THE SALOBO IRON OXIDE COPPER-GOLD DEPOSIT, CARAJÁS, NORTHERN BRAZIL

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Abstract - The Salobo iron oxide copper-gold deposit is located in the Carajás Mineral Province, northern Brazil. The copper-gold ore is hosted by the Archaean Salobo-Pojuca Group, which is formed by a sequence of amphibolites, banded iron formations, meta-greywackes and quartzites. These rocks were deposited in a trondhjemitic basement, where a continental rift basin, that has been further described as a pull apart basin, was developed. Principal ore assemblages are magnetite-bornite-chalcocite and magnetite-bornite-chalcopyrite, with magnetite dominant and variable amounts of copper sulphides. The iron oxide copper-gold ore shows elevated concentrations of Ag, U, Co, Mo, F and LREE. Differences in geochemistry and textures between magnetite of iron-rich rocks and magnetite of banded iron formation suggest a hydrothermal origin for the mineralisation. Fluid inclusion data for quartz veins and apatite indicate the involvement of highly saline fluids in the deposit formation. A dominantly magmatic source of the sulphur is indicated by isotope ratios determined for chalcopyrite and bornite (δ^{34}S between 0.2 and 1.6‰). Petrographic evidence supported by preliminary geochronological data indicates that the mineralisation post-dates the metamorphism. Hydrothermal alteration effects on host amphibolites have been also investigated. The studied amphibolites occur as lenses or layers close to the contact with the gneissic basement or included in meta-greywackes of the Salobo-Pojuca Group. Trace element chemistry of these rocks indicates that they are subalkaline basalts with tholeiitic affinity. Based on the K_2O content, three alteration groups have been defined and informally named "less altered", "medium altered" and "very altered" types. They characterise rocks affected by different degrees of alkali metasomatism, resulting in major compositional changes. "Less altered" rocks (<0.5 wt.% K_2O) show minor chemical modifications compared to the inferred average compositions of unaltered precursors. "Medium altered" rocks (0.5 to 3.5 wt.% K_2O) show alkali metasomatism expressed by incipient sodic alteration (up to 4.5 wt.% Na_2O) and superposed potassic alteration. "Very altered" rocks are characterised by extensive potassic alteration, with K feldspar and biotite formation and high K_2O (>3.5 wt.%) values. The spatial association of "very altered" rocks with the main ore zone suggests a relationship between alkali metasomatism and mineralisation. Similarities in the the hydrothermal alteration pattern combined with the ore mineralogy and chemistry indicate that the Salobo deposit belongs to the class of iron oxide (Cu-U-Au-REE) deposits.

Introduction

The Salobo iron oxide copper-gold deposit is located in the Carajás Mineral Province, northern Brazil. It is the largest Brazilian copper deposit with a resource of 1200 Mt @ 0.86% Cu and reserves estimated at 450 Mt @ 1.15% Cu and 0.5 g/t Au (Souza, L.G and Angelim, E., 2000). Research carried out on the Salobo deposit has concentrated mainly on the petrology of the host rocks (Lindenmayer, 1990), on the ore mineralogy and genesis (Figueiredo *et al.*, 1994; Requia *et al.*, 1995), and on the geochronology and regional geotectonic context (Machado *et al.*, 1991; Siqueira, 1996). Studies of the fluid phases present in the Salobo deposit were conducted by Requia and Xavier (1995), Requia *et al.* (1995) and Requia (1995). Hydrothermal alteration effects on the Salobo host rocks have been investigated by Lindenmayer *et al.* (1995) and Requia and Fontboté (1999, 2000). However, the age and the origin of the polymetallic mineralisation of Salobo are still

a matter of debate. Some authors have assumed syngenetic processes for the Cu-Au mineralisation (Docegeo, 1988; Lindenmayer, 1990; Figueiredo *et al.*, 1994), suggesting a sedimentary-exhalative origin for the Salobo deposit, while an epigenetic origin for the Au-Mo-U mineralisation, related to the intrusion of the Salobo anorogenic granite at 1880 Ma, has been proposed by Lindenmayer *et al.* (1995). A hypothesis that the Salobo deposit would be a porphyry copper deposit type was raised by Lyndenmayer and Teixeira (1999). Recently, Requia and Fontboté (1999) have proposed the Salobo deposit as part of the iron oxide (Cu-Au-U-REE) deposit class. Preliminary results of Re-Os and Pb-Pb determinations in sulphides and magnetite indicate ages around 2500 Ma for the Salobo mineralisation (Requia, 2002).

