

**THE ROLE OF RESIDUAL 2:1 PHYLLOSILICATES IN LATERITIC
METALLOGENESIS: Ni AND Cu DEPOSITS IN SERRA DOS CARAJÁS,
BRAZILIAN AMAZONIA**

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ABSTRACT

In lateritic deposits, the upper levels of the weathering profile consist mainly of iron oxy-hydroxides and kaolinite-group minerals. However, if the parent rock contains 2:1 phyllosilicates, they can remain, although transformed, up to the most altered horizons, becoming in addition to the iron oxy-hydroxides efficient metal traps.

This article deals with two lateritic deposits formed under humid tropical climate conditions in Brazilian Amazonia. They are the Cu deposit of Salobo 3A and the Ni deposit of Vermelho, both containing the metals associated mainly with the two phases above mentioned. Partitioning of the metals among the phases in the mineralized horizons has been investigated through microchemical and X-ray diffractometric techniques. The iron oxy-hydroxides display a large range of crystallinity, being the transition metals preferentially associated with the less crystallized phases. The phyllosilicates are progressively transformed and enriched in the transition metals toward the most altered horizons. The presence of such phyllosilicates enhances the grade of the oxidized ore, but, on the other hand, can lead to difficulties in applying the hydrometallurgical techniques classically employed for the treatment of this type of ore.

RESUMO

Nos depósitos lateríticos, os níveis superiores do perfil de alteração consistem, principalmente, de óxi-hidróxidos de ferro e de minerais do grupo da caulinita. Entretanto, se a rocha-mãe contiver filossilicatos 2:1, estes podem permanecer, embora transformados, até os níveis mais alterados, constituindo, junto com os óxi-hidróxidos de ferro, armadilhas eficientes para os metais.

Este artigo trata de dois depósitos lateríticos formados sob clima tropical úmido, na Amazônia brasileira. São os depósitos de Cu do Salobo 3A e o depósito de Ni do Vermelho, ambos contendo metais associados, principalmente, às duas fases acima mencionadas. A partição dos metais entre as fases nos horizontes mineralizados foi investigada através de técnicas difratométricas e microquímicas. Os óxi-hidróxidos de ferro apresentam uma larga gama de cristalinidade, estando os metais de transição, preferencialmente, associados às fases menos bem cristalizadas. Os filossilicatos encontram-se progressivamente transformados e enriquecidos nos metais de transição em direção aos horizontes mais alterados. A presença desses filossilicatos melhora o teor do minério oxidado mas, por outro lado, pode causar dificuldades na aplicação das técnicas hidrometalúrgicas, classicamente utilizadas no tratamento desse tipo de minério.

INTRODUCTION

In humid tropical regions, the intensity of the weathering processes leads to the development of thick lateritic profiles that can be enriched in Ni, Co, Cr, Mn, Cu etc. In the upper horizons of these profiles, which represent the most evolved products of lateritisation, an essentially neoformed paragenesis prevails, formed by iron oxy-hydroxides and kaolinite-group minerals. Some transition metals, originally associated with the hypogene minerals, can be more or less retained by the iron oxy-hydroxides. The retention of such metals depends mainly on the sorption of the ion by the hydroxides. Ionic radius, charge and electronic configuration of the ion are important factors.

However, if the parent rock contains 2:1 phyllosilicates, some of them, although transformed, can remain in the profile, up to the upper horizons and incorporate the transition

elements. In this process, there is a broad conservation of the original crystal network with ionic substitutions in the interlayer sheet and in the 2:1 layer as well. Thus, in addition to iron oxy-hydroxides, phyllosilicates contribute to enhance the retention of transition metals in an environment specially favorable to intense leaching. As a consequence, the oxidized horizons become richer and more interesting for exploration. On the other hand, the distribution of the metal among different phases that are differentially susceptible to the extraction processes could be a problem for the establishment of ore dressing techniques.

This paper aims to examine and compare the case of two lateritic deposits, formed under the same climatic conditions, with mineralized horizons containing the transition elements partitioned between the iron oxy-hydrox-

ides and the phyllosilicates inherited from the parent rock. The examples are the copper deposit of Salobo 3A and the nickel deposit of Vermelho, both belonging to the "Carajás Mineral Province", Brazilian Amazonia.

REGIONAL CONTEXT

"Serra dos Carajás" is one of the most important Brazilian mineral provinces, known, above all, by its iron mines, but also including important deposits of Al, Mn, Ni, Au, Cu, etc. It is situated in the State of Pará, 500km south of the city of Belém (Fig.1). The region is dominated by plateaus, at altitudes between 400 and 700m, drained by the Itacaiunas river, a left affluent of the Tocantins river.

