Hydrothermal alkali metasomatism in the Salobo iron oxide Cu (-Au) deposit, Carajás Mineral Province, northern Brazil

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ABSTRACT: Hydrothermal alteration effects on host amphibolites of the Archean iron oxide Cu (-Au) deposit of Salobo, northern Brazil, have been investigated. Preliminary results indicate that the studied rocks were affected by different degrees of alkali metasomatism, resulting in major compositional changes. In addition, similarities in the hydrothermal alteration assemblages and in the ore mineralogy and chemistry suggest that the Salobo iron oxide Cu (-Au) deposit may belong to the class of iron oxide (Cu-U-Au-REE) deposits.

1 INTRODUCTION

The Carajás Mineral Province, northern Brazil, ranks as one of the world's greatest mineralized districts, with deposits of iron, copper, manganese, gold, nickel, tin and bauxite. The Salobo iron oxide Cu (-Au) deposit is located in the north part of the Carajás Mineral Province. It is the largest Brazilian copper deposit with reserves estimated at 256 million metric tons of ore grading 0.8 to 1.1% Cu and 0.48 g/t Au (Vale do Rio Doce Company in Requia, 1995).

2 GEOLOGY AND MINERALIZATION

The Salobo deposit occurs in a sequence of amphibolites, banded iron formation, metagraywackes and quartzites (Fig. 1), which was named Salobo Sequence by Lindenmayer (1990). These rocks were deposited in a trondhjemitic basement dated at 2851±4 Ma (Machado et al., 1991), where a continental rift basin (Farias & Saueressig, 1982; Lindenmayer, 1990) or a pull apart basin (Araújo & Maia, 1991) was developed. Trace element chemistry of amphibolites analyzed in the present investigation indicates that they are subalkaline basalts with tholeiitic affinity, confirming the previous classification obtained by Lindenmayer (1990). The lower part of the Salobo Sequence consists of metagraywackes and amphibolite lenses or layers and hosts the iron oxide Cu (-Au) mineralization.
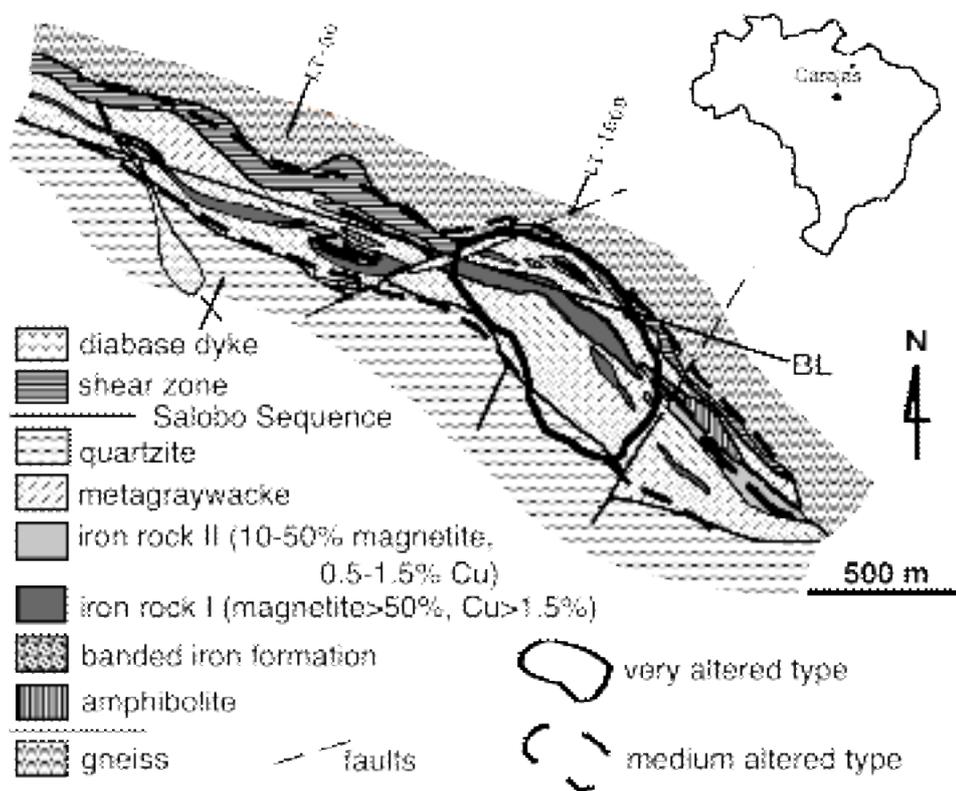
Figure 1. Schematic geologic map of the Salobo deposit (level 250, modified after Lindenmayer, 1990) showing a rough distribution of alteration types.