The present contribution summarises results of ongoing investigations in the Salobo iron oxide copper-gold deposit (Requia, 2002). It describes the petrography and
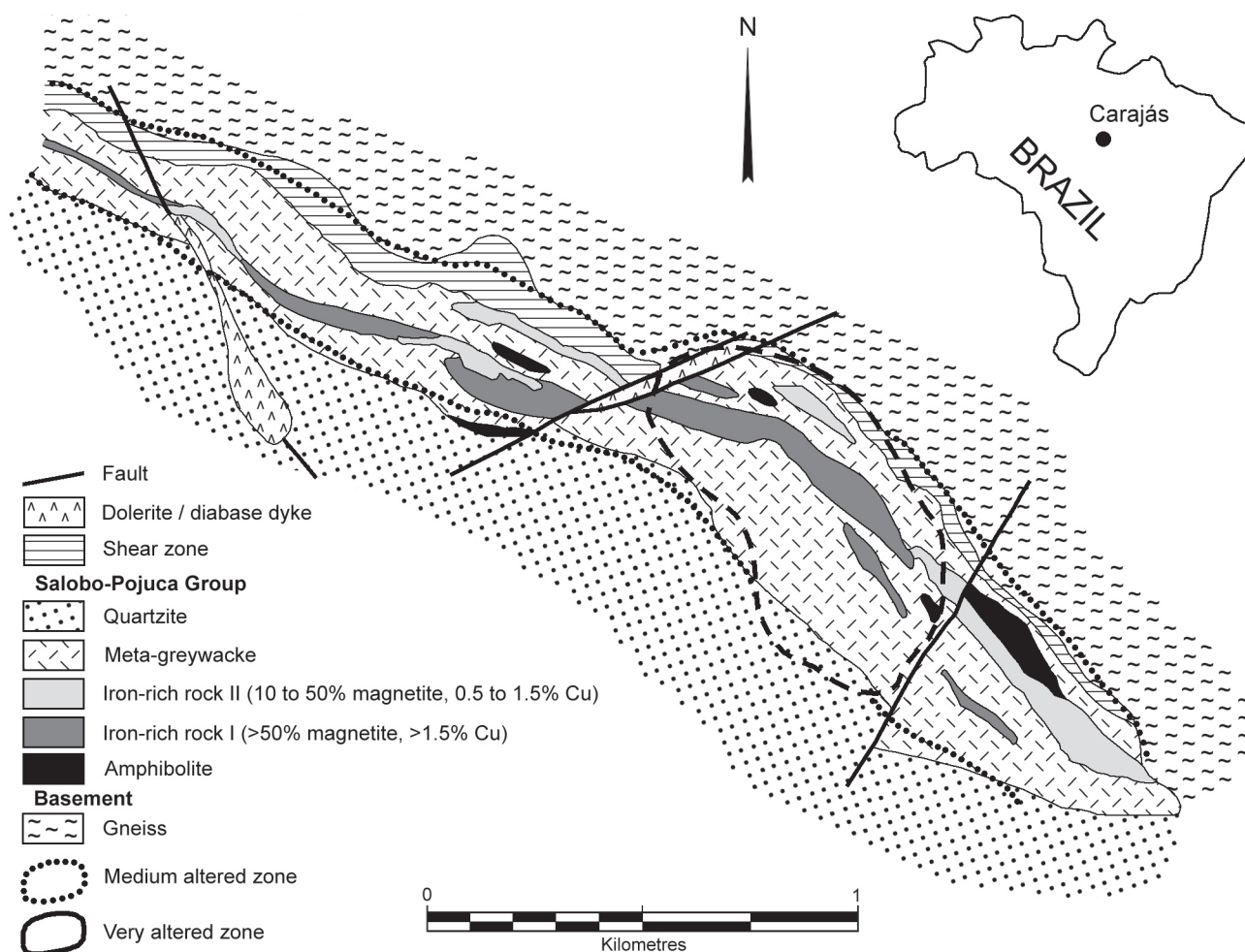
Figure 1: Schematic geologic map of the Salobo deposit (level 250, modified after Lindenmayer, 1990), showing an approximate distribution of alteration types.

geochemistry of the analysed amphibolites and shows that these rocks were affected by intense hydrothermal alteration, with important changes in their mineralogy and chemistry. It also indicates a hydrothermal origin for the iron oxide ore, showing a spatial relationship between alkali metasomatism and mineralisation.

Geological Setting

The Salobo deposit is formed by a sequence of amphibolites, banded iron formations, meta-greywackes and quartzites (Farias and Saueressig, 1982; Lindenmayer, 1990; Fig. 1), which are included in the Salobo-Pojuca Group. These rocks were deposited in a throndhjemitic basement dated at 2851±4 Ma (Machado *et al.*, 1991), where a continental rift basin (Docegeo, 1988; Lindenmayer, 1990), that has been further described as a pull apart basin (Pinheiro *et al.,* 1991; Araújo and Maia, 1991), was developed. The Salobo-Pojuca Group ranges in thickness from at least 300 to 600 m, showing shearing contacts with the basement gneisses. The lower part of the sequence consists of meta-greywackes and amphibolite lenses or layers and hosts the iron oxide copper-gold mineralisation. At the top, quartzites constitute the only lithology. Two granitoid intrusions dated at 2573±2 Ma and 1800 Ma (Machado *et al.*, 1991), dyabase dykes and veins cut the deposit area. According to Siqueira and Costa (1991), the Salobo deposit

is part of a duplex structure created by the convergence of two shear zones: one curved, placed to the north and another straight placed to the south. They are 2555±4 Ma old shear zones (Machado *et al.*, 1991) that developed a sub-vertical mylonitic foliation N70°E affecting all lithologies of the deposit, excepting the younger intrusive rocks. The Salobo rocks underwent high amphibolite facies metamorphism at 2763 to 2759 Ma (Machado *et al.*, 1991), with metamorphic peak at 650°C and pressure of 3 kbar, followed by a retrograde metamorphic event at greenschist facies, with temperature of 350°C indicated by the chlorite compositions (Requia, 1995).

As detailed below, the Salobo mineralisation contains large amounts of iron oxides. Based on this observation, different authors, including Farias and Saueressig (1982) and Lindenmayer (1990), termed these iron-rich rocks as "iron formations". The present investigation shows that at least significant parts of the iron oxides of the Salobo mineralisation are probably epigenetic and genetically related to a large hydrothermal system. Thus, we prefer to name the iron oxide rich rocks with the genetically neutral term "iron rocks". We reserve the term "iron formations" to those of inferred sedimentary origin. Consequently, the "iron formations" I (>50% of magnetite) and II (10% to 50% of magnetite) of Lindenmayer (1990) are termed in the present work "iron rocks" I and II.

Mineralisation

Magnetite forms generally massive lense-like bodies, which occur along a NNW-SSE shear zone and dip 85°SW. Principal ore assemblages are magnetite-bornite-chalcocite and magnetite-bornite-chalcopyrite, with magnetite dominant and variable amounts of copper sulphides. Magnetite grains are usually idiomorphic (Fig. 2a), which differs texturally from magnetite of banded iron formation. Bornite and chalcocite commonly display mirmekitic texture, probably due to exsolution processes. Chalcopyrite may occur with a lamellar texture in bornite (Fig. 2a), which is indicative of conversion of cubic high temperature chalcopyrite to tetragonal low temperature form. Accessory ore minerals are hematite (Fig. 2b), molybdenite, ilmenite, uraninite, graphite, digenite and covellite. Native gold grains occur as small inclusions (<10 μm) in cobaltite, saflorite and copper sulphides or interstitially to magnetite and chalcopyrite grains. Copper sulphides also occur in veins cutting "iron rocks", with or without gold, chlorite and stilpnomelane.

The paragenetic sequence in the Salobo deposit is illustrated by Fig. 3. An early mineralisation phase is marked by magnetite, with small amounts of hematite. In parts of the deposit, the conditions were relatively reducing during this phase, which is indicated by the presence of graphite. The sulphide stage is characterised by the formation of tetragonal chalcopyrite, probably originated from a copper-rich cubic solid solution, and subsequent formation of bornite and chalcocite. At the end of the sulphide stage, native gold precipitation occurred in spatial association with cobaltite and safflorite. Petrographic evidence, as magnetite cutting rotated garnet and chalcopyrite interstitially to fayalite grains or filling its fractures, indicates that the mineralisation is post-metamorphism.