The climate of the area is typically tropical, with alternating seasons. There is a long humid season from November to May and a drier season from June to October. Mean annual rainfall is about 2200mm and mean annual temperatures range between 19 and 31°C. Vegetation is dominantly forest.

Geologically, the province belongs to the oriental part of the meridional Amazonian Craton. There is a granitic-gneissic Archean base-

ment (Xingu Complex), which is covered by the following Proterozoic units: Salobo-Pojuca Sequence, Grão-Pará Group, Rio Fresco Formation, Uatumã Group, Gorotire Formation and Tocantins Group (Hirata et al., 1982). Lateritisation has been pervasive, affecting all these units and is responsible for the formation of most of the ore deposits.

GEOLOGY OF THE DEPOSITS

The nickel deposit of Vermelho (Alves et al., 1986) lies 60km south-westward of the principal iron mines, and it is formed by lateritisation of a mafic-ultramafic massif that is interpreted as part of the greenstone belt sequences incorporated to the high grade terrains of the Xingu Complex. The massif is composed of two bodies, designated V1 and V2, formed by concentrically disposed units: gabbros, pyroxenites and serpentized peridotites/dunites. The mafic zones correspond to flat areas at altitudes of about 300-350m and their weathering products are a dark reddish brown argillaceous saprolite without nickel enrichment. The serpentized ultramafic rocks, in the center of the bodies at altitudes reaching 500m, are al-

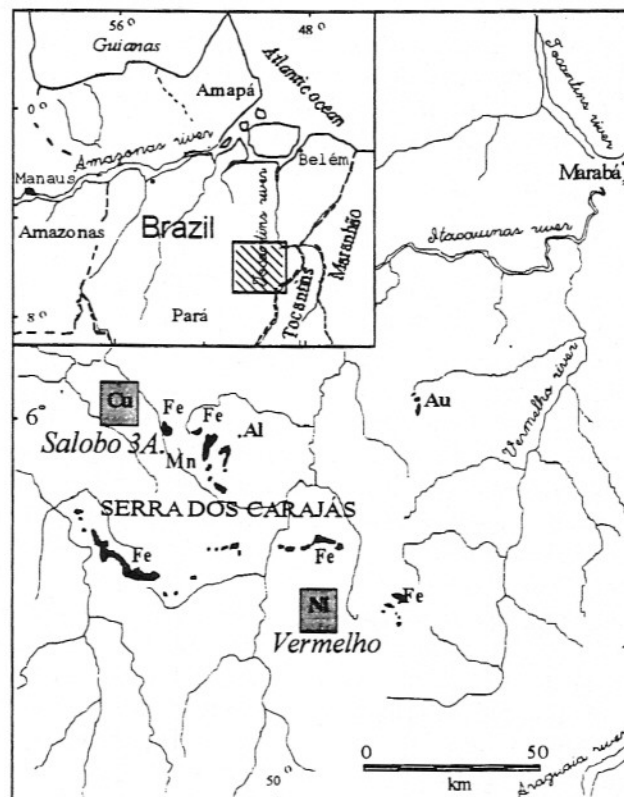


Figure 1 - Location map of Vermelho and Salobo 3A deposits.

most entirely covered by a thick siliceous cap. The rock is generally a serpentinite with typical mesh texture composed mainly of antigorite and chlorite, with chromite and magnetite in minor amounts. The weathering profile, overlying the serpentinite, contains horizons enriched in nickel. It is a classic example of a lateritic nickel deposit, totaling 40.10^6 t with 1.2 to 1.8% Ni on average.

The copper deposit of Salobo 3A (Amaral et al., 1986), situated 50km north-eastward of the large iron body, is included in the Salobo-Pojuca Sequence, originally volcano-sedimentary rocks, but now metamorphosed to the amphibolite facies. In the vicinities of the deposit, the lithological units consist of lower gneisses, schists, banded iron formation, upper gneisses and quartzite. This sequence is almost vertical, outcropping at altitudes of about 500m. The primary mineralization is made up of disseminated sulfides, mainly confined within the schists at the contact with the lower gneisses. The more abundant ore minerals are bornite and chalcocite with subordinate chalcopyrite, molybdenite, gold and silver. Capping the primary deposit is a weathering blanket up to 100m thick - the "altered ore"-, composed, mainly, of goethite and clay minerals. The resources add 10^9 t of sulfide ore with 0.84% Cu and 10^8 t of altered ore with 0.75% Cu.