The Salobo rocks underwent high amphibolite facies metamorphism at temperature of 650°C and pressure of 3 kbar, followed by a retrograde metamorphic event at greenschist facies and temperature of 350°C, indicated by chlorite compositions (Requia et al.,1995).

As detailed below, the Salobo mineralization contains large amounts of iron oxides. Based on this observation, different authors, including Farias & Saueressig (1982) and Lindenmayer (1990), termed these iron-rich rocks as "iron formations". The present investigation shows that most of iron oxides of the Salobo mineralization 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 (Tab. 1).

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

sample	KRI-65	KRI-43	KRI-54
% *	iron rock I	iron rock II	banded iron formation
SiO$_2$	10.88	32.99	33.37
Al$_2$O$_3$	1.64	7.48	0.37
Fe$_2$O$_3$	83.44	53.3	67.01
MnO	0.4	1.36	0.26
TiO$_2$	0.11	0.5	0.02
Cu**	3.15	1.3	0.03
ppm**			
Zn	6	11	68
Ni	46	182	16
Co	87	105	85
V	27	111	4
Au	2.58	0.38	0.006
Ag	4.2	1.7	<
As	14.4	5.3	3
Mo	269	94	19
W	126	127	178
U	57.4	28.6	<
La	712	366	21.5
Ce	681	457	19
Nd	166	108	5
Sm	35.2	17.4	0.6
Eu	13.2	4.4	0.7
Yb	4.4	8.9	0.3
Lu	0.55	1.28	<

<less than the detection limit

*fusion-ICP whole rock analysis

**INAA combined with total digestion-ICP analysis

The mineralization of the Salobo deposit consists mainly of iron oxides (magnetite>hematite) with dissemination of chalcopyrite, bornite and chalcocite. Accessory ore minerals are hematite, molybdenite, ilmenite, uraninite, graphite, digenite, covellite and sulphosalts. Native gold was described by Requia et al. (1995) as grains smaller than 10 μm in cobaltite, safflorite, magnetite and copper sulphides or interstitial to magnetite and chalcopyrite grains. Native gold grains contain up to 10 wt% Cu, with subordinate Ag, As and Fe, which is a composition stable at temperatures below 400°C (Chang et al., 1977). The Salobo iron oxide copper ore shows low titanium and elevated LREE, Au, Ag, Co, U and Mo values, whereas the banded iron formation is depleted in these elements (Tab. 1). The mineralogical and chemical characteristics of the Salobo mineralization are common features found in the iron oxide (Cu-U-Au-REE) deposit class, as in the Olympic Dam deposit (Hitzman et al., 1992) or in the Candelaria-Punta del Cobre ore systems (Marschik & Leveille, 1998).

3 HYDROTHERMAL ALTERATION

In order to verify possible effects of hydrothermal alteration, 23 samples of amphibolites supposed to have comparable primary compositions were analyzed for major and trace elements. The studied rocks occur as 2 to 5 m thick layers or lenses intercalated close to the contact with the basement gneisses or included in metagraywackes of the Salobo Sequence. Less altered amphibolites are mainly composed of Ca-amphibole and plagioclase, with subordinate biotite, cummingtonite, quartz and chlorite, and minor tourmaline, titanite, stilpnomelane, epidote, sericite and calcite.

The present investigation permitted the identification of an intense hydrothermal alteration in part of the host amphibolites of the Salobo deposit (Fig. 2). As mentioned above, the analyzed rocks are subalkaline basalts with tholeiitic affinity. Due to the scarcity of completely unaltered precursors, compositions of unaltered basalts were taken from the literature as a reference (Tab. 2). Based on the K$_2$O content, three alteration groups have been defined and informally named "less altered", "medium altered" and "very altered" types (Tab. 2; Fig. 2).

1. "Less altered" type (<0.5 wt% K$_2$O): 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 microprobe analysis as Mg-hornblende. Plagioclase was identified as labradorite to andesine. This type shows depleted Na$_2$O, high FeO and slightly high CaO (10.71-11.41 wt%) values. Although K$_2$O contents are compatible to the inferred average compositions of unaltered precursors, incipient potassic alteration is locally observed, marked by partial replacement of andesine by orthoclase.

