Proceedings of the 2nd International Seminar on lateritisation processes, Sao Paulo; July 4-12, 1982. ed by J Melfi and A. Carvalho

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THE CARAJÁS NICKEL DEPOSITS*

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ABSTRACT

The nickeliferous deposit - Vermelho - of Serra dos Carajás resulted from prolonged chemical weathering of Precambrian ultramafic rocks. The ultramatic massif is made up of a serpentinic core with intercalated pyroxenites, surrounded by basic rocks. It emerges from the plain as an elevation 250 m high and 4 km^2 in area.

Several types of weathering profiles can be distinguished according to topographic position. On the tabular top the profile is very thick (~ 100 m) and consists, from bottom to top, of coarse saprolite, silicified ferruginous saprolite or silcrete and a thin larger horizon of lateritic soil. The silcrete is the product of silicification of the ultramafic rock without destruction of the original structure. For mining purposes, the silcrete is poor in Ni (0.5 - 0.6%), except in less silicified pockets where the material (ferruginous saprolite or, less frequently, coarse saprolite) reaches 1 to 5% Ni.

On the slopes the profile is thinner and the silcrete is absent. In the ferruginous saprolite horizon, composed essentially of goethite, Ni ranges from 0.9 to 2%, from top to bottom. In the coarse saprolite horizon the nickel content is more irregularly distributed, varying from 0.3 to 3%; the highest values are related to the less altered material (MgO < 25%).

In the sadle valley of the northern flank of the massif, the alterites rest on pyroxenite. The alteration process has led first to the formation of nontronite and later goethite. Because of low Ni values in the fresh rock (< 0.1%) these alterites have no economic interest.

The lateritisation processes in action on the Vermelho deposit were intense and have resulted in the formation of a ferruginous saprolite horizon thicker and more evolved than those of other Brazilian deposits. These processes began in Tertiary, after the silicification event, and continue till today. Post-Tertiary erosion has had no influence in the formation of the deposit.

* This research has been carried out with Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Financiadora de Estudos e Projeto (FINEP) financial support.

INTRODUCTION

The nickel deposit of Vermelho, discovered at the beginning of the seventies by the DOCEGEO geologists presents a reserve of 40 millions tones of ore with 1.56% Ni (Bernadelli, 1981).

The climate of the Serra dos Carajás region, with equatorial characteristics, is the one responsible for the important development of a ferruginous level, much more significant than those in other Brazilian lateritic deposits. However, despite this abnormal development, the most interesting nickel concentrations are associated to a silicated ore, which corresponds to a coarse saprolite.

Aiming to characterize the mineralogical and geochemical evolution of the facies that constitutes the alteration profiles of Vermelho, studies have been made in about 20 profiles situated in 3 topographic sequences developed on serpentinites and pyroxenites.

The results allowed the discussion of the main aspects connected with the deposit genesis, the dynamic behaviour of the elements (Si, Fe, Mg, Al, Cr and Ni) in the different alteration facies and the position of that occurrence in relation to other Brazilian deposits.

GEOGRAPHIC SITUATION

The Vermelho deposit is located in the Distrito Mineiro de Carajás, in the State of Pará, at the Oriental Amazon, being around 150 km distant from Marabá and 550 km from Belém, the capital of the State (Figure 1).

The region climate is warm and humid, with a little pronounced dry season. The average annual rainfall is around 2000 mm, 90% of which being concentrated between October and May. The temperature varies between 18° and 30°C. The average of the coldest months is 21°C and the average of the warmest months is 26°C. The vegetation is a transition between equatorial forest and savannah.

The mineralized area relief is formed by two small serpentinite hills, locally named V1 and V2, which emerge from a plane 300 m high correlated to the "Velhas" levelling surface. The tops present altitudes from 450 to 500 m. The two small hills are lined in the E-W direction and their approximate dimensions are 2.5 x 1.5 km (V1) and 1.5 x 0.5 km (V2).