THE VERMELHO ALTERED ORE

The weathering profile

Despite local variations due to the heterogeneity of the parent rock, a typical profile for the deposit can be outlined (Bernardelli et al., 1983). From bottom to top, it can be subdivided into the following horizons: a fresh to slightly altered rock, a coarse saprolite, a ferruginous saprolite and a lateritic soil. Figure 2 shows the profile with the different horizons and the average Ni grades of the ore. Only the two intermediate horizons are considered nickel ore, corresponding to the classically described silicated and oxidized ores, such as, for instance, in the nickeliferous laterites of New Caledonia (Trescases, 1975). However, for the purpose of this paper, both mineralized horizons are considered together as "altered ore" in a broad sense.

The fresh to slightly altered rock is made up of mainly three generations of serpentine associated with finely grained magnetite and Cr-spinels, generally fractured and crisscrossed

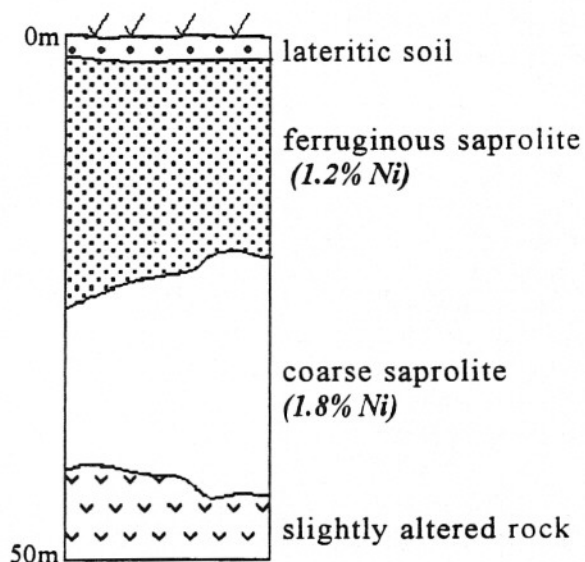


Figure 2 - Typical weathering profile of the Vermelho deposit.

by serpentine. Chlorite occurs as irregular agglomerates, forming a network crossing serpentine or as a rim around chromite crystals. A change in the coloration of the serpentine crystals toward brownish tones and an enhancement in birefringence are the first signs of the weathering action. Table 1 shows the average chemical composition for the different horizons of the typical profile in V1 and indicates that the fresh to slightly altered rock contains high amounts of MgO, and NiO grades between 0.33 to 0,64%. It is the protore of the deposit.

Gradually, the rock changes into a coarse saprolite becoming softer and friable, but preserving the original parent rock texture. This horizon still contains serpentine and chlorite, already transformed and somewhat dissolved. New phases gradually appear, such as quartz, goethite, ferruginous amorphous compounds and small amounts of smectite. Only exceptionally, this mineral is abundant in certain horizons of the profile. The chemical composition (Table 1) reflects these transformations: MgO contents decrease and Fe_2O_3 contents increase. NiO contents are on average 1.8%, but, locally, can attain up to 4.5%.

The transition to the ferruginous saprolite is marked by a strong decrease in MgO contents (Table 1) as a consequence of the almost total dissolution of serpentine. It is a friable and low density material with poorly preserved original textures made up, essentially, of goethite, but containing also chlorite, quartz and spinels. The NiO contents average 1.7%.

Table 1 - Mean chemical composition (wt %) of the different weathering horizons at the Vermelho deposit.

VI	SiO ₂	MgO	Fe ₂ O ₃	Al ₂ O ₃	Cr ₂ O ₃	MnO ₂	NiO	CoO	CuO	LOI
FR (n=3)	33,18	35,93	11,69	1,05	1,36	0,10	0,33	0,01	0,00	14,40
SAR (n=7)	36,43	31,17	13,86	1,66	0,80	0,16	0,64	0,02	0,01	15,73
CS (n=12)	35,64	22,07	24,82	1,71	1,13	0,21	1,78	0,03	0,01	13,39
FS (n=11)	11,34	3,36	65,74	3,85	2,98	0,96	1,71	0,16	0,02	9,40

n = number of samples

FR = fresh rock

SAR = slightly altered rock

CS = coarse saprolite

FS = ferruginous saprolite

The lateritic soil that caps the profile is rich in goethite and quartz, with NiO contents always under 1%, being, therefore, considered a barren horizon.