2. "Medium altered" type (0.5-3.5 wt% K$_2$O): consists of K-feldspar - quartz - Ca-amphibole ± plagioclase ± sericite ± epidote ± chlorite, with or without biotite, tourmaline, calcite, stilpnomelane and titanite. It is extensively distributed in the deposit area, but it seems to occur mainly surrounding the
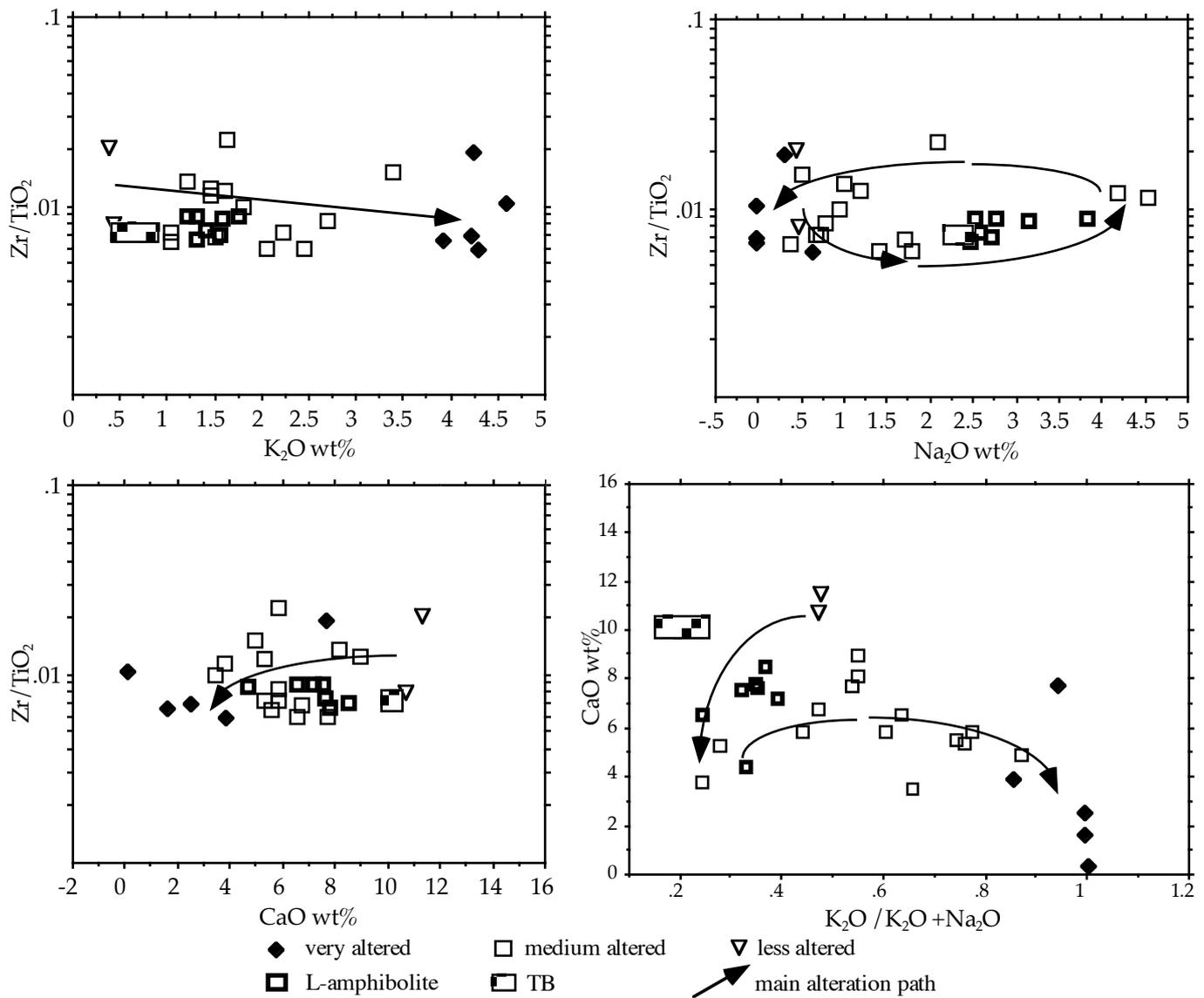
Figure 2. Discrimination of alkali metasomatized amphibolites of the Salobo deposit, showing the main alteration path (arrows). L-amphibolite: amphibolite from Lindenmayer (1990); TB: compositional range of tholeiitic basalts from Middlemost (1985) and Ragland (1989).

Table 2. Reference values and compositional ranges of analyzed amphibolites of the Salobo deposit.