Both "iron rocks" I and II show low titanium and elevated Cu, Au, Ag, Co, U, Mo, LREE and F values, whereas the banded iron formation is depleted in these elements (Requia and Fontboté, 1999; Table 1).

Fluid Inclusion and Sulphur Isotope Studies

Two broad but very variable fluid populations have been distinguished in quartz veins and apatite of the Salobo deposit (Requia *et al.,* 1995; Requia, 1995). One homogenises to liquid at an average temperature of 360°C, which represents the minimum temperature

Table 1: Typical values of "iron rocks" I and II and banded iron formation of the Salobo deposit analysed in this study.

Sample	KRI-65	KRI-71	KRI-43	KRI-91	KRI-54
Type	IR I	IR I	IR II	IR II	BIF
%*					
SiO_2	10.88	11.06	32.99	28.67	33.37
TiO_2	0.11	0.03	0.5	0.7	0.02
Al_2O_3	1.64	0.56	7.48	6.32	0.37
Fe_2O_3	83.44	77.24	53.3	52.88	67.01
MnO	0.4	0.31	1.36	0.52	0.26
MgO	0.18	0.06	2.74	6.58	0.13
CaO	3.74	8.45	0.92	0.83	0.03
Na_2O	0.04	0.07	0.13	0.12	<
$K2O$	0.07	0.06	0.74	1.33	0.03
P_2O_5	0.17	0.13	0.17	0.16	0.01
L.O.I.	0.31	0.73	<	1.46	<
Total	100.99	98.71	99.28	99.56	100.2
ppm**					
F	18 900	48 300	1470	1750	50
Cu	31 521	27 419	12 957	14 798	271
Zn	6	21	11	19	68
Ni	46	38	182	141	16
Co	87	74	105	88	85
V	27	5	111	127	4
Au	2.58	0.16	0.38	0.023	0.006
Ag	4.2	3.8	1.7	1.6	<
As	14.4	10	5.3	4.2	3
Mo	269	210	94	98	19
W	126	30	127	58	178
U	57.4	26	28.6	14.1	<
La	712	547	366	327	21.5
Ce	681	599	457	383	19
Nd	166	140	108	92	5
Sm	35.2	26.5	17.4	16.9	0.6
Eu	13.2	4.2	4.4	3.5	0.7
Yb	4.4	1.1	8.9	3.2	0.3
Lu	0.55	<	1.28	0.52	<

< indicates below the detection limit; * fusion-ICP whole rock analysis; **INAA combined with total digestion-ICP analysis

of entrapment of this fluid, and contains salinities of up to 58 wt.% NaCl $_{equiv.}$). The other homogenises between 133 and 270°C, with a strong mode in 195°C, and shows moderate to low salinities (1 to 29 wt.% NaCl $_{equiv.}$). Monophase carbonic inclusions are locally observed, with $CH_4 < 10$ mol.% and coexisting with saline inclusions. The authors above proposed an interaction of a lower fluid (probably a mixture of connate and magmatic brines) with an upper (more oxidised) fluid. They also suggested the aqueous inclusions might be trapped during the metamorphic-hydrothermal events (amphibolite to greenschist facies), and/or during the emplacement of the granitic intrusions like the Old Salobo Granite, at 2573±2 Ma ago (Requia *et. al*, 1995).

Sulphur isotope analyses of chalcopyrite and bornite have shown $\delta^{34}S$ values ranging from 0.2 to 1.6‰, with an average of 1.0‰. The narrow range of $\delta^{34}S$ values close to 0‰ indicates a dominantly magmatic sulphur source for the Salobo deposit.
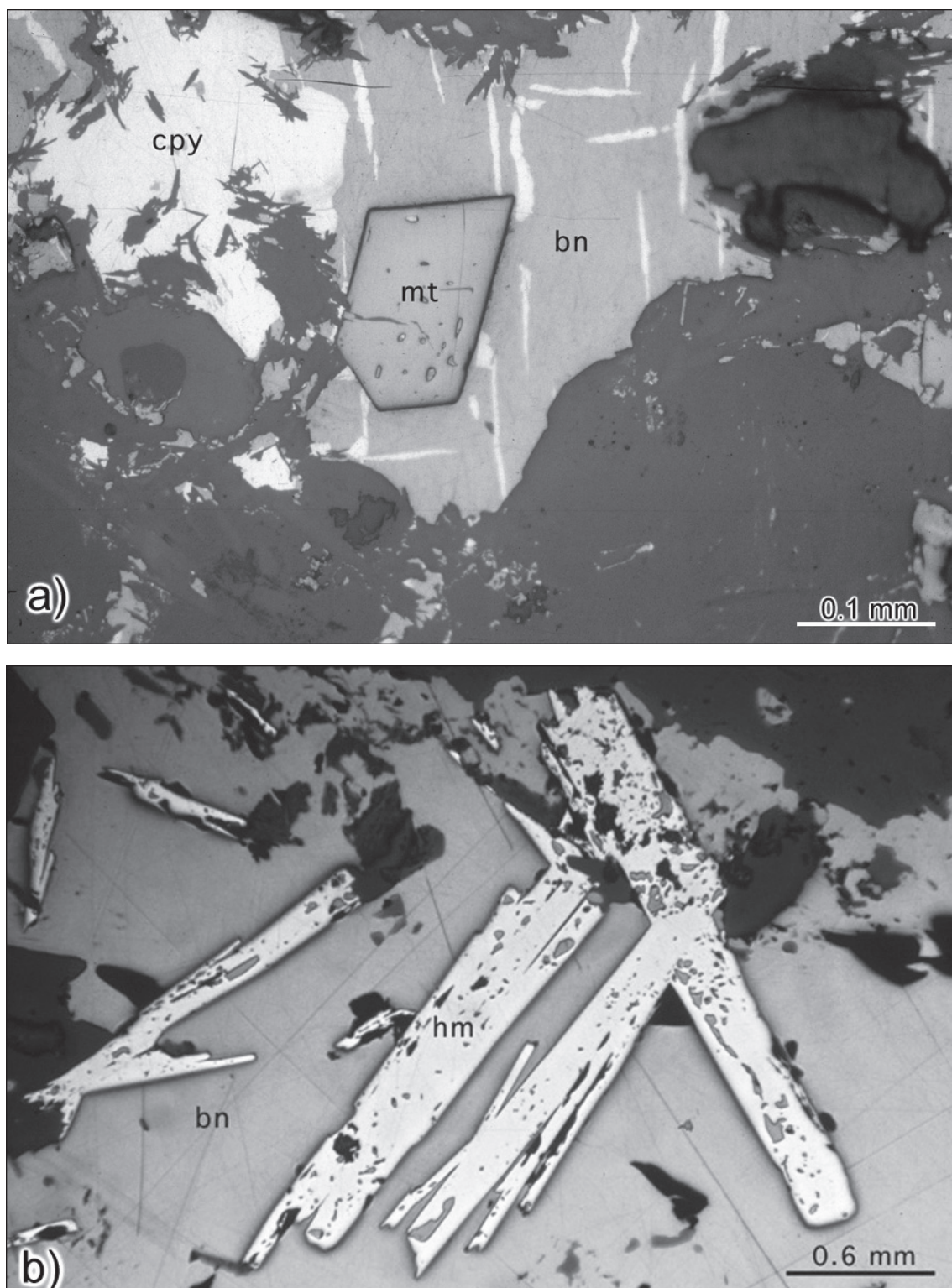