Distribution of Ni among phases in the altered ore (Table 2)

The main nickel-bearing phase at the bottom of the profile is serpentine; upwards smectite, chlorite and goethite become also important (Carvalho e Silva & Oliveira, 1995). Whenever rich in Ni, serpentine crystals are brownish. Maximum content is 5,2% NiO, but on average serpentine contains 2.5% NiO.

Smectites are neoformed minerals, probably derived from pyroxenes. They have been identified as nontronites, according to X-ray diffraction and infrared spectroscopic data. NiO contents may attain up to 9 % (Carvalho e Silva, 1994).

Chlorites occur all along the weathering profile as a residual mineral, but progressively transformed upwards. It has been possible to follow their chemical evolution from the fresh rock to the oxidized horizons (Table 3). NiO contents increase gradually, from 0.1% in the fresh rock, attaining up to about 18% in the more altered horizons (Fig. 3).

Goethite is a neoformed mineral, derived mainly from the hydrolysis of serpentine, with

Table 2 - Nickel distribution among phases in the altered ore (microprobe analyses).

Ni-bearing minerals	NiO (weight %)	
	average	maximum
serpentine	2,5	5,2
smectite	8,0	9,0
chlorite	8,3	18,0
goethite	1,3	1,8

leaching of Mg and Si, and relative concentration of Fe. NiO contents range between 0.9 to 1.8%, averaging 1.3%. X-ray diffraction patterns show broad and ill-defined peaks pointing out to poor crystallinity. A significant positive correlation has been found between the b cell parameter, measured for goethite, and the contents of NiO in samples of the oxidized ore (Fig. 4). These data suggest that Ni must be, at least partially, structurally incorporated into goethite, behaving similarly to Mn (Stiers & Schwertmann, 1985), and Cr (Schwertmann et al., 1989) in synthetic goethites.

THE SALOBO 3A ALTERED ORE

The weathering profile

The primary ore of Salobo 3A is an iron-rich schist with variable proportions of biotite, amphiboles, garnets, magnetite and quartz, with copper sulfides disseminated in millimetric to centimetric levels, concordant with the rock structures.

The weathering blanket, about 60m thick, is just slightly less enriched in Cu than the primary ore. The typical weathering profile (Fig. 5) presents from the fresh rock upwards a transitional layer, an isalteritic saprolite, a fine grained alloteric saprolite and a partially allocthonous lateritic soil as a cover (Toledo-Groke, 1986). The altered ore includes the isalteritic and the alloteric horizons.

The transitional layer, thin and discontinuous, is characterized by a millimetric to centimetric fracture network cutting the slightly altered rock, filled with malachite and green smectites. The CuO contents vary according to the density of the fracture network, but is generally not very high, about 0.3% (Table 4). The alteration of sulfides proceeds to comple-

Table 3 - Mean chemical composition (microprobe data wt %) of chlorites from different horizons of the weathering profile.

	SiO ₂	Al ₂ O ₃	FeO	Fe ₂ O ₃	Na ₂ O	MgO	K ₂ O	CaO	TiO ₂	Cr ₂ O ₃	MnO	CoO	NiO
FR (n=2)	32,29	11,56	2,06	---	0,02	31,91	0,04	0,01	0,05	0,44	0,00	0,02	0,15
SAR (n=15)	33,49	11,17	4,95	---	0,10	31,31	0,25	0,07	0,23	0,51	0,08	0,02	0,88
CS (n=4)	34,26	11,17	5,30	---	0,14	30,48	0,16	0,09	0,11	0,31	0,04	0,09	2,33
FS (n=7)	34,14	13,71	---	4,67	0,08	19,03	0,12	0,17	0,34	0,41	0,08	0,27	11,66

n = number of samples
 FR = fresh rock
 SAR = slightly altered rock
 CS = coarse saprolite
 FS = ferruginous saprolite

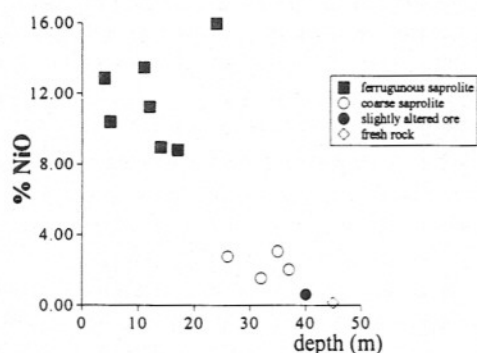


Figure 3 - Ni contents in chlorites (microprobe analyses) from the different horizons of the Vermelho deposit.

