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NICKELIFEROUS LATERITES OF BRAZIL*

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ABSTRACT

Nickeliferous deposits have been known in Brazil from about a century ago. These ores are lateritic weathering products of ultramafic rocks. They occur between 8° and 25° South; most are in Goiás State, central Brazil.

The Brazilian ultramafic rocks can be related to at least three orogenic cycles: Early Precambrian; Late Precambrian and Cretaceous. All of these ultramafic rocks are partially or completely serpentinised.

There are other small Precambrian (age not established) mineralised massifs: Americano do Brasil, Go: Sanclerlandia, Go, Carajas, PA.

Brazilian nickeliferous deposits occur in varied conditions of relief and climate. Their formation can be related to the Early Tertiary "South American erosion cycle". The weathering products of this cycle are lateritic, with residual concentration of iron, but show silica accumulation (chalcedony, quartz) as silcretes over ultramafic rocks.

This silcrete, often of the "box-work" type, apparently formed at the bottom of Tertiary profiles and was later exposed by erosion ("Velhas cycle", Late Tertiary). Beneath the silcrete, a new profile, lateritic or saprolite, formed. Erosion slopes and especially the lower, new-formed plains have weathered according to more recent climatic conditions, forming laterites in humid central Brazil, and saprolites in the arid Northeast.

Brazil occupies the seventh position in the world in its estimated reserves of nickel ore (4.10⁶ tons Ni in 1975). The main features of these deposits are:

- initial stage of lateritic weathering in Early Tertiary,
- important silicification related to this cycle.
- the silicated ore-type predominates over the limonitic type, as a result of post-Tertiary tectonomorpho climatic evolution.

Thus, Brazilian nickeliferous deposits are different from the majority of other lateritic deposits in the world.

INTRODUCTION

According to their conditions of formation nickel deposits are of two types (Lombard, 1956 and Boldt, 1967): sulfide deposits of hypogene origin, and lateritic deposits of supergene origin. Nickeliferous laterites constitute a thick weathering cover of ultramafic rocks in tropical areas.

Some sulfides of copper and nickel have been prospected in Brazil (for example in the Sao Joao massif, at Americano do Brazil-Goiás). But all the Brazilian nickeliferous reserves are in lateritic weathering products of ultramafic rocks.

Ultramafic massifs occur in the majority of the Brazilian states, from the equator to 32°S latitude.

However, three areas show a higher density of ultramafic rocks (Fig.1) (Berbert, 1977).

A central band, elongated N-S: in Goiás and continuing to the state of Para; the largest Brazilian massifs and the best nickel ore reserves are here (Fig.2) (Angeiras, 1968; Godoy, 1968, Lindenmayer and Lindenmayer, 1971; Vasconcellos, 1973).

A second area in Northeast Brazil, mainly in the state of Bahia.

And a third area in the state of Minas Gerais in Southeastern Brazil.

The Amazon Basin is very poorly known, which explains the apparent absence of ultramafic rocks in the northwestern part of the country, covered by a great equatorial forest.

