of both areas underwent similar metasomatic processes.

Petrography of the sulfide ore The sulfide mineralization in the Boa Vista deposit is always present at the lowest part of an ultramafic sequence overlying a mafic sequence. Within low-strain zones this stratigraphic relationship is well

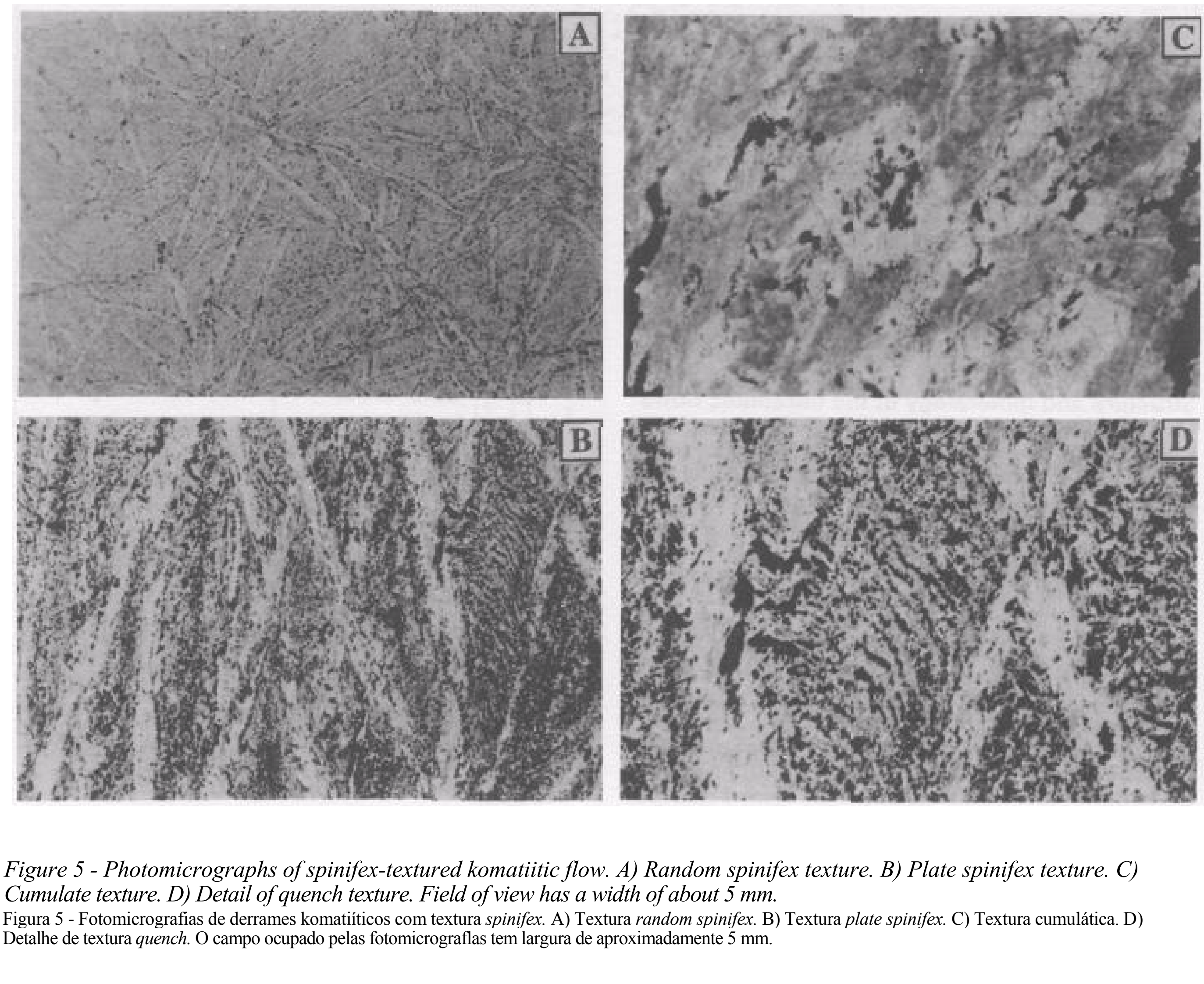

Figure 5 - Photomicrographs of spinifex-textured komatiitic flow. A) Random spinifex texture. B) Plate spinifex texture. C) Cumulate texture. D) Detail of quench texture. Field of view has a width of about 5 mm.