GEOLOGY

The serpentinite bodies V1 and V2 are part of a basic-ultrabasic massif, prolonged in the NE-SW direction, being 2.5 km large and a minimum 5 km long (Figure 2). This massif is fitted in the granitic rocks of the Xingu Complex, over than 2 b.y. old and is part of an important basic-ultrabasic bodies alignment which extends along 50 km.

The fine to medium granulation serpentinite is a product of the dunites and peridotites hypogene alteration. It is a dark green to black rock, which density is around 2.5. On the microscope, it shows a serpentine network (serpentine I) whose nuclei are seldom

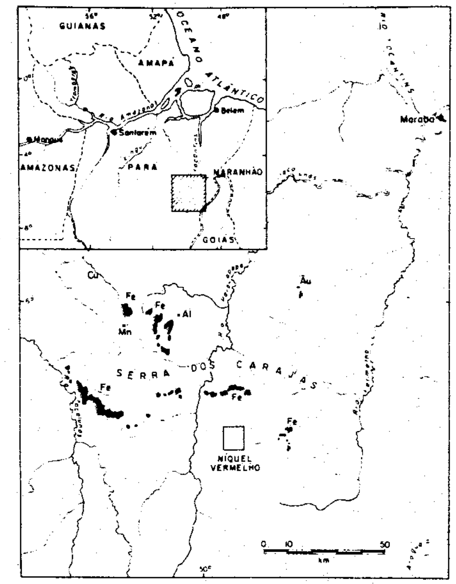

FIG. 1. Map showing the localization of the study area.

occupied by olivine rests, and generally by less well crystallized serpentine. Between the two layers that form the serpentine I network, magnetite grains are lodged. The serpentine can still appear in 2 ways: as veins cutting the rock (serpentine III), in association with brucite and with a hydrated carbonate of the hydrotalcite-pyroaurite group, or substituting pyroxene crystals (bastite). The chlorite is associated with serpentine in isolated crystals dispersed throughout the rock, or surrounding and cutting the chromite crystals. It can also occur in the form of small pseudomorphic grains on the serpentine or pyroxene, or in veins cutting the rock. In some samples the flogopite and vermiculite presences have been registered. This mineralogical assemblage is characteristic of late transformations at low temperatures.

The basic zones occur in the massif northern, southern and central part (Figure 2) and they are formed by gabbros and mainly by pyroxenites. The pyroxenite lenticular intercalations are common in the serpentinitic body. In the deposit V1 northern side, an expressive pyroxenite lent crops out. In a general way, the basic rocks correspond to zones with a lowered relief: the 3 main zones are raised to the "Velhas" surface level, while the pyroxenite to a suspended valley in massif V1. The pyroxenite is a green rock composed, predominantly, by orthopyroxenite of the hyperstene-bronzite series and also by serpentine, talc, amphibole and chlorite. Amphibolitized clinopyroxene can occur associated to this rock and in transition to the gabbro plagioclases.

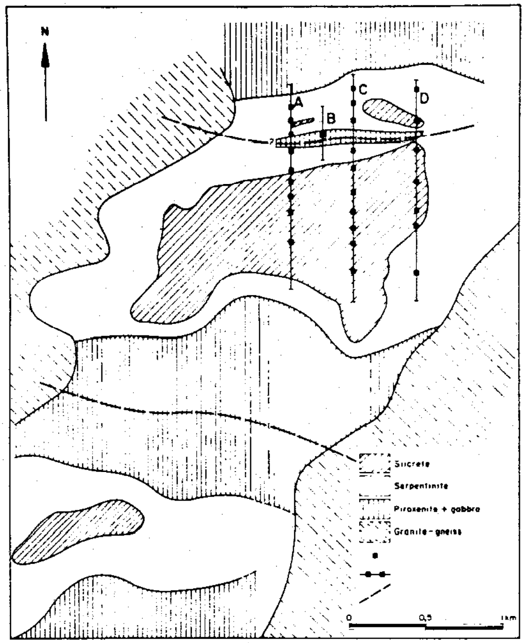

FIG. 2. Geological Map of the Nickel Deposit of Carajãs showing the location of the sampled profiles (A, B, C and D).