Figure 2: Microphotographs of Salobo mineralisation. **a)** Chalcopyrite displaying a lamellar texture in bornite and idiomorphic magnetite in "iron rock" I. **b)** Tabular hematite (specularite) with interstitial bornite in "iron rock" II.

Geochemistry of Amphibolite Host Rocks

Description of Analysed Rocks

25 samples of amphibolites supposed to have comparable primary compositions were analyzed for major and trace elements. The analyzed amphibolites consist of 2 to 5 m thick layers or lenses intercalated close to the contact with the basement gneisses or included in meta-greywackes of the Salobo-Pojuca Group. They are medium to fine-grained dark green rocks, mainly composed of Ca-amphibole and plagioclase, with subordinate biotite, cummingtonite, quartz and chlorite, and minor tourmaline, titanite, stilpnomelane, epidote, sericite and calcite. Microprobe analysis indicated that K feldspar also occurs in altered amphibolites. Small amounts of ilmenite, magnetite, hematite, uraninite, graphite, chalcocite, bornite, covellite, zircon and titanite are present in these rocks. The amphibolites show strong foliation and/or schistosity, but granoblastic and mylonitic textures are also observed. The foliation is defined by the preferred orientation of amphibole prisms and/or plagioclase lenses and the schistosity is marked by oriented biotite. Ca-amphiboles and plagioclase in granoblastic amphibolites usually display straight boundaries and triple junctions. Cummingtonite crystals commonly show lamellar twinning, and display intergrowth textures with

Ca-amphiboles or form rims around the latter. They occur also along fracture and cleavage planes of Ca-amphiboles. Plagioclase occurs as granular or lenticular crystals, rarely twinned, with straight, embayed or lobate boundaries. Narrow rims of Na-plagioclase surrounding Ca-plagioclase were observed. The replacement of plagioclase by orthoclase at different degrees of intensity was identified by microprobe analysis. Biotite is commonly surrounding cummingtonite and tourmaline in foliated, schistose or mylonitic rocks. Quartz shows undulose extinction and forms lenticular aggregates interstitial to amphibole and plagioclase. Chlorite is an alteration product of mafic minerals or feldspars in association with epidote and calcite. It is also found interstitial to quartz and feldspars in mylonitic matrix.

Petrogenetic Classification

Most of the previous classifications of the Carajás metavolcanic rocks were based on major elements and they have not considered the intensity of the hydrothermal alteration processes. This has lead to controversial interpretations of the magmatic affinity and geotectonic setting of these rocks. Several authors have proposed them as tholeiitic continental basalts (Olszewski *et. al.*, 1989; Sachs, 1993), calc-alkaline basalts
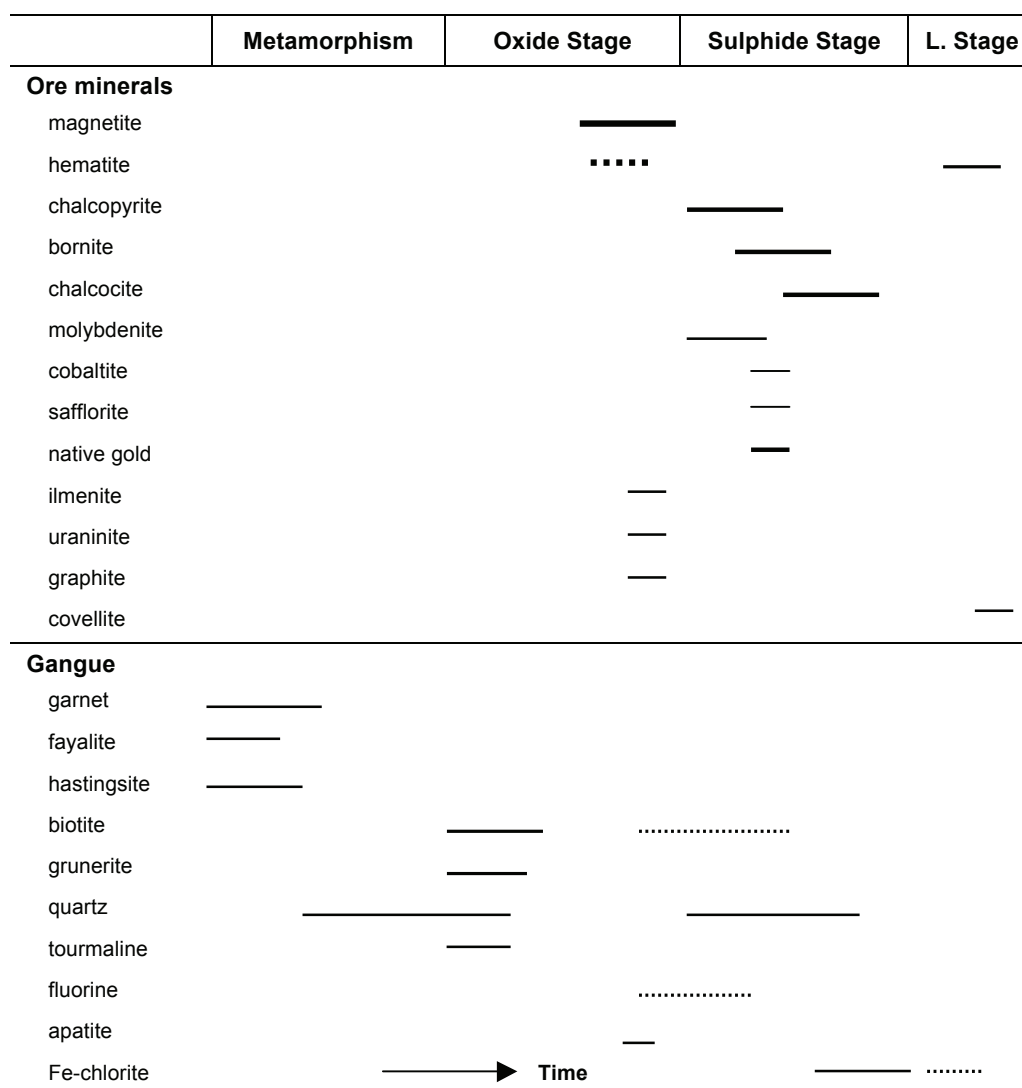