Figura 5 - Fotomicrografias de derrames komatiíticos com textura *spinifex.* A) Textura *random spinifex.* B) Textura *plate spinifex.* C) Textura cumulática. D) Detalhe de textura *quench.* O campo ocupado pelas fotomicrograflas tem largura de aproximadamente 5 mm.

Table 1 - Chemical composition (wt. %) of the Boa Vista komatiites.
Tabela 1 - Composições químicas (% em peso) dos komatiítos de Boa Vista.

(sample)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	NiO	S	PF
BVD31-145.70	44,3	0,59	3,6	10,4	5,6	22,2	8,0	0,05	0,01	0,04	0,20	0,19	0,32	3,90
BVD31-142.50	46,0	0,53	3,2	9,0	6,3	21,3	8,7	0,04	0,01	0,10	0,18	0,18	0,56	3,49
BVD31-141.80	47,6	0,45	3,1	8,8	4,2	22,2	8,7	0,02	0,01	<0.01	0,17	0,23	0,54	3,80
BVD31-47.55	44,1	0,32	1,7	8,6	4,4	25,6	4,4	0,01	<0.01	<0.01	0,17	0,29	0,31	9,68
BVD31-61.60	51,7	0,19	2,1	5,6	5,5	22,6	9,8	0,04	0,01	<0.01	0,08	0,32	0,44	3,37
BVD31-62.88	49,6	0,36	1,1	7,5	3,8	24,3	8,0	0,02	0,01	<0.01	0,13	0,20	0,27	4,26
BVD31-63.76	49,1	0,44	0,8	4,6	8,4	23,0	8,8	0,02	<0.01	0,01	0,14	0,18	0,24	3,32
BVD31-65.20	51,3	0,21	2,3	4,9	3,8	23,5	9,3	0,03	0,01	<0.01	0,08	0,31	0,45	3,60
BVD31-75.70	47,5	0,49	2,4	9,6	5,3	21,2	9,4	0,04	0,01	<0.01	0,19	0,17	0,18	2,88
BVD31-77.40	47,2	0,48	2,1	9,9	5,0	21,9	9,0	0,03	<0.01	0,02	0,17	0,19	0,36	3,10
BVD31-77.72	47,3	0,51	2,2	9,7	4,8	21,9	9,0	0,02	0,01	0,06	0,16	0,18	0,24	3,35
BVD31-96.58	44,7	0,53	2,9	10,8	5,9	22,0	8,3	0,02	<0.01	0,03	0,19	0,16	0,16	3,55
BVD32-62.28	44,2	0,49	3,0	8,9	5,6	25,0	5,7	0,03	0,01	<0.01	0,20	0,21	0,24	5,76
BVD32-62.54	47,3	0,41	2,1	8,2	5,5	23,6	7,3	0,03	0,01	0,03	0,17	0,18	0,18	4,27
BVD32-67.63	42,3	0,32	2,4	5,0	5,8	31,6	1,5	<0.01	<0.01	<0.01	0,15	0,35	0,42	9,66
BVD32-67.77	46,4	0,48	1,7	8,7	5,8	24,4	6,1	0,03	0,01	0,02	0,19	0,23	0,31	5,06
BVD32-68.30	47,2	0,44	2,1	8,0	5,3	23,0	8,2	0,03	<0.01	0,06	0,15	0,17	0,16	4,46
BVD32-68.30A	46,8	0,45	2,1	8,9	4,9	22,9	8,3	0,03	0,01	0,06	0,15	0,18	0,16	4,42
BVD32-95.00	43,3	0,51	2,6	10,0	5,6	25,1	5,5	0,03	0,03	0,02	0,22	0,23	0,13	8,02
BVD32-95.26	42,4	0,50	2,3	10,7	5,0	25,9	5,3	0,03	0,02	0,03	0,19	0,20	0,11	6,60
BVD32-95.80	42,0	0,31	2,0	5,5	6,2	31,9	1,0	0,01	0,02	<0.01	0,15	0,31	0,22	9,65

(Geosol Laboratory)

set by primary volcanic textures (flow top, spinifex). Figure 7 is a schematic cross section through the ore body. The thickness of the mineralized horizon is variable but is usually less than few-meters thick. The basal massive sulflde (40 vol. % sulfides) is usually less than 1 meter-thick brecciated ore.