The serpentinite small hill tops are covered by a silcrete layer, which can overreach 50 m thickness.

THE ALTERATION PROFILES

The study of the alteration profiles disposed in 3 topographic sequences (A, C, D, on Figure 2) carried out through wells and probings allowed the characterization of the spacial distribution of the different alteration facies (Figure 3).

Profiles on serpentinite

The serpentinite alteration "profile type" occurs on the elevation tops, under a thick cover of silcrete.

Gradually, the <u>fresh rock</u> changes into <u>partially altered rock</u>, with a density decrease attaining 2.2 values, and changing colour to grayish tones. This level presents a

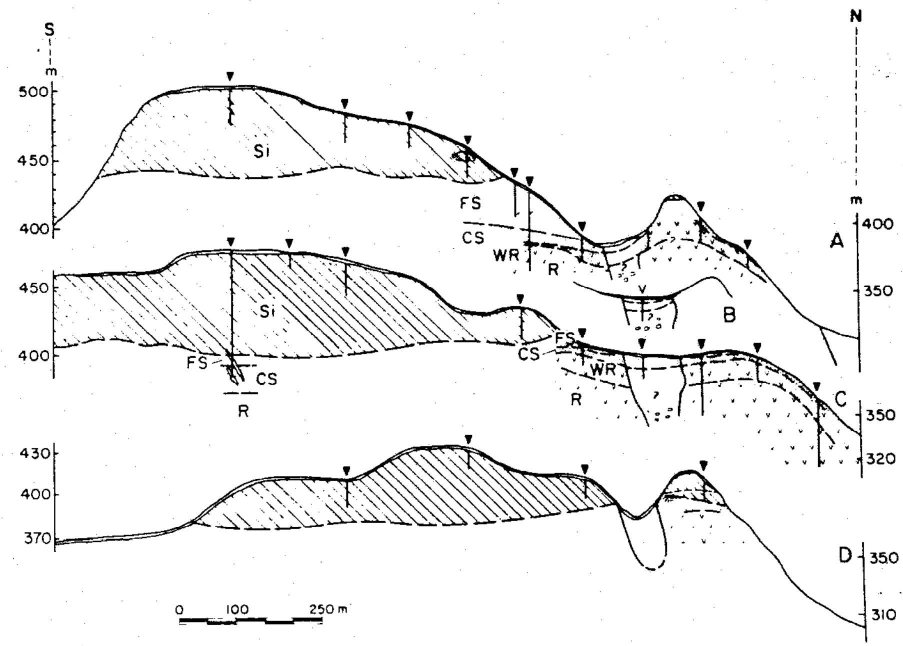

FIG. 3. Longitudinal sections showing the distribution pattern of several lateritic ore facies of Carajãs (Si = silcrete; FS = ferruginous saprolite; CS = coarse saprolite; WR = weathered rock and R = rock.

thickness that varies from a few meters up to 15 m.

With the progressive density and cohesion decrease, this facies evolves into <u>coarse saprolite</u>, yellow, medium density around 1.6 and thickness of about 10 m. Just as in the partially altered rock, the original rock structure is preserved. The transformation from the partially altered rock into saprolite starts along the fractures, penetrating in the fresh rock interior, and finishing off topwards the profile.

The <u>ferruginous saprolite</u> dominating the profile superior levels presents a yellow-orange colouration and a density around 1.0. The thickness of this horizon, which can be absent in some profiles, varies a lot, attaining locally values around 30 m.

In all the profiles, there are from the fresh rock to the ferruginous saprolite a progressive decrease of density, cohesion, granulometry and MgO content.