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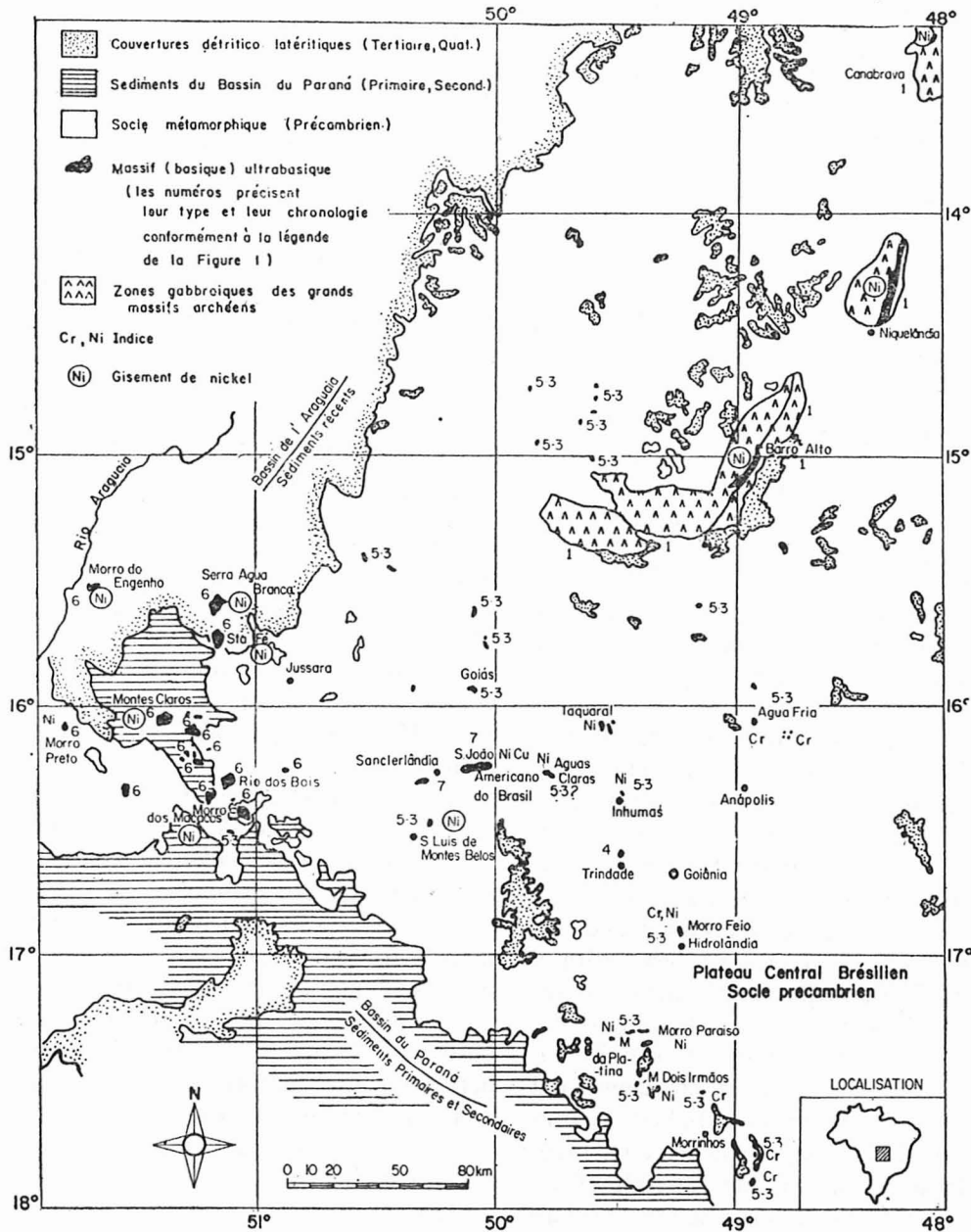


Fig. 2

The published works on weathering of Brazilian ultramafic rocks and nickel deposit formation are few, with the exception of some mining reports (Andrade and Botelho, 1974; Berbert, 1977; Ferran, 1974; Lages et al., 1975, 1976). The geochemical study of this process in different climatic zones of Brazil began three years ago at the Geosciences Institute of the University of Sao Paulo, by a French-Brazilian team. The present work is a preliminary inventory of the characteristic features of the so-called "nickeliferous laterites" of Brazil.

ENVIRONMENT OF THE DEPOSITS

Geological environment

The classifications of ultramafic rocks proposed by Thayer (1960), Wyllie (1967), Naldrett and Gasparini (1971), and Naldrett (1973) are not always appropriate in the Brazilian context. We use here the classification of Berbert (1970) and (1977), with some modifications.

(A) *Distribution of the massifs* (Figs. 1 and 2)

(1) The oldest massifs occur in Goiás. They are

Table 1. Nickel deposits of Brazil.