Four types of ore are recognized. In order of decreasing abundance they are stringer ore, disseminated ore, massive ore and matrix ore. Most of the drill cores consist of completely sheared rocks where stringer ore and disseminated ore (within sheared ultramafic rocks) predominate. Primary structures and textures are restricted to few low-strain zones where the typical morphology of magmatic sulfide ore is preserved. The following description focuses on textural-mineralogical aspects of sulfides within low-strain zones.

Figure 8 is a drill-core based schematic section through the mineralized horizon. The basal massive sulfide is mainly a brecciated ore with ultramafic fragments (Fig. 9A) that become more abundant toward the top. The massive ore progressively changes upward to net-textured and disseminated ore.

The Boa Vista sulfide ore mineralogy is typical of magmatic sulfides associated with ultramafic rocks. It consists mainly of pyrrhotite (70 vol. %) associated with pentlandite and chalcopyrite and minor magnetite and sphalerite (± traces of galena). Pentlandite consists mainly of polycrystalline aggregates (Fig. 9B) and eventually as exsolution lamellae (flames) within pyrrhotite (Fig. 9C) or as exsolution rims bordering pyrrhotite crystals (Fig. 9D). Pentlandite polycrystalline aggregates are frequently bordering larger masses of pyrrhotite (Fig. 9B). Textural relations suggest that all pentlandite exsolved from pyrrhotite. It thus supports the existence of a monosulfide solid solution as the primary high temperature sulfide phase. Chalcopyrite consists of anhedral crystals unevenly distributed within the sulfide ore. Magnetite associated with the massive sulflde consists of euhedral crystals commonly with rounded edges. Pentlandite is frequently altered to violarite whereas pyrrhotite is frequently altered to marcasite.

Geochemistry of the sulfide ore Representative analyses of the Boa Vista deposit ore are presented in Table 2. Considering the analytical techniques used (see Table 2 for details) the data for Pt, Pd and Rh should be considered as preliminary and semi-quantitative. The composition of the sulfide ore was recalculated to 100 % sulfide (Table 3) following the guidelines of Naldrett (1989). Recalculation of the metal concentration in 100 % sulfides is based upon the assumption that the Boa Vista ore formed originally as a magmatic sulfide liquid, and enables different textural ore types with variable sulfide contents to be compared.

Analyses of sulfide ore recalculated to 100 % sulfides plot within the field of the monosulfide solid solution (MSS) at high temperature (Kullerud *et al.* 1969; see also Ebel & Naldrett 1996, for new experimental data and an updated review of the Fe-Ni-S system) (Fig. 10). The Fe-Ni-S variation