The <u>silcrete</u> occurs above the 380 m quota in the eastern section and 440 m in the western section. It is made up of a remarkable accumulation of silica blocks immersed in a ferruginous matrix. These blocks results from the serpentinite epigenesis by a microcrystalline quartz and chalcedony, preserving perfectly the original rock structure. When achieved, the process leads to the silexite formation; otherwise it let nuclei and pockets of rock now altered in ferruginous saprolite, with disturbed structure. This fact indicates that the silicification preceeded the lateritisation. Clear and well crystallized quartz veins cut this whole level, showing silica dissolution and reprecipitations.

Below 380/440 m, the profiles have no silcrete and are increasinly thinner towards the foot-hill, where the slopes are steeper.

When the slopes are not too steep, a thin layer (0-2 m) of a red soft laterite, covers the silcrete or the saprolite. This facies is partially colluvionar made up of ferruginous concretions and remains of silicified rock. The formation of a ferruginous crust in this laterite is not an expressive phenomenon in Vermelho.

Profile on the pyroxenite

The pyroxenite alteration "profile type" occur in the suspended valley in the northern side of the V1 deposit, and is very different from the one previously mentioned. A coarse dark green saprolite with around 10 m thickness occur over the fresh rock. Towards the top this saprolite exhibit a transition to a light green brown clayey saprolite. The thickness of this horizon ranges from 5 to 10 m. A dark red ferruginous level can occur at the profile upper part.

MINERALOGICAL EVOLUTION

Hypogene transformations

In the alteration profile roots, there are rocks already transformed by processes probably related to serpentinization. So, for dunites and peridotites the transformation from olivine into serpentine and magnetite together with brucite and carbonate suggests lower temperature alteration. The serpentine showing bastite shape seems to be formed from the pyroxene (probably clinopyroxene) which also presents a marked tendency to change into chlorite.

Concerning the pyroxenites, besides the orthopyroxene occur talc, amphibole, chlorite and serpentine, all hydrated minerals formed under low temperatures conditions. They probably originated from hydrothermal alteration of the orthopyroxene itself or of a clinopyroxene from which there are no traces anymore.

Supergene transformations

The olivine, present in small quantity in the fresh rock, is one of the first minerals to be altered. It dissolves leaving holes often filled up with amorphous iron hydroxides, which evolve into goethite. The iron left by the olivine dissolution can still be deposited as films on the fresh serpentine fibers.

For the serpentine, the alteration rate depends on the crystallinity degree. Thus, serpentine II is the first to evolve, producing an amorphous ferruginous material. The serpentine I and the bastite start to alter themselves later on, throughout a process that seems to lead to a vermiculitisation or a chloritization, as indicated by the crystals birrefringence increase. In the most weathered facies, this material is dissolved leaving behind a residue of amorphous iron hydroxides. Finally, the serpentine III, a well crystallized mineral that has less iron than the other varieties, is also dissolved leaving no residue.

The goethite crystallized from the amorpho-ferruginous material changes into hematite by dehydratation.

The chlorite is more resistent to alteration, remaining nearly intact up to the ferruginous saprolite horizon. Nevertheless, in the interlayer space there is a green micaceous mineral, which probably represents the chlorite itself with a more ferruginous composition.

The vermiculite, like the chlorite, evolves to a green "chlorite", which remains up to the ferruginous saprolite horizon. Both minerals seems to be dissolved, since they are rarely found in the red laterite.

The opaques, magnetite and chromite, are concentrated residually in the more weathered levels. They show little modifications during the alteration process: the magnetite is coated by an oxidised film and the chromite shows dissolution at the crystal borders. When the chlorite is associated with vermiculite or chlorite it remains intact.

The carbonates and the brucite are dissolved right from the beginning of the alteration. On the other hand, the quartz is formed by precipitation of silica originated from olivine and serpentine dissolution. Once formed it can be dissolved and reprecipitated.

In the pyroxenites, the evolution is clearly towards the formation of smectite. The orthopyroxene as well as its products of hypogene transformation (chlorite, serpentine and amphibole) show the cleavages and fractures invaded by the smectite, from the beginning of the alteration. The pyroxene is completely transformed, no more existing in the coarse saprolite. As for the other minerals, the transformation is not complete and they are present even in the red laterite. The smectite remains still stable in the coarse saprolite; from this stage on it evolves to goethite and possibly to kaolinite.