	Metamorphism	Oxide Stage	Sulphide Stage	L. Stage
Ore minerals				
magnetite		▬▬▬		
hematite		▪▪▪▪▪		▬▬
chalcopyrite			▬▬▬	
bornite			▬▬▬	
chalcocite			▬▬▬	
molybdenite		▬▬		
cobaltite			▬	
safflorite			▬	
native gold			▬	
ilmenite		▬		
uraninite		▬		
graphite		▬		
covellite				▬
Gangue				
garnet	▬▬▬▬			
fayalite	▬▬			
hastingsite	▬▬			
biotite		▬▬▬	··············	
grunerite		▬▬		
quartz	▬▬▬▬		▬▬▬	
tourmaline		▬		
fluorine			··········	
apatite		▬		
Fe-chlorite	▬▬▶ Time		▬▬▬ ·······	

Figure 3: The paragenetic sequence at the Salobo deposit.

Table 2: Compositional ranges and selected analyses of amphibolites studied from the Salobo deposit. Reference values from the literature are given for comparative purposes.

%	Basalt*	Tholeiitic basalt *	Amphibolite**	Less altered basalt (LA)	KR-9 LA	Medium altered basalt (MA)	KRI-61 MA	Very altered basalt (VA)	KRI-141 VA
SiO_2	45.7-50.19	46.3-51.75	44.7-50.6	47.92-49.94	47.92	39.32-51.31	45.64	40.53-46.67	40.53
TiO_2	0.88-3.2	1.2-2.4	1.8-2.0	0.15-0.51	0.51	0.44-1.48	0.7	0.5-1.21	0.5
Al_2O_3	13.23-18.6	13.8-16-3	12.5-13.5	6.81-8.5	8.50	7.31-17.74	14.09	9.71-15.5	9.84
FeO	8.7-14.2	10.4-11.4	16.8-19.5	16.49-19.13	19.13	8.61-34.29	25.23	12.52-35.33	35.33
MnO	0.15-0.22	0.17	0.09-0.33	0.13-0.21	0.21	0.12-0.66	0.16	0.15-0.26	0.26
MgO	4.4-9.8	5.9-7.4	4.7-5.7	10.85-11.30	11.30	1.50-14.59	1.5	3.61-13.04	3.61
CaO	8.2-11.1	9.8-10.6	4.7-8.5	10.71-11.41	10.71	3.40-8.97	3.81	0.15-7.67	0.15
Na_2O	2.5-3.1	2.2-2.5	2.5-3.8	0.44-0.49	0.49	0.00-4.54	4.54	0.00-0.65	0
K_2O	0.26-1.3	0.4-0.9	1.2-1.8	0.4-0.44	3.93	1.03-3.39	1.47	3.93-4.6	4.6
P_2O_5	0.12-0.67	0.21-0.26	0.14-0.23	0.02-0.23	0.02	0.01-0.53	0.05	0.01-0.18	0.01
L.O.I.	0.3-1.92	0.19	0.62-3.85	0.84-1.15	1.42	0.03 - 4.02	1.08	1.42-4.57	2.31
ppm									
Cu	87	_	115-310	11-380	11	11- >1152	>1152	75- >1000	>1000
Zn	122	_	32-290	<2-25	24	23-70	34	32-73	72
Co	49	_	44-140	63-85	85	48-127	126	45-120	120
Cr	34-563	350	76-130	<2-793	793	16-1365	985	15-1341	15
Rb	002-40	7	29-61	16-22	17	17-125	48	91-210	91
Sr	123-842	344	56-120	005-39	5	004-72	11	003-74	21
Ba	12-600	_	79-692	<9-22	22	20-437	100	254-784	784
Y	21-43	23	28-55	52-305	67	016-98	18	18-144	144
Zr	71-213	129	129-178	30-41	41	42-215	49	44-169	51
Nb	2.7-84	9	7-011	011-18	17	006-45	6	006-105	105
Ga	18-24	20	9-022	007-19	16	003-26	15	13-41	41

*Chemical composition of basaltic rocks and tholeiites from Ragland (1989) and Middlemost (1985); **Chemical composition of seven Salobo amphibolites, from Lyndenmayer (1990); Total Fe expressed in FeO.
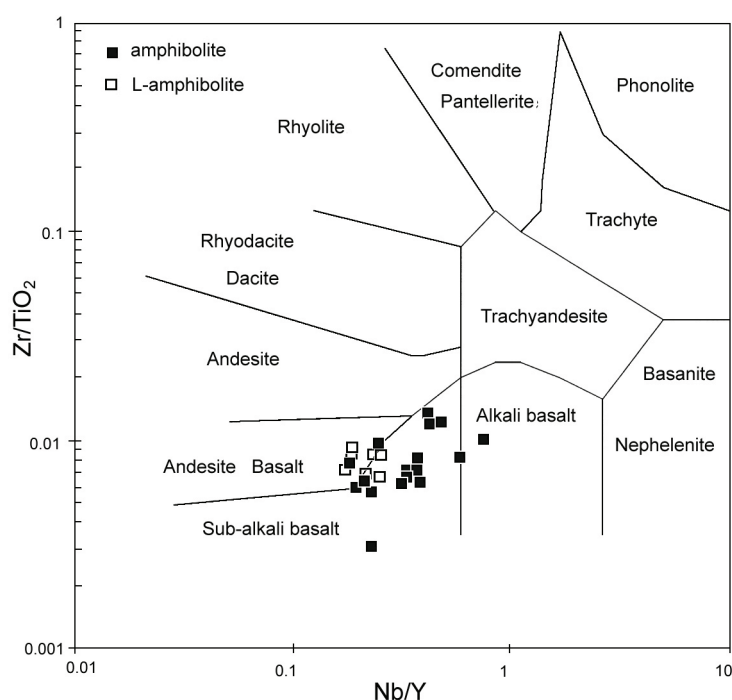
Figure 4:   Discrimination diagram (Floyd and Winchester, 1978) showing that the Salobo amphibolites are sub-alkaline basalts. For comparative purposes, 7 amphibolite samples from Lindenmayer (1990) were plotted in the discrimination diagram. Abbreviation: L-amphibolite: amphibolite from Lindenmayer (1990).