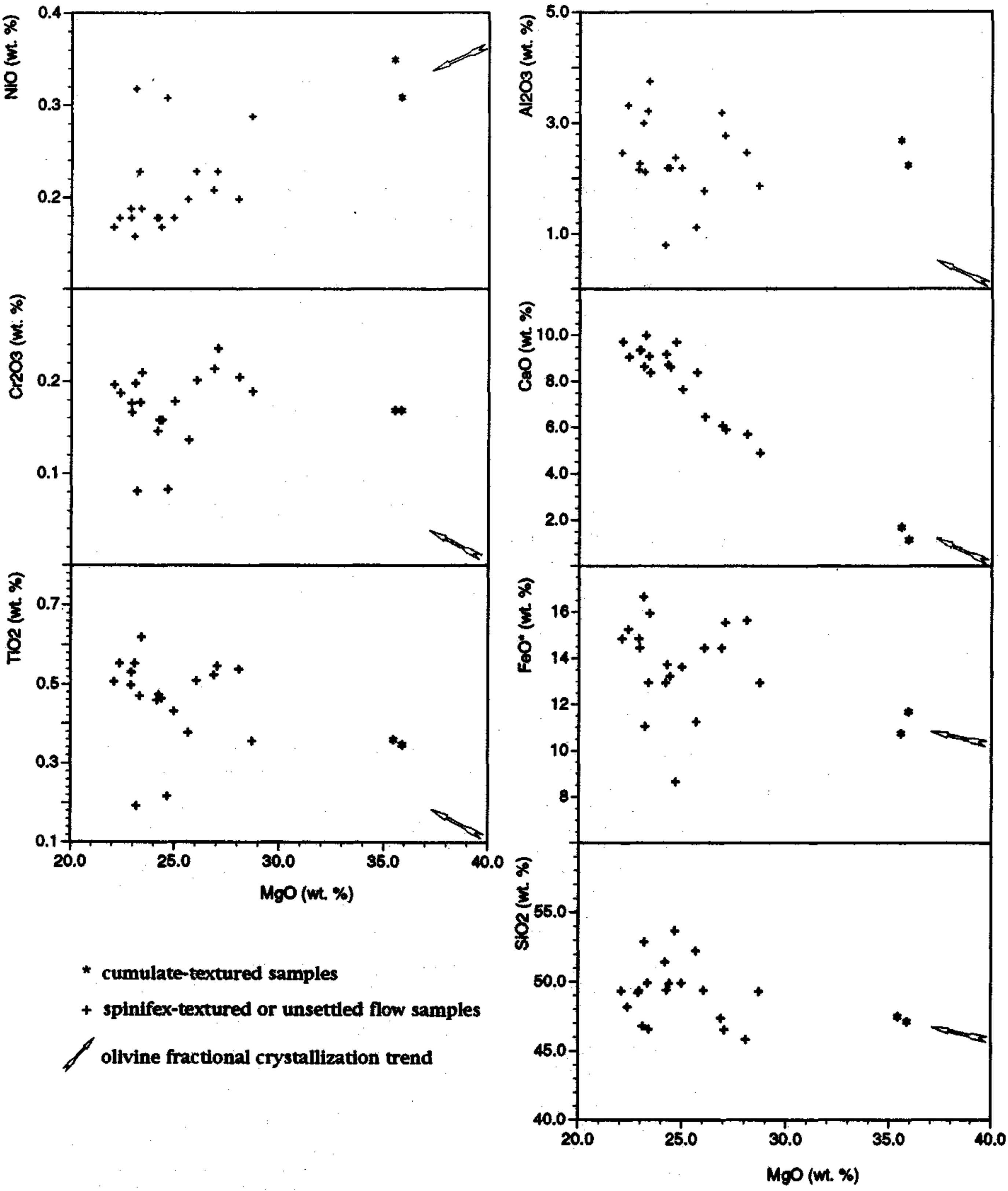

Figure 6, Variation diagrams for the Boa Vista komatiites.
Figure 6 - Diagramas de variaçäo para os komatiítos de Boa Vista.

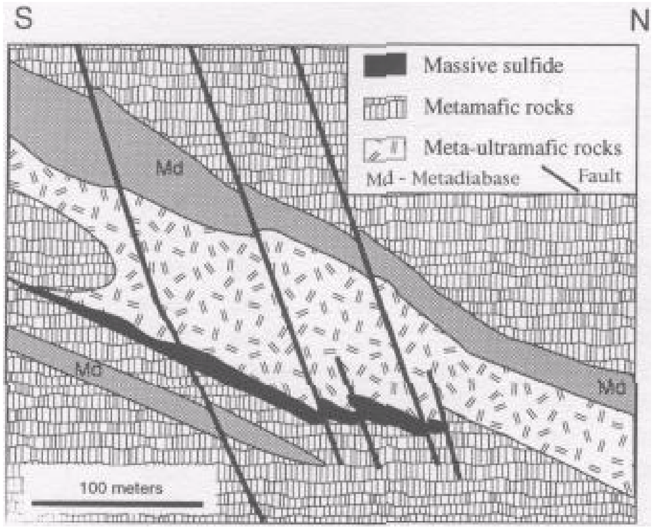

Figure 7 - Schematic cross section through the Boa Vista deposit.
Figura 7 - Seção esquemática através do depósito de Boa Vista.

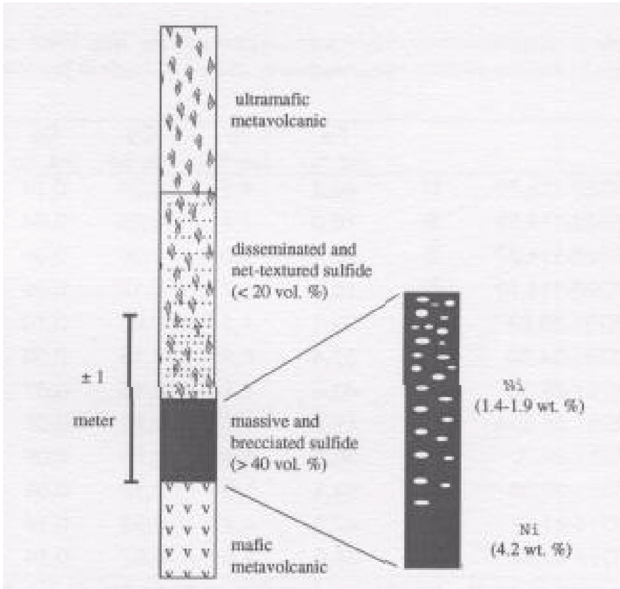

Figure 8 - Schematic section through the ore zone of the Boa Vista deposit.
Figura 8 - Seção esquemática através de uma zona mineralizada do depósito de Boa Vista.