The main stages of the mineralogical evolution are synthetized in Figure 4.

GEOCHEMICAL EVOLUTION

Serpentinites evolution

Table 1 shows the average percentage for the main oxides in each "profile type" alteration facies developed on the serpentinite.

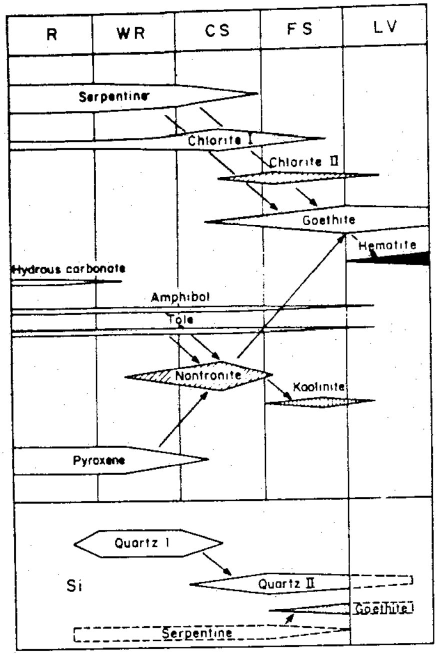

FIGURE 4
Mineralogical evolution of the weathering profiles (rock = R; weathered rock = WR; coarse saprolite = CS; ferruginous saprolite = FS and red laterite = RL).

TABLE 1. AVERAGE CHEMICAL COMPOSITION (% IN WEIGHT) OF THE ALTERATION FACIES OF PROFILES ON SERPENTINITE (FERRUGINOUS SAPROLITE AND SILCRETE CAN BE FOUND MIXED IN WHATEVER PROPORTIONS.

Alteration Facies	Number of Samples	SiO_2	MgO	Fe_2O_3	Al_2O_3	Cr_2O_3	NiO	P.F.
Red Laterite (RL)	11	17	0	63	6	2	0.3 - 1.0	6
Ferruginous Saprolite (FS)	15	5	0.7	69	4	2	0.4 - 0.5	10
Coarse Saprolite (CS)	18	34	27	22	1.0	1	0.5 - 3.0	15
Weathered Rock (WR)	32	37	34	14	1.0	0.7	0.4 - 1.0	15
Rock (R)	2	32	36	12	1.0	0.4	0.3	15
Silcrete (Si)	6	80	0	12	0.5	0.5	0.5	3

The alteration is characterized by a rapid decrease of the MgO content and, in a smaller degree, of SiO_2, followed by an increase of Fe_2O_3, Al_2O_3 and Cr_2O_3, showing a typical lateritic evolution.

The fresh serpentinite presents approximately 0.3% NiO, which is characteristic for this lithologic type. In the partially altered rock, the values never overreach 1%. In the Vermelho deposit, differently from other ones (Niquelândia, Morro do Níquel, Santa Fé, etc.), there are not garnierite veins, so common at the alteration profile roots.

During the alteration process the nickel contents increase up to 3.0%, the maximum values being in the coarse saprolite facies and the biggest amount corresponding to the most altered material (MgO < 25%). This is the so-called Carajás "silicated ore", with an average thickness of 7 m, density around 1.6 and a tonnage of 20 million tons with 2.5% Ni. Based on similar deposits such as New Caledonia (Trescases, 1975) and Santa Fé (Oliveira, 1980), it seems that in this material nickel is associated with amorphous compounds.

In the ferruginous saprolite, with no silicification, the Ni contents varies from 0.4% to 5.0%, being 0.9 to 2.0% the most common values. The highest values are found at this horizon bottom. This is the oxidised ore (10 m average thickness, 20 million tons with 1.4% Ni). In this case, the Ni is probably in the goethite structure.