State	Name of the massif	Aproximate size of the ultrabasic massif	Reserves— 10^3t ore (measured and estimated)	Content %Ni	Bibliographic reference
Goiás	Niquelandia	100km ² (39 × 2.6 km)	38000	1.40	(1)
	Barro Alto	45km ² (24 × 1.9 km)	73000	1.67	(1)
	Canabrava	?	9500	1.3	(3)
	Santa Fé	38 km ²	61000	1.5	(2)
	Serra Agua Branca	35 km ²	60000	1.3	(2)
	Morro do Engenho	12 km ²	18000	1.03	(2)
	Morro dos Macacos	30 km ²	10000	1.3	(3)
	Rio dos Bois				
	Montes Claros (Salobinha)	?	15000	1-1.5	(3)
	Sao Luis Montes Belos	12 km ²	?	?	—
Minas Gerais	Morro do Niquel	0.5 km ²	2300	1.7	(1)
	Liberdade	0.2 km ²	7900	1.7	(1)
	Ipanema	4 km ²	7300	1.24-1.59	(1)
Sao Paulo	Jacupiranga	6 km ²	3200	1.47	(1)
Piaui	Sao Joao do Piaui	6 km ²	20000	1.57	(1)
Bahia	Serra das Marrecas	?	900	1.5	(4)
	Sao Felix do Xingu	?	13000	2.1	(2)
Pará	Quatipuru	90 km ² (45 × 2 km)	13000	1.3	(5)
	Carajas	?	?	?	—

(1) M.M.E. 1978.

(2) Lages et al., 1976.

(3) Berbert, C. O., 1978 (Conference at the Instituto de Geociencias de Rio Claro).

(4) Bruni et al., 1976 (Carta geologica do Brasil ao milionesimo, Folha Aracaju, 226 p., DNPM, Brasilia).

(5) Cordeiro & McCandless, 1976.

secondary rejuvenation after a tectonic uplift (Trescases, 1975; Lelong et al., 1976). All these favourable conditions are not simultaneously satisfied for each Brazilian nickeliferous deposit. And each deposit shows characteristic features, according to its particular recent evolution.

(A) Climate

The following main bio-climatic zones can be distinguished in Brazil (Romaris, 1974).

(i) In the Northeast, the climate is hot and semi-arid. The vegetation is a dry brushland, with thorny shrubs and cacti ("caatinga"). The average temperature is 24° to 26°C, and precipitation is below 800 mm, with 8 to 9 months of very dry season.

(ii) In Central Brazil, the climate is hot and humid, with contrasting seasons. The vegetation consists of savannah with some trees ("cerrado" or "campo limpo"). The average temperature is between 22° and 25°C, and the rainfall is between 1200 and 1800 mm, with only 3 to 4 months of dry season.

(iii) On the Atlantic Coast of Southeastern Brazil, the tropical climate is semi-hot and semi-humid (average temperature 20°C, and rainfall 1500 to

1900 mm). The vegetation is of the tropical forest type. In the Amazon Basin of Northern Brazil, the climate is equatorial, hot, and very humid (average temperature above 26°C, and precipitations above 1800-2000 mm). The vegetation is of the great equatorial forest.

(iv) The climate of Southern Brazil is transitional to a temperate climate.

Nickel deposits occur in the first four climatic zones and mainly in the second one (tropical climate with contrasting seasons).