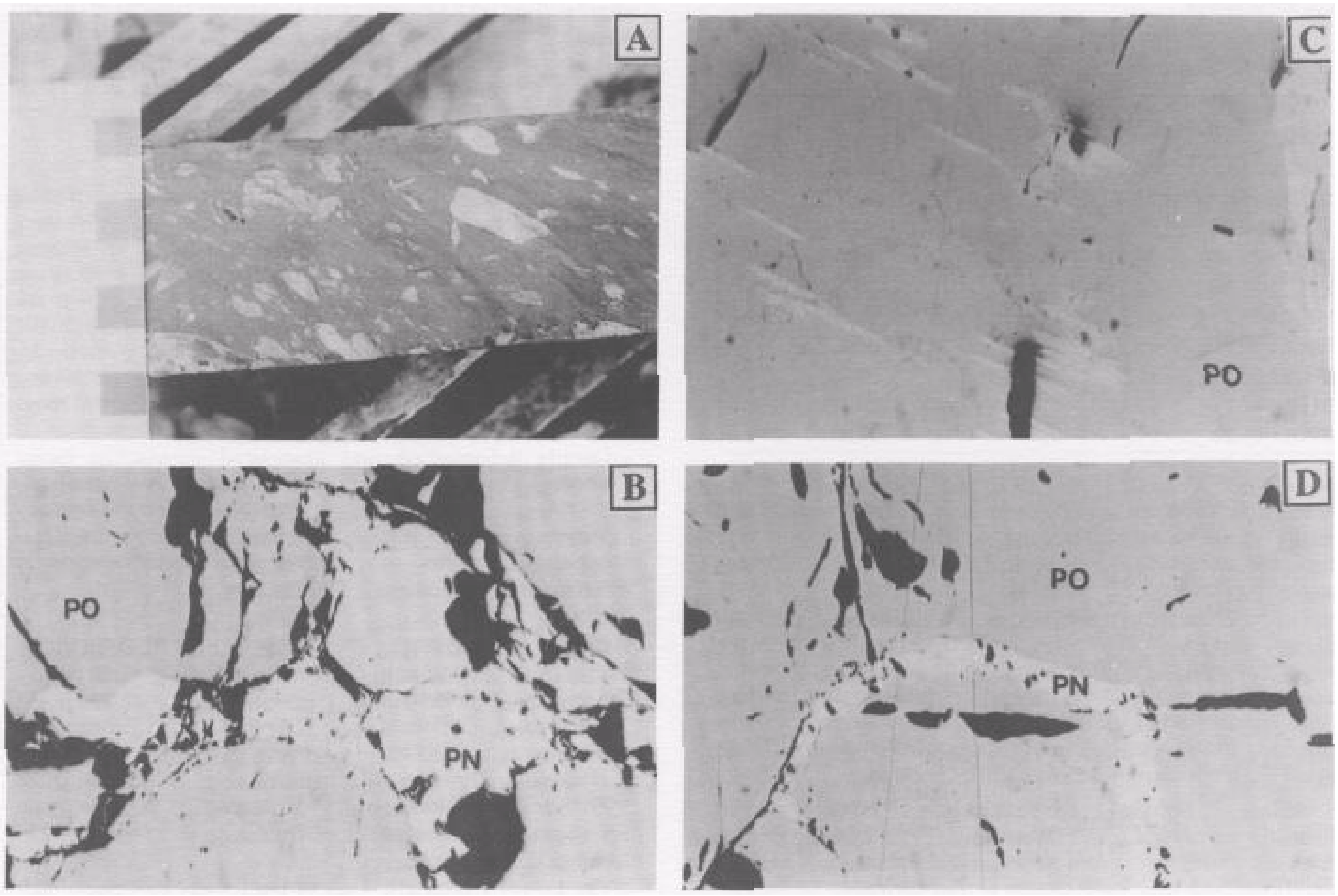

Figure 9 - Photographs of textures in nickel-sulfide ore. A) Brecciated sulfide ore. B) Photomicrograph of polycristalline aggregate of pentlandite. C) Photomicrograph of pentlandite exsolution lamellae (flames) within pyrrhotite. D) Photomicrograph of pentlandite exsolution rims around pyrrhotite crystals. Pentlandite (PN); Pyrrhotite (PO). Field of view of photomicrographs has a width of about 1.25 mm.
Figura 9 - Fotografias de texturas do minério sulfetado. A) Minério de sulfeto brechado. B) Fotomicrografia mostrando agregado policristalino de pentlandita. C) Fotomicrografia mostrando lamelas de exsolução *(flames)* de pentlandita em pirrotita. D) Fotomicrografia mostrando auréola de exsolução de pentlandita envolvendo cristais de pirrotita. Pentlandita (PN); Pirrotita (PO). O campo ocupado pelas fotomicrografias tem largura de aproximadamente 1,25 mm.

Table 2 - Representative chemical analyses of the Boa Vista sulfide ore.
Tabela 2 - Análises químicas representativas do minério sulfetado de Boa Vista.

		Fe (wt. %)	Ni (wt. %)	Cu (wt. %)	Co (wt. %)	Zn (ppm)	Pt (ppb)	Pd (ppb)	Rh (ppb)	Au (ppm)	S (wt. %)	Se (ppm)
BVD22-115,00	M	40,4	4,2	0,04	0,14	120	<10	282	33	<0.05	19,1	1
BVD22-114,39	B	16,0	1,4	0,28	0,04	330	19	245	<20	<0.05	10,7	2
BVD22-114,27	B	21,1	1,9	0,38	0,06	320	15	156	<20	<0.05	14,6	3
BVD22-114,13	B	18,6	1,7	0,19	0,05	350	<10	201	<20	<0.05	10,0	9
BVD31-23,83	B	39,1	1,1	0,26	0,10	170	<10	74	<20	<0.05	18,6	17