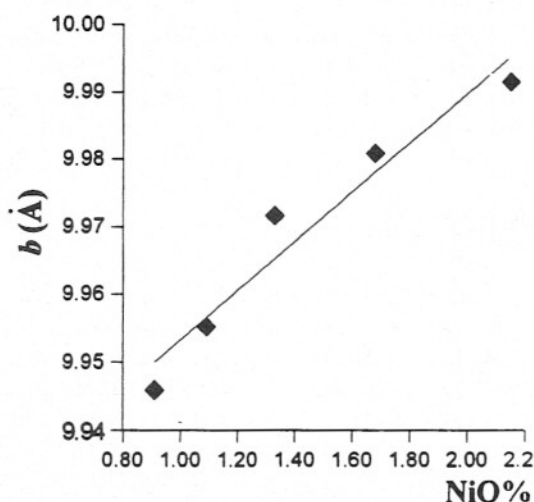


Figure 4 - Unit-cell *b* dimension as a function of %NiO. (Ni contents from bulk chemical analyses of ferruginous saprolite).

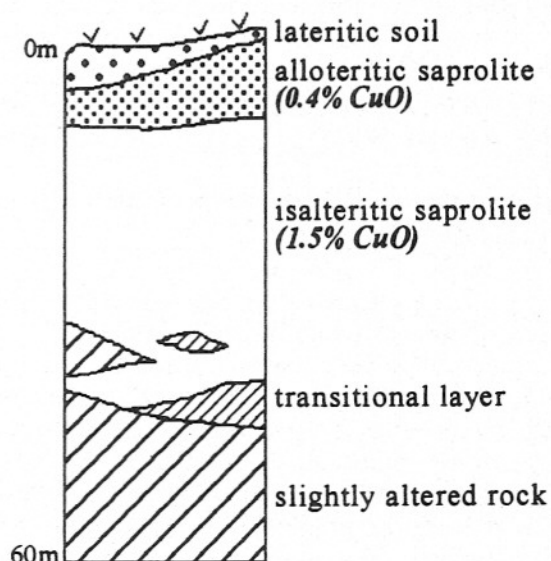


Figure 5 - Typical weathering profile of the Salobo 3A deposit.

tion in this horizon, so they are not found anymore upwards.

Though friable, the isalteritic saprolite (mean thickness about 40m) preserves the textures of the parent rock. Amphiboles and garnets are altered pseudomorphically into ferruginous products. Biotites begin initially to change towards an interstratified biotite-vermiculite and then to vermiculite that can finally evolve to smectite and kaolinite. Quartz and magnetite remain residually in this horizon. Malachite dissolves and some accumulations of cryptomelane begin to form. In this horizon, the CuO content is approximately 1.4% (Table 4).

Table 4 - Mean chemical composition (wt %) of the different weathering horizons at Salobo 3A.

	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	MnO	Na ₂ O	K ₂ O	CaO	CuO	TiO ₂	LOI
FR (n=35)	38.18	42.32	9.47	2.03	0.64	0.52	1.71	1.31	1.27	0.49	0.54
TL (n=9)	42.70	33.25	11.82	3.30	0.45	0.95	2.30	1.06	0.34	1.25	1.48
IS (n=146)	35.10	38.05	11.66	1.39	0.59	0.06	1.49	0.29	1.44	0.87	7.55
AS (n=23)	29.50	39.65	15.72	0.14	0.71	0.07	0.16	0.11	0.35	0.58	10.63

n = number of samples

FR = fresh rock

TL = transitional layer

IS = isalteritic saprolite

AS = alloteritic saprolite

The alloteritic saprolite, about 10m thick, does not preserve the original textures anymore. It is composed of residual primary minerals (quartz and magnetite), transformed primary minerals (vermiculite changing into kaolinite) and neoformed minerals as goethite and cryptomelane. Here, the CuO contents decrease, amounting in average to 0.4% (Table 4).

The soil layer covering the profile is thin and partially colluvial, composed essentially of kaolinite and iron oxy-hydroxides. CuO contents are very low.

Distribution of Cu among phases in the altered ore (Table 5)

Cu is basically associated with three kinds of phases (Toledo-Groke, 1986):

(a) silicated phases: products derived from the transformation of biotites, mainly interstratified biotite-vermiculite minerals and vermiculite containing up to 11.4% CuO (average 7%), small amounts of brown smectites derived from the phyllosilicates with up to 6% CuO (average 3%), and green smectites found in the fissures at the bottom of the profile with up to 5% CuO (2% on average);

(b) ferruginous phases: iron oxides and hydroxides presenting a variable degree of crystallinity, with up to 5% CuO (average 1.5%);

(c) other phases: cryptomelane-type minerals containing up to 25% CuO and malachite.