(B) Relief

Most of the ultramafic massifs of Brazil comprise hills, sometimes tabular, or mountains. These elevations look down on broad levelled plains. The ultrabasic reliefs are of three types:

(i) Tabular hills and mountains. This is the most frequent topographic form. Hill tops and plateaus are capped by a hard layer of silcrete. The slightly weathered rock crops out on steep slopes. Figure 3 shows some cross-sections of Alpine ultramafic massifs, with the silcrete horizon and the weathered zone; Morro do Niquel (MG) and Sao Joao (Piaui),

A similar landscape can be presented by the ultramafic-alkaline massifs (Serra Agua Branca, GO,—Lessa Sobrinho et al., 1971; Justo, 1973). The largest massifs show a contrast of reliefs, with highlands, foothills, and lowlands. It is possible, however, to identify the highlands as plateaus, as in the case of the Southern part of Niquelandia (Fig. 3), where the dunitic zone is a relict of an old plateau with silcrete (the pyroxenite bands correspond to valleys, slightly carved into the old peneplain) (Pecora and Barbosa, 1944; Pecora, 1944; Barbosa, 1968; Costa, 1970).

(ii) Plains and hills. The largest massifs show characteristic features of a dissected, old plateau; foothills and plains are dominant, with ferruginous detrital material, sometimes with ironcrust near the creeks; around these low zones are some hills with steep and silcrete on their tops (Santa Fe and the Northern part of Niquelandia, Fig. 3).

(iii) Finally, some massifs have been wholly levelled by erosion, mainly in the semi-arid Northeast.

(C) Interpretation of the evolution of the relief

The suggested course of evolution of the relief is as follows:

(i) During the late Cretaceous, the uplift of South America began. A very long period of erosion established an extensive peneplain: the South American erosion surface (King, 1956). The weathering products of this cycle are lateritic (Braun, 1971), but show silica accumulation (silcrete) over ultramafic rocks (Santos, 1974; Trescases and Oliveira, 1978).

(ii) In the late Tertiary, a new erosive cycle began; the Velhas Cycle (King, 1956). A new, lower surface was formed, after incision and dismantling of the South American Surface. In areas of ultramafic rocks, however, silcrete impeded the levelling of the relief. Thus plateaus and tabular hills with silcrete are relicts of the South American Surface.

(iii) In the Quaternary, erosion has continued, restricting the hills even more. The landscapes of Niquelandia and Santa Fe are in a more advanced stage of erosion than the others. During the Quaternary, the weathering attached at the same time both:

—the relicts of the South America Surface (Highlands), where weathering profiles are developed under the silcrete:

—and the new base level (Velhas Surface), with deep weathering profiles. This weathering is controlled by recent climatic conditions.

DIFFERENT TYPES OF WEATHERING PROFILES

Weathering profiles of the highlands (Plateaus, tops of hills)

These highlands are relicts of the South American Surface. Their weathering profiles were the first to begin their evolution. Several types of weathering can be distinguished according to the climate.

(a) Hot and humid tropical climate, with contrasting seasons (Go, Mg, Central Brazil)

This climate is considered as the most propitious for the genesis of a thick lateritic profile with nickel accumulation (Trescases, 1975). Indeed, it is in this climate zone that the biggest Brazilian deposit occurs. Most of the bed-rocks are dunites or serpentinites, sometimes harzburgites. Figure 4 shows some weathering profiles at Morro do Niquel (Griffon and Richer, 1976; Langer, 1969, Santivanez, 1965; Trescases and Oliveira, 1978), Barro Alto and Niquelandia and gives for comparison one profile on pyroxenite in Niquelandia. The profile appears really different only on Pyroxenites. On rocks rich in olivine and/or serpentine, the profiles always appear as one of the two extreme types: Morro do Niquel and Barro Alto. Two principal layers can be distinguished:

Weathered zone, with preservation of the structure of the rock.

Silicated and/or reworked top zone.

Weathered zone. The weathering of the hard, dark, dense fresh rock begins with the modification of the colour during the "slightly weathered rock stage" (R-SG in Fig. 4). The thickness of this layer is between 2 and 5 m. Next, cohesion and bulk density decrease, with densities between 2 and 1.5: this is the coarse saprolite stage (SG). When cohesion disappears, the rock is transformed into a brown argillaceous mass, with conservation of the rock structure, but with very low density (under 1.5). This is the fine saprolite stage (SF), never very thick (1 to 2 m,) and sometimes absent.