(Rivalenti *et. al.*, 1992) and shoshonitic basalts (Gibbs *et. al.*, 1986; Meirelles and Dardenne, 1991). The former authors thus have different interpretations for the Carajás tectonic setting, as Archaean continental rift or island arc. Based on the trace element chemistry of the Salobo amphibolites, Lyndenmayer (1990) classified these rocks as tholeiitic basalts, which as discussed below, is confirmed by the present work.

Since the classification based on major elements could not be applied to the Salobo amphibolites due to the strong hydrothermal alteration that affected these rocks, producing significant metasomatic changes of the original composition, the petrogenetic classification may rely on immobile elements. In the diagram Nb/Y vs. Zr/TiO_2 of Floyd and Winchester (1978), the amphibolites plot mainly in the subalkaline basalt field (Fig. 4). The SiO_2 values remain roughly unchanged, despite the strong hydrothermal alteration. This is suggested by the plot of Nb/Y vs. SiO_2, according to Winchester and Floyd (1976), which confirms that the amphibolites are subalkaline basalts. The diagram $Zr/P_2O_5.10^4$ vs. Nb/Y, according to Floyd and Winchester (1975), indicates a tholeiitic affinity for these rocks (Fig. 5). A similar discrimination can be achieved with the diagram Zr vs. P_2O_5 (Winchester and Floyd, 1976), where a tholeiitic character is defined for the amphibolites. In the plot $Zr-Ti/100-Y*3$ of Pearce and Cann (1973), these rocks appear to cluster in the ocean-floor basalt field.

According to the diagrams above, the analysed amphibolites are subalkaline basalts with tholeiitic affinity, indicating a continental rift setting for the Carajás basin. This is also consistent with the previous classification obtained by Lindenmayer (1990) for the Salobo amphibolites.

Hydrothermal Alteration

The present investigation permitted the identification of an intense hydrothermal alteration in part of the host amphibolites of the Salobo deposit. Due to the scarcity of completely unaltered precursors, compositions of unaltered basalts, in particular with tholeiitic affinity, were taken from the literature as a reference (Table 2). Based on the K_2O content, three alteration groups have been defined and informally named "less altered", "medium altered" and "very altered" types. Even though the classification above is arbitrary and each group includes different types of alteration, it seems to be consistent with the current results.

1. "Less altered" type (<0.5 wt.% K_2O): is formed by Ca – amphibole ± plagioclase ± quartz ± sericite ± epidote ± chlorite, with or without tourmaline, biotite and K feldspar. Its occurrence is limited to the southeastern part of the deposit, where an association with medium altered type rocks is observed. The amphibole was determined by X-ray diffractometry and microprobe analysis as Mg-hornblende. Plagioclase was identified as labradorite to andesine. This type shows depleted Na_2O, high FeO and slightly high CaO (10.71 to 11.41 wt.%) values, whereas K_2O contents are compatible to the inferred average compositions of unaltered precursors (Table 2). Incipient potassic alteration is locally observed, marked by partial replacement of andesine by orthoclase.

2. "Medium altered" type (0.5 to 3.5 wt.% K_2O): consists of K feldspar – quartz – Ca – amphibole ± plagioclase ± sericite ± epidote ± chlorite, with or without biotite, tourmaline, calcite, stilpnomelane and titanite. It is
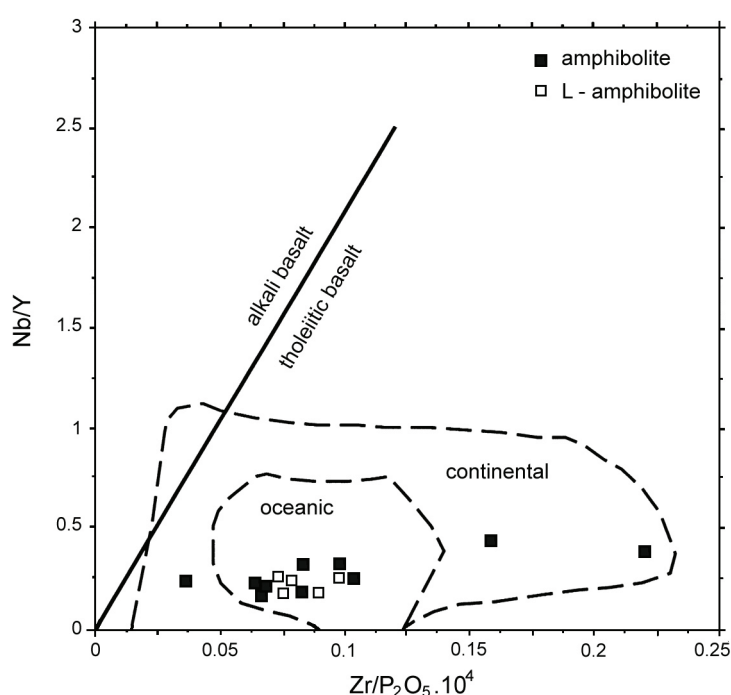

Figure 5: $Zr/P_2O_5.10^4$ vs. Nb/Y diagram (Floyd and Winchester, 1975) indicating that the analysed amphibolites have a tholeiitic affinity. For comparison purposes, 7 amphibolite samples from Lindenmayer (1990) were plotted in the discrimination diagram. Abbreviation: L-amphibolite: amphibolite from Lindenmayer (1990).