BVD31-24,60	B	37,4	0,9	0,15	0,08	280	<10	102	<20	<0.05	18,4	1
BVD31-26,30	B	40,6	1,1	0,13	0,07	150	<10	83	<20	<0.05	17,7	1
BVD31-26,30A	B	41,1	1,1	0,15	0,09	200	<10	122	<20	<0.05	19,5	1
BVD31-32,70	B	36,5	0,9	0,15	0,06	260	<10	137	<20	<0.05	17,3	13
BVD31-33,26	B	39,4	1,0	0,12	0,08	210	<10	9	<20	<0.05	17,8	1
BVD14-47,77	B	40,2	4,4	0,58	0,14	280	<10	263	43	<0.05	22,5	1
BVD14-65,22	M	39,0	4,5	0,07	0,14	110	<10	176	44	<0.05	23,9	13

M = massive ore; B = breccia ore; Analytical methods: Cu, Zn, Co, Au by AA;
(Geosol Laboratory) Ni, S, Se, Fe by XRF; Pt, Pd, Rh lead fire assay and optical spectrography

Table 3 - Chemical analyses of the Boa Vista sulfide ore recalculated to 100 % sulfides.
Tabela 3 - Análises químicas do minério sulfetado de Boa Vista recalculadas para 100 % sulfeto.

	Fe (wt. %)	Ni (wt. %)	Cu (wt. %)	S (wt. %)	Pd (ppb)
BVD22-115,00	53,4	8,4	0,08	38,2	564
BVD22-114,39	55,3	5,0	1,01	38,6	875
BVD22-114,27	55,4	5,0	1,00	38,5	410
BVD22-114,13	54,4	6,5	0,73	38,3	768
BVD31-23,83	58,0	2,3	0,55	39,1	155
BVD31-24,60	58,5	1,9	0,32	39,2	217
BVD31-26,30	58,2	2,4	0,29	39,1	183
BVD31-26,30A	58,3	2,2	0,30	39,2	245
BVD31-32,70	58,3	2,0	0,34	39,2	304
BVD31-33,26	58,3	2,2	0,26	39,2	20
BVD14-47,77	53,4	7,5	0,98	38,1	446
BVD14-65,22	54,4	7,2	0,11	38,3	282

of the Boa Vista ore is consistent with a primary magmatic origin for the nickel mineralization. The ore composition is also consistent with the pyrrhotite ± pentlandite sulfide ore assemblage observed in sections.