In the altered pockets within the silcrete the NiO content is generally low (0.5%), but it can attain values up to 4 or 5%. The silicificated ferruginous saprolite presents lower amounts of NiO, generally under 1.0% and on average 0.5%. These two facies, ferruginous saprolite and silcrete, can be found mixed in any proportion.

The red lateritic cover shows, almost always, very low NiO contents, around 0.3%.

Pyroxenites evolution

The smectitic level (nontronite) formed from pyroxenites alteration, although having been NiO enriched in respect to the fresh rock (< 0.1%), never attains amounts over 0.5% and consequently does not present any economic interest.

Isovolumetric balance

Figure 5 shows the variation of the absolute amount of SiO_2 and MgO in samples taken from all the alteration horizons developed on serpentinite, in function of the respective bulk densities. The path IIa (rock-coarse saprolite) and III (coarse saprolite-ferruginous saprolite) indicates progressive loss of SiO_2 and MgO, which corresponds to the hypogene minerals dissolution.

The silicification process (path I and IIb) indicates a massif importation of SiO_2 and an accentuated loss of MgO; it is a phenomenon very different from the lateritic alteration. Thus it can be said that the alteration process had two stages: a previous silicification followed by lateritisation.

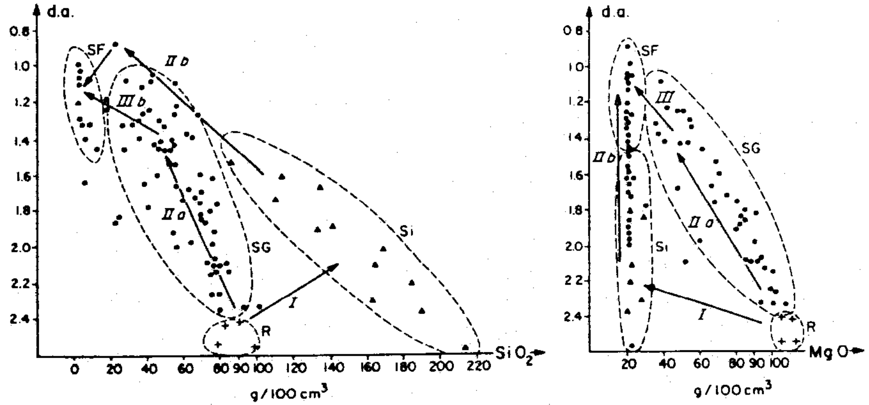

FIG. 5. Variation of the absolute amount of SiO_2 and MgO in alteration horizons developed on serpentinite.

Finally, it is noteworthy that both silcrete and coarse saprolite evolve to ferruginous saprolite.

The iron remains constant, in absolute values, in the first alteration stages (Figure 6) and shows an enrichment as the process progresses. This enrichment can be due to the

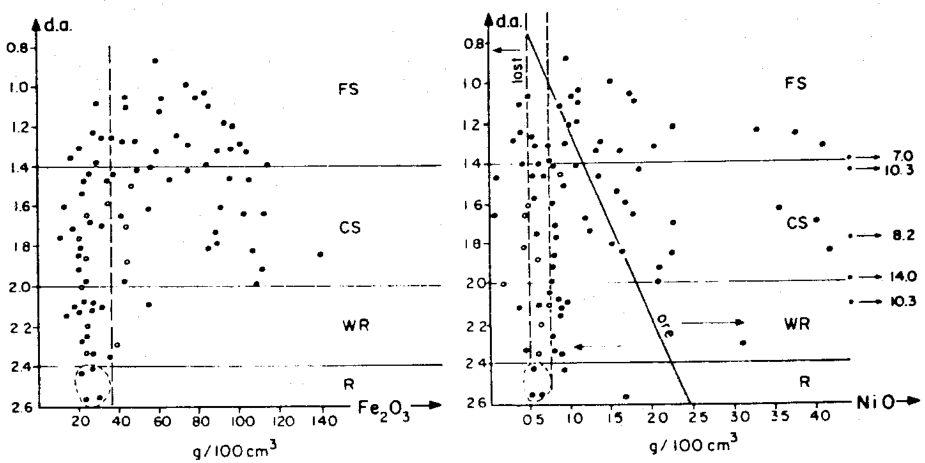

FIG. 6. Variation of the absolute amount of Fe_2O_3 and NiO in alteration horizons developed on serpentinite.

goethite illuviation or to the compactation phenomenon that starts in the ferruginous saprolite horizon.