Biotites, originally depleted in copper, in-

corporate this element during the weathering transformations (Table 6). Figure 6 shows a negative correlation between K and Cu in fresh and altered biotites, indicating that the Cu incorporation occurs according to the intensity of weathering (Ildefonse et al., 1986). Cu occurs also associated with the ferruginous compounds that are present along cleavage planes, being certainly outside of the crystalline structure. The transformation of vermiculite into kaolinite is accompanied by loss of Cu (Toledo-Groke et al., 1989 a and b).

The ferruginous phases occur in the ore either replacing pseudomorphically garnets and pyroxenes, or as a secondary plasma associated to kaolinite with variable contents of CuO, from 0.7 to 5.5% (Toledo-Groke, 1986). Diffractometric, microanalytical and selective extraction studies have shown that the iron oxy-hydroxides are present in a large range of crystallinity and that Cu is rather associated to the poorly crystallized phases (Veiga et al, 1991).

The manganese products belong to the hollandite group and as well as malachite were formed as a result of a transfer of solutions through a fissure system. Although not important as Cu-bearing phases due to their low concentrations in the ore, these products are the richest Cu phases.

DISCUSSION

Lateritic metallogenesis is a process of ore formation that takes place essentially through the retention of metals in the weathering profile, as a result of the intense leaching of the other elements present in the protore. The concentration of metals results either from the accumulation of metal-bearing minerals resistant to weathering as in the case of Fe, Nb and P lateritic ores, or through the incorporation of the metal by transformed primary phases or secondary neoformed phases, as in the case of

Table 5 - Copper distribution among phases in the altered ore (microprobe analyses).

Cu-bearing minerals	CuO (weight %)	
	average	maximum
vermiculite/biotite-vermiculite	7	11.4
brown smectite	3	6
green smectite	2	5
Fe oxy-hydroxides	1.5	5
cryptomelane	10	25

Table 6 - Chemical composition (microprobe data wt %) of biotites and weathered biotites of the Salobo 3A deposit.

		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	MnO	TiO ₂	CuO
Biotite (average n = 20)		33.45	13.30	34.72	0.00	0.11	8.05	1.82	0.12	1.09	0.00
Weathered biotite (range)	<i>min</i>	32.38	11.50	11.28	0.02	0.00	0.58	1.27	0.00	0.31	0.00
	<i>max</i>	40.69	30.33	32.15	0.26	0.16	4.44	3.19	0.12	1.19	11.40

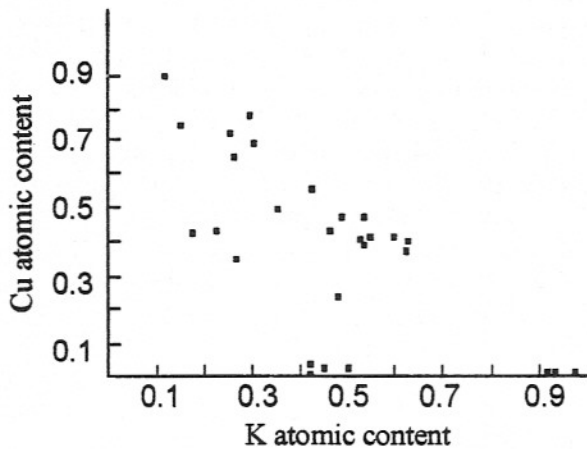


Figure 6 - Correlation between Cu and K (atom contents on a O₁₀(OH)₂ basis) in weathered biotites throughout the profile (microprobe analyses).

Ni, Co, Mn and Al.

The deposits discussed in this paper belong to the second category, being made up of an alteration blanket in which most evolved horizons, the main neoformed phase, is goethite. In both cases, the parent rock contains phyllosilicates of primary origin as the biotite in the Salobo 3A deposit and of hydrothermal origin as the chlorite in the Vermelho deposit. Despite the extreme conditions of weathering prevailing in the Amazonian region, these phyllosilicates, although transformed, remain even in the most altered horizons of the profile, trapping Cu and Ni. Neoformed minerals as smectites and manganese oxides are also formed in such deposits incorporating the metals, but are transitory phases of restricted occurrence in the profile and generally without major economic importance.

The transformation and concomitant incorporation of Cu or Ni is similar in both cases. Biotites are transformed into interstratified

biotite-vermiculite minerals and vermiculite remains in the profile, whereas other primary silicates of the protore, amphiboles and garnets, are already totally altered. However, in the upper horizons of the profile, they are not stable anymore, changing into kaolinite, releasing Cu. The process is similar for chlorites. Nevertheless, they are more resistant to weathering, being found even at the top of the profile, despite partially dissolved along the crystal discontinuities.