The Ni/Cu ratios of the sulfide ore are variable but generally aligned along a 10:1 ratio (Fig. 11). These Ni/Cu ratios are consistent with the sulfide liquid being segregated from the overlying peridotitic komatiites. As pointed out by Naldrett (1989), most Archean KHNS deposits have high Ni/Cu ratios reflecting the Ni-rich ultramafic composition of the silicate liquid from which immiscible sulfides formed.

Sulfide ore sampled at the eastern part of the deposit have distinctly lower Ni, Cu and Pd contents (Fig. 12). Considering that both petrographic and geochemical data do not suggest significant post-magmatic chemical transformation of the sulfide ore, these differences should be related to primary magmatic processes. The lower contents of these metals indicate that sulfide ore at the eastern part of the Boa Vista deposit resulted from a lower silicate magma to sulfide liquid ratio (the "R" factor of Campbell & Naldrett 1979). This difference in R factor can be interpreted in two different ways: i) sulfide ore at the eastern part of the deposit represents a different event of sulfide liquid segregation; thus not stratigraphically equivalent to the other samples; ii) sulfide ore at the eastern part of the deposit represents the marginal facies of the komatiitic volcanism; thus formed away from the main lava channel where sulfide liquid equilibrates with larger amount of silicate magma. Eventhough the virtual restriction of mineralization to the base of a thick ultramafic unit overlying a mafic unit suggests a single event of sulfide segregation at Boa Vista, structural-stratigraphic data are not available to support this interpretation.

Genetic Model The Boa Vista deposit is considered to be a magmatic nickel sulfide deposit similar to the Western Australia examples. The following points support a magmatic origin for the Boa Vista deposit: the stratigraphic association of nickel sulfide ore with ultramafic komatiitic flows, the location of the nickel sulfide ore at the base of an ultramafic sequence, the presence of massive sulfide ore overlain by net-textures and disseminated sulfide ore, petrographical and geochemical similarity of the sulfide ore with classical magmatic sulfide deposits.

Ductile deformation and associated greenschist facies metamorphism, considered to be related to the Brasiliano Cycle (Neoproterozoic), have partially modified the primary magmatic features of the Boa Vista deposit. Pervasive metamorphic and tectonic overprint is expected to be a major limitation for detailed studies of the ores.

DISCUSSION OF RELEVANCE TO EXPLORATION

The Boa Vista nickel-sulfide deposit provided the first opportunity to study nickel-sulfide mineralization processes in the Crixás greenstone belt. Considering that KHNS deposits occuring in greenstone belts worldwide tend to be restricted to specific ultramafic units (Gresham & Loftus-Hills 1981, Duke 1990), geological and petrological studies of the Boa Vista deposit provide important clues for future nickel-sulfide exploration in the region.

The Lower Ultramafic Unit of the Crixás greenstone belt (Corrego Alagadinho Formation) consists of a thick sequence of ultramafic komatiitic rocks. The ultramafic rocks, with minor interlayered metasediments, are especially abundant in the southern part of the belt. Textures and volcanic structures, as well as petrological and geochronological data, suggest that the ultramafic komatiites of Crixás formed in a petro-tectonic setting similar to the Western Australia nickel-mineralized ultramafic volcanics. Stratigraphic correlation between the

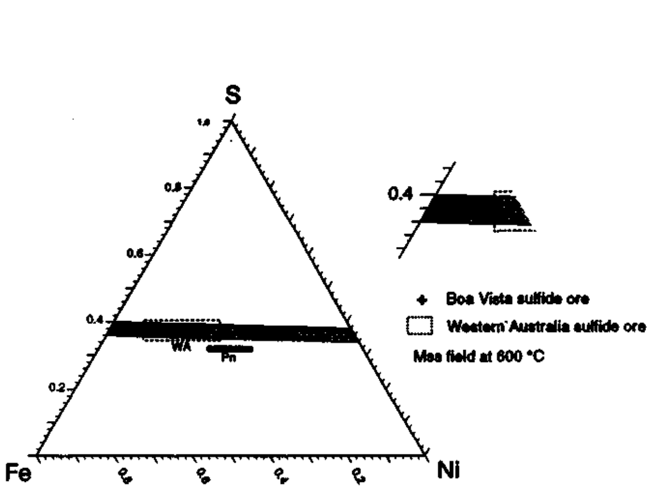

Figure 10 - Portion of the Fe-Ni-S system showing the composition of the Boa Vista sulfide ore. The monosulflde solid solution field at 600 °C (Kullemd et al. 1969) is shaded.
Figura 10 - Parte do sistema Fe-Ni-S mostrando a composição do minério sulfetado de Boa Vista. O campo ocupado pela *monosulfide solid solution* a 600 °C (Kullerud *et al.* 1969) está delineado na figura.