In the Brazilian profiles, the coarse saprolite is the thickest horizon of the weathered zone. This stage is intermediate between the slightly weathered rock and the fine saprolite. But depending on the case, it maintains some features of the former (rocky type, as at Morro do Niquel), or it quickly loses all cohesion (argillaceous type, as at Barro Alto). Some silicification can occur in the coarse saprolite as vertical veins (Barro Alto, Fig. 4) or fractures fillings.

Calcite, brucite and olivine disappear first (in the slightly weathered rock).

Residual iron and nickel hydroxides precipitate in the cleavages of the serpentinous network (in the coarse saprolite); next, this network is replaced by a nickeliferous goethite network (fine saprolite).

However, prior to this, quartz, chalcedony and nickeliferous silicates (mainly hydrated talc-like

forms) can precipitate in the coarse saprolite (Brindley and Souza, 1975; Esson and Carlos, 1978).

The silcrete consists mainly of quartz and chalcedony. In the reworked red laterite, goethite, and hematite appear abundantly. When the rock includes pyroxenes, the minerals are transformed into smectites (nontronite), and the profile is of the argillaceous type.

Table 2. Average chemical composition of the two types of weathering profiles in the Highlands.

A—"Rocky" type profile; Morro do Niquel (after Trescases and Oliveira 1978).

	H_2O^+	SiO_2	MgO	$Fe_2O_3^*$	Al_2O_3	Cr_2O_3	NiO^{**}	CoO	CuO
LR	3.9	74.3	0.3	17.2	3.79	0.84	0.26	0.042	0.003
Si	2.8	85.7	2.4	6.8	0.95	0.19	0.44	0.034	0.003
SF	10.1	50.3	22.7	10.4	0.99	0.24	3.37	0.078	0.002
R/SG-SG	13.2	41.5	30.6	9.8	0.78	0.18	2.40	0.033	0.003
R-SG	13.3	45.2	35.2	4.15	0.62	0.053	1.08	0.016	0.003
R	16.6	35.7	38.5	5.7	0.75	0.052	0.41	0.015	0.002

B—"Argillaceous" type profile; Barro Alto (after Stache, 1974).

	H_2O^*	SiO_2	MgO	$Fe_2O_3^*$	Al_2O_3	Cr_2O_3	NiO^{**}	MnO_2	CoO	CuO
LR	9.2	17.0	1.5	51.7	14.2	3.19	1.18	0.91	0.092	0.037
SF	10.8	20.3	12.1	41.5	7.9	2.68	2.58	0.67	0.059	0.041
SG-SF	14.8	34	25.8	16.8	4.1	1.04	2.51	0.40	0.030	0.026
R-SG	1.63	34	31.1	13.6	2.9	0.86	1.56	0.27	0.027	0.027

*Total Fe as Fe_2O_3 .

**The nickel content shows a strong variation from one sample to another.

LR: Reworked red laterite, partially developed from the silcrete.

Si: Silcrete.

SF: Fine saprolite (=yellow laterite).

SG-SF: Greenish-brown coarse saprolite (argillaceous type).

R" SG-SG: Mainly friable weathered rock (rocky type).

R-SG: Hard, slightly weathered rock.

R: Fresh rock.

Chemical evolution of the profiles. Table 2 gives the mean chemical composition of each layer of the two types of highland profiles: "rocky" type (Morro do Niquel) and "argillaceous" type (Barro Alto). The magnesium content decreases with weathering. This progressive leaching is correlated with a relative concentration of the residual elements: iron, aluminium, chromium, cobalt. The silica content increases a little in the Morro do Niquel saprolite, but the ratio SiO_2/Fe_2O_3 decreases with increased weathering. In the Barro Alto profile (as in the majority of the profiles), the content of silica of the saprolite decreases. Nickel is strongly concentrated in the upper part of the weathered zone. The silcrete is very rich in silica and poor in nickel. In the Barro Alto profile, the "red laterite" is constituted mainly by the residual elements (Fe, Al, Cr, Co), and nickel content is medium (1%).