The iron oxy-hydroxides are the other metal-bearing phases in the upper levels of both profiles. Their composition is almost entirely goethitic, and yet with lower Ni contents than the phyllosilicates, they are the most important metal-bearing phases, due to their greater abundance. Veiga et al. (1991) showed that the iron oxy-hydroxides account for 80% of total Cu in the altered ore of the Salobo 3A deposit. As to the Vermelho deposit, the knowledge about the mineralogical composition of the ore at the scale of the deposit does not allow this kind of estimate. However, it can be said that, although goethite is also the dominant Ni phase; at least locally, chlorite represents about 20% of the ferruginous saprolite, accounting in this case for up to 50% of the total Ni in the oxidized ore.

The role of the iron oxy-hydroxides as efficient scavengers of base metals is well known and generally attributable to a high degree of structural imperfection (Forbes et al, 1976, Schellmann, 1978, Schwertmann et al., 1989, Gerth, 1990; Enzweiler & Joekes, 1991). The proposed models for the incorporation of metals are mainly the isomorphic substitution and the adsorption phenomena simultaneous with the precipitation or colloidal coagulation, when goethite would have high surface activity. In the case of Vermelho, there is no conclusive evidence concerning this matter, lacking investigations about the iron amorphous

phases. Nonetheless, there are indications that at least part of the Ni would be incorporated in the poorly-crystallized goethite. At Salobo 3A, there is an important amount of poorly-crystallized iron oxy-hydroxides to which Cu would be adsorbed through the mechanism of adsorption-precipitation.

From the metallogenetic point of view, the existence of 2:1 phyllosilicates inherited from the protore and transformed during weathering, has an important role in the enhancement of average grades in the altered ore of the Salobo 3A and Vermelho deposits. Due to their resistance to weathering, these metal-bearing phyllosilicates are responsible for higher grades than the ore would have if made up only of iron oxy-hydroxides, of lower capacity of metal retention. On the other hand, the incorporation of the transition elements by the phyllosilicates could be itself a factor in their higher stability, favoring their subsistence in a strongly leached environment, not at all suitable to the persistence of primary silicates.

Comparing the two cases, the effect of enhancement of the ore grades is more conspicuous for Ni because chlorite remains even in the most altered horizons, and is progressively richer. As for Cu, there is a loss in the upper horizons of the profile caused by the change of vermiculite into kaolinite. This is certainly due to the higher stability to weathering of chlorite than vermiculite, but can also

be attributable to the different geochemical behavior of Ni and Cu, the latter moving more readily to the iron association than Ni. In the lateritic profile of Ora Banda, Western Australia, formed from ultramafic rocks with Cu and Ni, this tendency is well demonstrated by the association of Ni with neoformed silicates in the same horizon of the profile where Cu is associated with the iron oxy-hydroxides (Smith, 1977).

For lateritic ores like those discussed in this paper, the establishment of metallurgical processes must take into consideration that the metal to be extracted is bound to two different phases by strengths of different order of magnitude. In the case of acid leaching, a classical technique used for this kind of ore, it is possible to remove through a rather moderate attack Cu and Ni associated with the iron phases. However, the same attack may be inefficient for the metals associated with the phyllosilicates, as well as in the case of biotites (Veiga et al., 1991), as for chlorites which cation exchange capacity is always very low (Grim, 1962).