%	basalt (1)	tholeiitic basalt (1)	amphibolite (2)	less altered basalt	medium altered basalt	very altered basalt
SiO2	45.7-50.19	46.3-51.75	44.7-50.6	47.92-49.94	39.32-51.31	40.53-46.67
TiO2	0.88-3.2	1.2-2.4	1.8-2.0	0.15-0.51	0.44-1.48	0.5-1.21
Al2O3	13.23-18.6	13.8-16-3	12.5-13.5	6.81-8.5	7.31-17.74	9.71-15.5
FeO*	8.7-14.2	10.4-11.4	16.8-19.5	16.49-19.13	8.61-34.29	12.52-35.33
MnO	0.15-0.22	0.17	0.09-0.33	0.13-0.21	0.12-0.66	0.15-0.26
MgO	4.4-9.8	5.9-7.4	4.7-5.7	10.85-11.30	1.50-14.59	3.61-13.04
CaO	8.2-11.1	9.8-10.6	4.7-8.5	10.71-11.41	3.40-8.97	0.15-7.67
Na2O	2.5-3.1	2.2-2.5	2.5-3.8	0.44-0.49	0.00-4.54	0.00-0.65
K2O	0.26-1.3	0.4-0.9	1.2-1.8	0.4-0.44	1.03-3.39	3.93-4.6
P2O5	0.12-0.67	0.21-0.26	0.14-0.23	0.02-0.23	0.01-0.53	0.01-0.18
L.O.I.	0.3-1.92	0.19	0.62-3.85	0.84-1.15	0.03 - 4.02	1.42-4.57
ppm						
Y	21-43	23	28-55	67-305	16-98	18-144
Zr	71-213	129	129-178	30-41	42-215	44-169
Nb	2.7-84	9	7-011	11-018	6-045	6-105

1. Chemical composition of basaltic rocks and tholeiites from Ragland (1989) and Middlemost (1985)
2. Chemical composition of seven amphibolites of Salobo from Lindenmayer (1990)
*Total Fe expressed in FeO

central zone dominated by "very altered" type rocks (Fig. 1). Microprobe analysis indicates the presence of hastingsite as the main Ca-amphibole. 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. In the absence of K-feldspar, biotite is the dominant alteration mineral. This alteration type is characterized by relatively high K_2O and FeO contents and low Na_2O and CaO values. Two rock samples have shown high Na_2O (up to 4.5 wt%) content, indicating that a sodic alteration may be locally preserved.

3. "Very altered" type (>3.5 wt% K_2O): is formed by K-feldspar - quartz ± Ca-amphibole ± cummingtonite ± plagioclase ± sericite ± epidote ± chlorite, with or without biotite, calcite, tourmaline and titanite. It is observed in the central part of the deposit, which is also the richest ore zone (Fig. 1). Microprobe analysis confirms the presence of Ca-amphiboles, mostly Mg-hornblende, with subordinate ferro-tschermakitic hornblende and ferro-hornblende. Fe-Mg-Mn amphibole, represented by cummingtonite, commonly replaces Ca-amphiboles. Plagioclase crystals, mainly of labradoritic composition, are extensively replaced by K-feldspar, which was identified as orthoclase. 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_2O values (up to 4.6 wt%), depletion of Na_2O and very low CaO contents.

Transitions between these alteration groups are observed and assemblages are pervasive. The chemistry of the analyzed amphibolites indicates that they are hydrothermally altered basalts with different types and degrees of alteration. The diagram $K_2O/(K_2O+Na_2O)$ vs. CaO discriminates basalts affected by alkali metasomatism and suggests a main alteration path (Fig. 2). Amphibolites taken from Lindenmayer (1990) were included in the data set for comparison purposes. They are "medium altered" rocks, which indicates that they also suffered alkali metasomatism. The forms of hydrothermal alteration displayed by the Salobo deposit are typical of most iron oxide (Cu-U-Au-REE) deposits, including Candelaria-Punta del Cobre (Marschik & Fontboté, 1996) and Olympic Dam (Hitzman et al., 1992) deposits.

4 DISCUSSION AND CONCLUSIONS

The alteration types described above characterize 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. It caused incipient Na-alteration, 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. "Very altered" rocks, which suffered intense potassic alteration, are spatially associated with the main ore zone, suggesting a relationship between alkali metasomatism and mineralization. Similarities in the ore mineralogy and chemistry, and in the hydrothermal alteration pattern suggest that the Salobo iron oxide Cu (-Au) deposit should be ascribed to the large class of iron oxide (Cu-U-Au-REE) deposits.

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