The isovolumetric balance (gain and loss) of the weathering confirms that magnesium and part of the silica are progressively leached in the weathered zone (part of the silica precipitates as amorphous compounds). Nickel shows absolute gains. The other elements are strictly constant. In the silcrete, the residual elements are again constant, but here, there is a loss of nickel and an absolute gain of silica.

Conclusion on the evolution of the highland profiles in a tropical climate with contrasting seasons. The evolution of the highland weathering profiles in a tropical climate with contrasting seasons comprises the progressive, but sometimes incomplete, destruction of the silicates in favour of a goethitic residue: this is an evolution with a lateritic tendency.

However, some residual free silica remains; and this evolution, in the recent morpho-climatic condi-

silica.

The small occurrences of Serra das Marrecas, in Central Bahia and Catingueira (Paraiba) are dismantled relicts of an old deposit.

In the Sao Joao do Piaui deposit, however, a strong silcrete cap protected the plateau relief (Santos, 1974). A new profile is developed beneath the silcrete, but here, the evolution does not show a lateritic tendency: magnesia is again leached away, silica and iron are strictly residual. The saprolitic weathered zone shows the massive transformation of the ultramafic rock into smectite, with local high nickel content (2% Ni). In some places the silica dissolved in the upper part of the silcrete precipitates in the saprolite. This silicified saprolite is less rich in nickel (0.5%-1% Ni). Thus here, there is a slow and gradual descent of the silcrete, which is destroyed at its top and regenerated at its bottom.

(c) *Permanently humid climatic conditions, (North and South Brazil)*

The nickel deposits in the Amazonian forest were discovered only a short time ago and they are not well known. Cordeiro and McCandless (1976) write about silicification lateritisation and peneplanation in the massif of Quatipuru (Pará). There seems to be strong analogies with the deposits of Goiás.

In southern Brazil, there is only one small deposit at Jacupiranga (State of São-Paulo, 25°S Latitude). The evolution of the weathered zone has a lateritic tendency at the top without total leaching of silica. The top layer is a very thick horizon of powdery "red laterite", with some blocks of silcrete. The nickel content is very low (Sl. 5% Ni) (Ferran, 1974). The localisation of the massif of Jacupiranga in a tectonic graben could explain a lower degree of erosion: the thick cover of red laterite could come from the evolution of the old weathering products of the South American surface.

In Parana, Santa Catarina and Rio Grande do Sul (South of 25° S Latitude) the recent weathering is not lateritic and the profiles are not thick. Vermiculite and smectites are the dominant minerals and nickel concentration does not occur. Even during the Tertiary, the weathering probably was not lateritic in the South.

Profiles of the plains and lowlands

(a) *Tropical climate with contrasting seasons (Goiás)*

The weathering profiles observed in the low parts of the massifs of Santa Fe and Niquelândia (Northern part) are very similar. The weathered zone show the same sequence of horizons present in the highlands: slightly weathered rock, coarse saprolite, and fine-grained ferruginous saprolite which is thicker here.

The superficial reworked layer is very different; the profiles of the lowlands never show the silcrete cover characteristic of the highlands. The upper part of the lowland profiles is always made up of about 3m (or more) of powdery red laterite, with ferruginous fine gravels.

The mineralogical evolution of the profile is the same in the lowlands as that previously described in highlands. The mean chemical composition of each layer for the massif of Santa Fe is given in Table 3. The similarity between these compositions and the corresponding horizons of the highland profiles (Table 2) is very high, with the evident exception of the top layer of red ferruginous laterite. A part of the accumulated nickel of the lowland profiles is of residual origin; but the rest comes from the highlands either through mechanical processes with the colluvial red laterite or by chemical processes, through lateral migration.

In conclusion, in the humid tropical region of Brazil with contrasting seasons, the weathered zones

Table 3. Average composition of each horizon in the massif of Santa Fe.