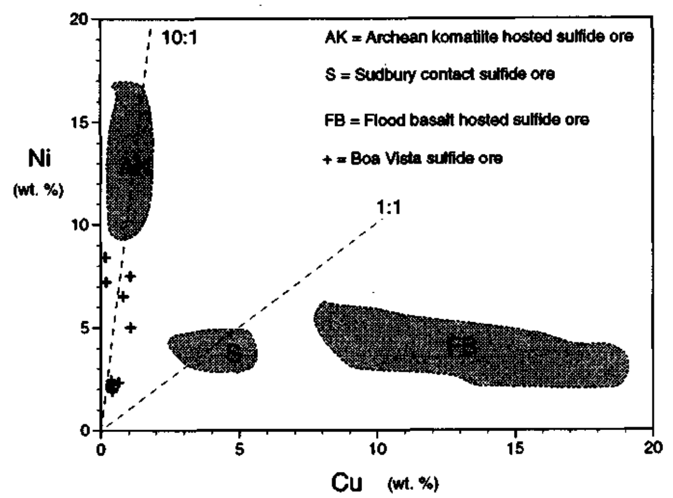

Figure 11 - Ni-Cu plot for the Boa Vista sulfide ore.
Figura 11 - Diagrama Ni-Cu para o minério sulfetado de Boa Vista.

ultramafic komatiites that host the Boa Vista deposit and the Lower Ultramafic Unit remains speculative. The authors are

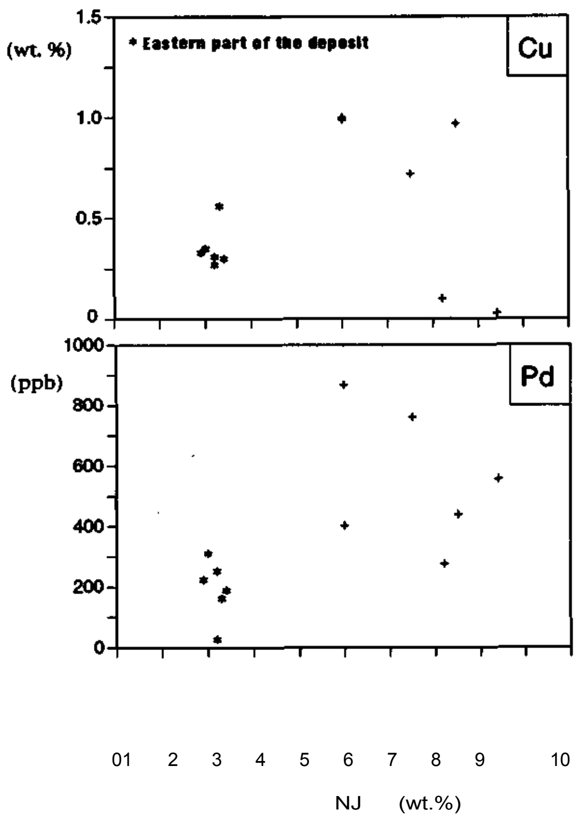

Figure 12 - Ni-Cu and Ni-Pd plots for the Boa Vista sulfide ore.
Figura 12 - Diagramas Ni-Cu e Ni-Pd para o minério sulfetado de Boa Vista.

now working with two possible scenarios for the ore-bearing mafic-ultramafic sequence:

a) The sequence belongs to the Lower Ultramafic Unit; the geological diversity observed in the sequence (including the thick footwall metabasalt), as opposed to the mainly ultramafic Lower Unit, merely reflects the larger amount of information provided by extensive drilling in the Boa Vista area.

b) The sequence does not belong to the Lower Ultramafic Unit; it thus represents a separate ultramafic unit (like the Mina Inglesa Sequence) overlying the Upper Metasedimentary Unit (Ribeirao das Antas Formation).

The two possibilities have metallogenetically significant implications. The first one points to extensive ore-bearing komatiitic magmatism in the belt. The second one suggests that mineralization is confined to a later and restrict episode of komatiitic magmatism. Geochemical data is currently being acquired to test these two possibilities.

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