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REFERENCES

- AMARAL, E.V.; FARIAS, N.F.; SAUERESSIG, R.; VIANA JR., A.; ANDRADE, V.L.L. (1988) Jazida de cobre Salobo 3A e 4A, Serra dos Carajás, Pará. In: Schobbenhaus, C. & Coelho, C.E.S. (eds.) Principais depósitos minerais do Brasil, DNPM, Brasília, 3:43-53.
- ALVES, C.A.; BERNARDELLI, A.L.; BEISIEGELGEL, V. de R. (1986) A jazida de níquel do Vermelho, Serra dos Carajás, Pará. In: Schobbenhaus, C. & Coelho, C.E.S. (eds.) Principais depósitos minerais do Brasil, DNPM, Brasília, 2:325-334.
- BERNARDELLI, A.L.; MELFI, A.J.; OLIVEIRA, S.M.B. de; TRESCASES, J.J. (1993) The Carajás nickel deposit. In: Melfi, A.J. & Carvalho, A. (eds). Laterisation processes: Proceedings at the II Int. Sem Lat. Proc. IAGUSP, São Paulo, p.107-118.
- CARVALHO E SILVA, M.L.M. de (1994) Cristaloquímica dos minerais do minério laterítico de níquel: o exemplo do Vermelho, Serra dos Carajás (PA). PhD Thesis, IG University of São Paulo, São Paulo, 88p.
- CARVALHO E SILVA, M.L.M. de & OLIVEIRA, S.M.B. de (1995) As fases portadoras de níquel do minério laterítico do Vermelho, Serra dos Carajás (PA). Rev. Bras. Geoc., São Paulo (submitted).
- ENZWEILER, J. & JOEKES, I. (1991) Adsorption of colloidal gold on colloidal iron oxides. J. Geoch. Expl. 40:133-142.
- FORBES, E.A.; POSNER, A.M.; QUIRK, J.P. (1976) The specific adsorption of divalent Cd, Co, Cu, Pb and Zn on goethite. J. of Soil Sc. 27:154-166.
- GERTH, J. (1990) Unit-cell dimensions of pure and trace metal-associated goethites. Geochim. Cosmochim. Acta 54:363-371.
- GRIM, R.E. (1962) Applied Clay Mineralogy. Mc Graw-Hill Book Co., Inc, USA, 246p.
- HIRATA, W.K.; RIGON, J.C.; CORDEIRO, A.A.C.; MEIRELES, E. de M. (1982)

- Geologia regional da província mineral de Carajás. In: Simpósio de Geologia da Amazônia, 1, Belém, 1982, Anais, 1:100-110.
- ILDEFONSE, P.; MANCEAU, A.; PROST, D.; TOLEDO-GROKE, M.C. (1986) Hydroxy-Cu-vermiculite formed by the weathering of Fe-biotites at Salobo, Carajas, Brazil. *Clays and Clay Min.*, **14**(3):338-345.
- PARISOT, J.C. (1989) L'altération latéritiques des protores cuprifères au Brésil. PhD Thesis University of Poitiers, 177p.
- PARISOT, J.C.; CREACH, M.; MELFI, A.J.; NAHON, D.; TOLEDO-GROKE, M.C.; TRESCASES, J.J. (1990) Dispersão e acumulação do cobre nos produtos do intemperismo de depósitos cupríferos do Brasil. *Bol. Inst. Geol., São Paulo*, **11**(2):21-33.
- SCHELLMANN, W. (1978) Behavior of Ni, Co and Cr in ferruginous lateritic nickel ore. *Bull. BRGM, Section II*, **3**:275-282.
- SCHWERTMANN, U.; GASSER, U.; STICHER, H. (1989) Cr for Fe substitution in synthetic goethites. *Geoch. Cosmoch. Acta* **49**:1909-1911.
- SMITH, B.H. (1977) Some aspects of the use of geochemistry in the search for nickel sulphides in lateritic terrain in Western Australia. *J. Geoch. Expl.* **8**:259-281.
- STIERS, W. & SCHWERTMANN, U. (1985) Evidence for manganese substitution in synthetic goethite. *Geochim. Cosmochim. Acta* **49**:1909-1911.
- TOLEDO-GROKE, M.C. (1986) Intemperismo das rochas mineralizadas em cobre do Salobo 3A, Serra dos Carajás. Mecanismos de alteração dos minerais primários e localização do cobre nos produtos secundários. PhD Thesis IG University of São Paulo, São Paulo, 173p.
- TOLEDO-GROKE, M.C.; BOULANGÉ, B.; PARISOT, J.C.; MELFI, A.J., (1989a) Altération des biotites dans les roches cuprifères de Salobo 3A, Serra dos Carajás (Brésil) I. Formation des phyllosilicates secondaires. *Geodynamique* **4**(2):135-150.
- TOLEDO-GROKE, M.C.; PARISOT, J.C.; MELFI, A.J.; BOULANGÉ, B. (1989b) Altération des biotites dans les roches cuprifères de Salobo 3A, Serra dos Carajás (Brésil) II. Association du cuivre aux phyllosilicates secondaires. *Geodynamique* **4**(2):151-160.
- TRESCASES, J.J. (1975) L'évolution géochimique supergène des roches ultrabasiqes en zone tropicale. Formation des gisements nickelifères de Nouvelle Calédonie. *Mémoire ORSTOM*, **78**, 280p.
- VEIGA, M.M.; SCHORCHER, H.D.; FYFE, W.S. (1991) Relationship of copper with hydrous ferric oxides, Salobo, Carajás, PA, Brazil. *Ore Geol. Rev.* **6**:245-255.