extensively distributed in the deposit area, but it seems to occur mainly surrounding the central zone dominated by "very altered" type rocks. Microprobe analysis indicates the presence of hastingsite as the main Ca-amphibole (Fig. 6a). Plagioclase composition ranges from bytownite to sodic oligoclase. Ca-plagioclase crystals are commonly surrounded by narrow rims of Na-plagioclase. K feldspar, identified as orthoclase, replaces partially the plagioclase (Fig. 6a). In the absence of K feldspar, biotite is the dominant mineral and in association with titanite and quartz, could represent the alteration product of Ca-amphibole in the presence of potassium-rich fluids. This alteration type is characterised by relatively high K_2O and FeO contents and low Na_2O and CaO values (Table 2). Two rock samples (KR4, KR61) have shown high Na_2O (up to 4.5 wt.%) content, indicating that a sodic alteration may be locally preserved.
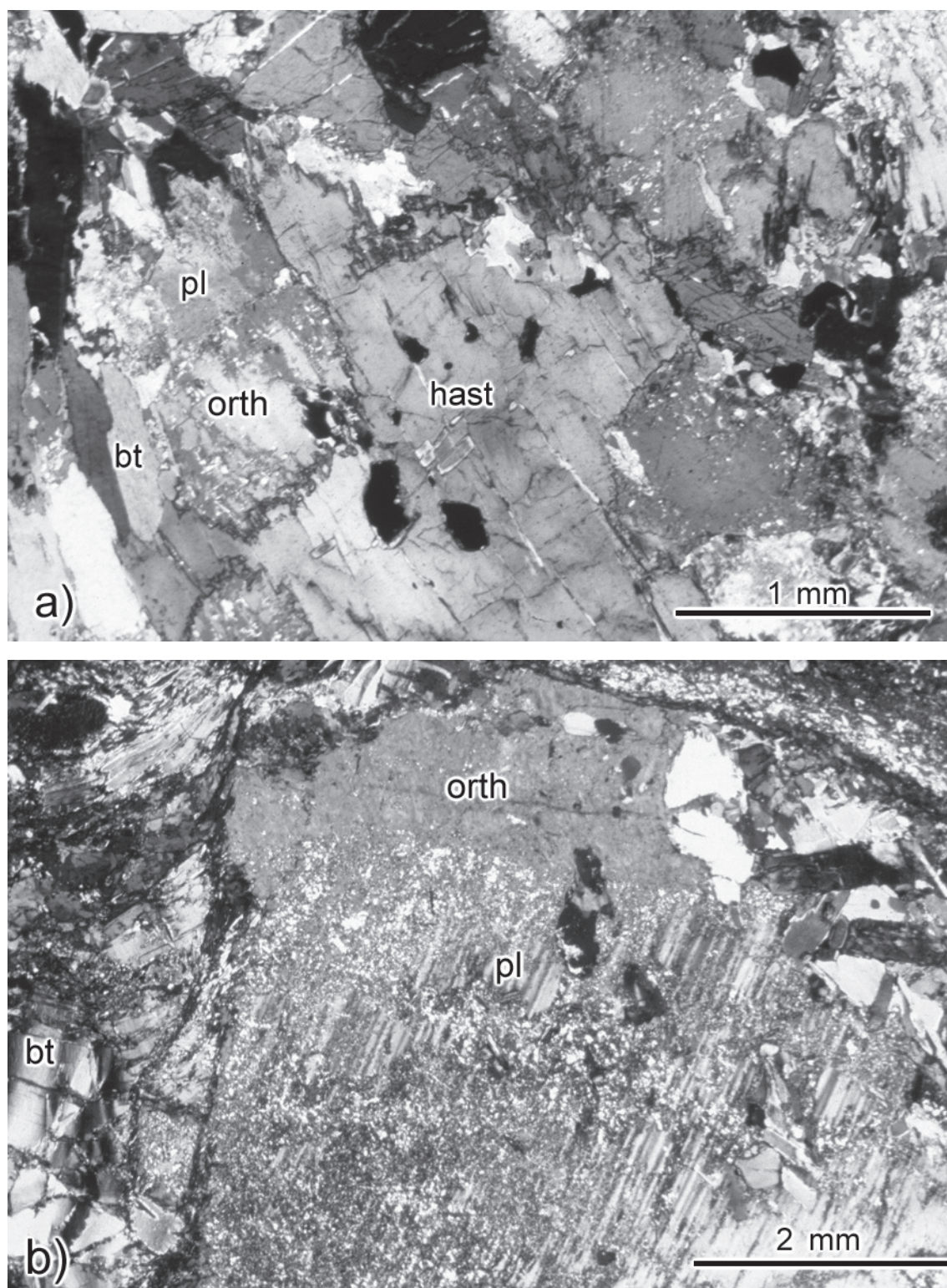

Figure 6: Microphotographs of hydrothermally altered amphibolites from the Salobo deposit. a) "Medium altered" amphibolite mainly composed of plagioclase partially replaced by orthoclase and of hastingsite with minor biotite.   b) Plagioclase crystal rimmed by orthoclase in "very altered" amphibolite with subordinate biotite.

3. "Very altered" type (>3.5 wt.% K$_2$O): is formed by K feldspar - quartz ± Ca-amphibole ± cummingtonite ± plagioclase ± sericite ± epidote ± chlorite, with or without biotite, calcite, tourmaline, titanite and kaolinite. It is observed in the central part of the deposit, which is also the richest ore zone. X-ray diffractometry and microprobe analyses confirm the presence of Ca-amphiboles, mostly Mg-hornblende, with subordinate ferro-tschermakitic hornblende, ferro-hornblende and actinolite. Fe-Mg amphibole, represented by cummingtonite, commonly replaces Ca-amphiboles. The local replacement of Mg-hornblende by actinolite is accompanied by epidote, chlorite and quartz formation. Plagioclase crystals, mainly of labradoritic composition, are extensively replaced by K feldspar, which was identified as orthoclase (Fig. 6b). Biotite dominates in rocks without K feldspar or with very little amounts, in association with titanite and quartz. This alteration type is characterized by high K$_2$O values (up to 4.6 wt.%), depletion in Na$_2$O and very low CaO contents (Table 2).

Different types and degrees of alteration of the Salobo amphibolites are put in evidence by the fairly constant ratios of Zr/TiO$_2$ throughout the whole range of K$_2$O, Na$_2$O and CaO values (Fig. 7). The diagrams above demonstrate that "less altered" rocks were less affected by hydrothermal alteration, whereas "medium altered" and "very altered" rocks underwent intermediate to strong potassic alteration. The diagram K$_2$O/(K$_2$O+Na$_2$O) vs. CaO discriminates basalts affected by alkali metasomatism and suggest a main alteration path (Fig. 7). The distribution of alteration types in the deposit area is illustrated by Fig. 1. Transitions between these alteration types are observed and assemblages are pervasive.