	H ₂ O*	SiO ₂	MgO	Fe ₂ O ₃ *	Al ₂ O ₃	Cr ₂ O ₃	NiO	CoO	CuO
LR	5.2	10.1	1.6	70.8	3.5	6.2	1.19	0.145	0.011
SF	8.9	32.9	9.9	39.0	2.4	4.1	1.40	0.063	0.010
SG	12.2	40.8	28.3	15.5	0.7	0.64	1.0	0.028	0.005
R-SG	12.8	41.0	33.4	10.4	0.5	0.44	(0.3-1.9) 0.33**	0.024	0.004
R	7.4	36.3	41.1	13.2	0.2	0.35	0.23	0.020	0.003

*Total Fe as Fe₂O₃ (FeO for the fresh rock only).

**Sample without the garnieritic veinlets.

LR: Red laterite.

SF: Fine saprolite=yellow laterite.

SG: Weathered rock=Coarse saprolite.

R-SG: Hard, slightly weathered rock,

R: Fresh rock.

(iii) In the Late Tertiary, with the breaking up of the South American Surface, the lateritised weathering products were removed, and the silcrete exposed. With this protection against erosion, the ultramafic massifs appeared little by little as plateaus above the levelled "Velhas" Surface.

(iv) During the "Velhas" cycle, weathering was active beneath the silcrete which covers the plateaus (South American relicts), and in the "Velhas" lowlands. In accordance with recent climatic conditions this weathering shows a lateritic tendency in Central Brazil (tropical climate with contrasting seasons). In the semi-arid North-East the weathering process is smectitisation.

(v) With the progress of erosion, the South American relicts disappear. The nickel is progressively transferred from the highlands towards the lowlands, where it enriches the new-formed weathering profiles.

CONCLUSION

The main features of the Brazilian deposits are:

(i) genesis correlated with two levelling cycles in the Early and Late Tertiary.

(ii) Restricted lateritisation, with silicated profiles, without great thickness.

(iii) Important silicification on the highlands.

(iv) Lateritisation more advanced in the lowlands.

(v) Thickness and nickel grade of the mineralised layer often modest: either because the climate is no longer aggressive (North East), or because the lateritisation acted for a short time (Central Brazil).

(vi) Preferential accumulation of nickel in the lowlands.

(vii) Preferential accumulation of nickel at the top of the weathered zone.

(viii) Huge predominance of the silicate type of nickel ore.

Thus, Brazilian nickeliferous deposits are different from the majority of the other lateritic deposits in the world. Oxidised deposits occur in the Northern Hemisphere in Cuba (De Vletter, 1955), Guinea (Bonifas, 1959; Percival, 1965), Philippines (Santos-

Ynigo, 1964), Venezuela (Jurko Vic, 1963). In these deposits, the weathering profiles are very deep and mainly goethitic; nickel is associated with goethite; the nickel content is never very high, but it is a little higher at the bottom (Schellman, 1971). Oxidised-silicated deposits occur in New Caledonia (Trescases, 1975), and in western United States (Hotz, 1964). The silicated layer of coarse saprolite is present here, but the thickest horizon is goethitic. The nickel content is high at the bottom of the coarse saprolite (2-5% Ni), but the goethitic fine saprolite is also nickel ore (1-2%). The best deposits are located in the highlands. The nickel ore reserves are principally of the oxidised type. These deposits are located in the Southern Hemisphere (New Caledonia), or to the north of the intertropical zone (USA). However, some small deposits of the Southern Hemisphere show similarities with the Brazilian type. In South Africa (De Waal, 1971) and in Australia silicification in the highlands and lateritisation in the lowlands have been mentioned. In these profiles the nickel content increases toward the upper part.

This differentiated supergene evolution of the ultramafic rocks of the two hemispheres could result from world climatic variations correlative with the movement of the poles and the continental drift during the Tertiary and Quaternary.

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