The nickel behaviour is more complex (Figure 6). The silcrete is impoverished, a great part of samples of partially altered rock and coarse saprolite preserves the original content and, finally, ferruginous saprolite samples and a part of coarse saprolite exhibit absolute enrichment. There is a relationship between the nickel and the iron absolute enrichment phenomenon. So the reasons suggested for the Fe behaviour can also explain the Ni behaviour. However, the enrichment rates for the Ni are much higher than the ones for the iron. Thus, besides the goethite nickeliferous mechanic illuviation and a possible compactation, the hypothesis of addition of nickel in solution seems necessary. The source of this nickel would be the laterirized material from the silcrete pockets, the ancient horizons that were over the silcrete and the red laterite (transformation goethite-hematite).

DISCUSSION AND CONCLUSIONS

The deposit genesis

In a first stage, a silicification in the alteration profile bottom occurred along the fractures of the serpentinite leaving pockets of fresh rock.

In a next step, a probable climatic change has favoured the lateritisation process, so that the pockets were attacked and a lateritic profile under this silicificated level was elaborated.

The silicification episode could be related to the Sul-Americano Cycle (King, 1954), during the early Tertiary, as it has occurred in other Brazilian deposits, such as Santa Fé (Oliveira, 1980), Barro Alto (Trescases and Oliveira, 1981) and Niquelândia (Oliveira and Trescases, 1982).

In the late Tertiary the Velhas surface erosion attained preferentially the basic rocks, with no silcrete cover and let the serpentinite small hills V1 and V2 residue. The silcrete borders removal, due to the present drainage erosion, allowed the lateritic profile exposition in certain topographic situations. Thus, coarse saprolite crops out in the steep slopes of the northern and southern zones of the hills.

On both sides of the suspended valley on the pyroxenite the less intense erosion allowed the complete lateritic profile preservation.

Comparison with other Brazilian deposits

In a general way, the Vermelho nickeliferous occurrence presents an evolutive history similar to the other Brazilian deposits, characterized by the existence of two stages, related to the two phases of the relief evolution: Sul-Americano and Vermelhas cycles (Melfi et al., 1980).

However, the ferruginous saprolite thickness is, in Vermelho, much bigger than in the other deposits and its composition is much more oxidised. So, the Vermelho deposit represents an evolution extreme, controlled by the present climate with equatorial characteristics.

Despite the existence of this important oxidised ore level, the more interesting nickel concentrations are found in the more alterated coarse saprolite (silicated ore). On the contrary of the majority of the nickel lateritic deposits, there is no enrichment by garnierite veins in the partially altered rock.

In the other Brazilian ultramaphic massives, the erosion promoted a second generation of weathering profiles at the Velhas surface level. It has not occurred in Vermelho where the horizon spacial distribution is structurally correlated to the silcrete level. This fact prevented the nickel transference from one level to another, as it happened, for example, in Santa Fé and Barro Alto.

The existence of a pyroxenite lense and the formation of a suspended valley is a situation similar to that in Niquelândia (Pecora and Barbosa, 1944, Pedroso and Schmalz, 1981, Oliveira and Trescases, 1982). However, in Niquelândia the altered pyroxenite constitutes a deposit, what does not occur in Vermelho. In this case, the Ni lateral migrations, setting out from the profiles on the serpentinite, have not been intense enough to transform the altered pyroxenite in ore. Thus the deposit remains restrict to the profiles on serpentinite.

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