Chloritisation of mafic minerals is widespread through the deposit area and is also found in the whole Carajás region. It may represent the regional metamorphic background. In addition, sericitisation and propylitisation occur in all alteration groups, and seem to post-date the alkali metasomatism.
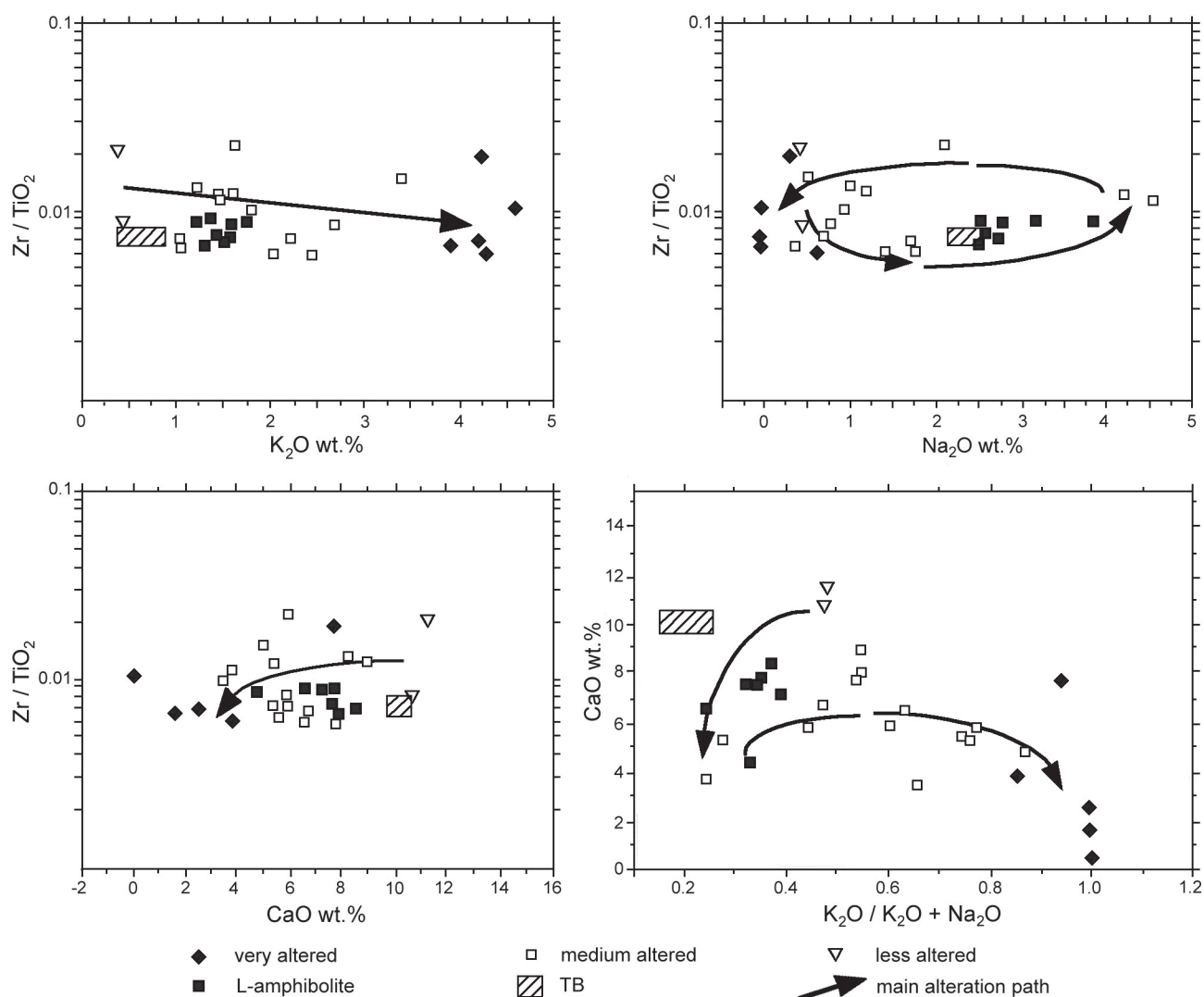

Figure 7: Discrimination of alkali metasomatised amphibolites of the Salobo deposit, indicating different degrees of hydrothermal alteration and the main alteration path (arrows). Abbreviations: L-amphibolite: amphibolite from Lindenmayer (1990); TB: compositional range of tholeiitic basalts from Middlemost (1985) and Ragland (1989).

Discussion and Conclusions

The alteration types described above characterise rocks affected by intense alkali metasomatism, resulting in major compositional changes. An early event of Na-metasomatism is locally preserved and was marked by high amounts of Na_2O (up to 4.5 wt.%). The incipient Na-alteration is indicated by the replacement of original Ca-plagioclase by Na-plagioclase. This episode was followed by extensive K-metasomatism, expressed by the partial or complete replacement of plagioclase by K feldspar, and also by biotite formation in the absence of K feldspar. A substantial increase in the K_2O values (up to 4.6 wt.%) characterises this alteration event.

Petrographic and geochemical evidences permitted the identification of different degrees of hydrothermal alteration in the Salobo amphibolites. "Very altered" rocks are characterised by strong potassic alteration, whereas "medium altered" rocks show incipient sodic alteration overprinted by potassic alteration. "Less altered" rocks present minor chemical modifications and higher CaO values, mainly expressed by the presence of Ca-amphibole and by the preservation of Ca-plagioclase.

The distribution of alteration types put in evidence an important hydrothermal centre in the deposit area. A strong relationship between hydrothermal alteration and mineralisation is shown by the spatial association of "very altered" rocks, which suffered strong potassic alteration, with the main ore zone. Differences in geochemical and textural characteristics between the "iron rocks", which are enriched in Cu, Au, Ag, U, F, Mo, Co and LREE, and the depleted banded iron formation indicate a hydrothermal origin for the iron oxide mineralisation. The narrow range of sulphur isotope values close to 0‰ in conjunction with fluid inclusion data suggest a dominantly magmatic sulphur source for the Salobo deposit. Major features shown by the Salobo deposit, including the alkali mestasomatism of the host rocks, and the ore and fluid chemistry, are quite similar to those presented by other iron oxide-rich copper-gold deposits as Olympic Dam (Oreskes and Einaudi, 1990; Hitzman *et al.*, 1992; Oreskes and Hitzman, 1993) and La Candelaria-Punta del Cobre (Marschik and Fontboté, 2001). Petrographic evidence indicates that the mineralisation post-dates the metamorphism, which has been confirmed by preliminary Re-Os and Pb-Pb determinations in sulphides and magnetite, with ages around 2500 Ma.

The hydrothermal alteration pattern displayed by the host amphibolites, combined with the chemical and mineralogical characteristics of the ore, are consistent with the hypothesis that the Salobo deposit belongs to the iron oxide (Cu-U-Au-REE) deposit class.

Acknowledgements

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