

## The lateritic ore deposits of Brazil. *Les gisements miniers d'origine latéritique du Brésil*

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## Résumé

Au Brésil, les mécanismes d'altération supergène ont conduit à la formation d'un épais recouvrement latéritique sur environ 65 % de la surface totale ; dans des conditions particulières, l'accumulation de certains métaux dans ce manteau peut atteindre le stade économique : il s'agit des gisements latéritiques. Pour l'élaboration de ce type de gisements, la composition de la roche-mère, les facteurs morphoclimatiques et biologiques jouent un rôle fondamental.

Les différents gisements miniers d'origine latéritique du Brésil sont discutés ici. Ainsi les gisements de fer, qui sont parmi les plus importants du monde (Carajas -Para, Quadrilatère ferrifère -Minas Gérais, Urucum -Mato Grosso), résultent-ils de l'altération d'itabirites (d'âge Archéen à Protérozoïque supérieur). De même, d'importants gisements de bauxites ont été élaborés par altération de divers types de roches : massifs de roches alcalines d'âge Crétacé dans le Sud-Est (Minas Gérais, Sao Paulo, Rio de Janeiro, Santa Catarina) ; Précambrien métamorphique ou volcanique dans le Centre-Est (Quadrilatère ferrifère, chaîne littorale Atlantique) ; et sédiments continentaux tertiaires du bassin amazonien (Trombeta, Paragominas, ...). L'altération latéritique a concentré le manganèse à partir de roches préalablement enrichies en cet élément par des mécanismes volcano-sédimentaires (Amazonie, Minas Gérais). Enfin, des latérites nickélifères ont été accumulées par l'altération de massifs ultrabasiques dispersés à travers tout le pays, depuis le Brésil central où ils sont les plus importants (Barro Alto et Niquelandia, Goias). jusqu'aux régions plus humides du littoral Atlantique et du Nord amazonien.

La latéritisation de ces diverses roches mères, tout à fait spécifiques de chaque type de gisement, est intervenue pour l'essentiel au Tertiaire, pendant des épisodes de stabilité tectonique auxquels correspondent des surfaces d'aplanissement généralisées. Le rôle des facteurs lithologiques, climatiques et morpho-tectoniques dans le mécanisme de genèse des gisements latéritiques est discuté.

## Abstract

In Brazil, the same processes responsible for the formation of the thick lateritic mantle, which covers nearly 65 % of its territory, are also responsible for metal accumulation which forms, under special conditions, the lateritic ore deposits. In the origin of those accumulations, the parent rock composition and/or the convergence of the biological and morphoclimatic factors play a fundamental role.

Considering this point of view, different lateritic ore deposits are discussed in this paper. Thus, the weathering of the Banded Iron Formations (from Archean to Upper Proterozoic) gave origin to some of the biggest iron deposits in the world at Carajas (Para), Quadrilatero Ferrifero (Minas Gerais) and Urucum (Mato Grosso). The products of the weathering of various rocks constituted very important bauxite deposits : Cretaceous alkaline massifs in the Southeast Brazil (Minas Gerais, Sao Paulo, Rio de Janeiro, Santa Catarina) ; Precambrian metamorphic or volcanic rocks in the Central-East Brazil (Quadrilatero Ferrifero, Atlantic coastal ridge) ; and Tertiary continental sediments in the Amazonian Basin (Trombetas, Paragominas, ...). The lateritic alteration concentrated the manganese from rocks that have been previously enriched in this element by volcanic-sedimentary processes (Amazônia, Minas Gerais). Finally, nickeliferous laterites were accumulated by the weathering of ultramafic massifs scattered all over the country, concentrated mainly in Central Brazil (Barro Alto and Niquelandia, Goias), but also occurring in the more humid regions (Atlantic Coast and Amazônia). All this lateritic evolution of very specific bed rocks occurred essentially in the Tertiary during periods of tectonic stability which are related with extensive erosional surfaces. The influence of lithologie, climatic and morphotectonic factors on the mechanism of formation of lateritic deposits is discussed.

## THE LATERITIC ORE DEPOSITS OF BRAZIL\*

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**ABSTRACT** — In Brazil, the same processes responsible for the formation of the thick lateritic mantle, which covers nearly 65 % of its territory, are also responsible for metal accumulation which forms, under special condition, the lateritic ore deposits. In the origin of those accumulation, the parent rock composition and/or the convergence of the biological and morphoclimatic factors play a fundamental role.

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Laterite, Ore deposit, Bauxites, Iron, Manganese, Nickel, Brazil

### Les gisements miniers d'origine latéritique du Brésil

**RÉSUMÉ** — Au Brésil, les mécanismes d'altération supergène ont conduit à la formation d'un épais recouvrement latéritique sur environ 65 % de la surface totale ; dans des conditions particulières, l'accumulation de certains métaux dans ce manteau peut atteindre le stade économique : il s'agit des gisements latéritiques. Pour l'élaboration de ce type de gisements, la composition de la roche-mère, les facteurs morphoclimatiques et biologiques jouent un rôle fondamental.

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Latérites, Gisements miniers, Bauxites, Fer, Manganèse, Nickel, Brésil

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## INTRODUCTION

In intertropical zones, the occurrence of supergenic metallic ore deposits associated with lateritic-type formations is very common. It is well known that the occurrence of the so-called lateritic deposits, formed mainly by rock weathering processes, depends on the convergence of a series of conditions, without which economical concentrations could never be formed (LELONG *et al.*, 1976). Among these conditions, we can mention the lithological, the climatic and the morphotectonic ones. The existence of a specific rock having some elements or minerals in a pre-concentration state, which consists in a protore, is very important for the formation of these deposits. The presence of a warm and humid climate in the area is also important, at least during a certain period of its evolution. Finally, the existence of stable morphological and morphotectonic conditions is also necessary in order not only to allow the deposit formation but especially to preserve these alterations.

In Brazil these conditions have existed and still exist in some regions, so that mantellic deposits of lateritic origin are abundant, playing an important role in the country economy, since they represent 30 % of Brazilian mineral production (excluding coal and oil).

The most important deposits are aluminum (bauxite), iron, manganese, and nickel, and their distribution is shown in figure 1. We can notice that the lateritic deposits occur all over the country from 3°N to 27°S latitude. Due to morphoclimatic conditions, they are rather scarce in northeastern Brazil and absent in Rio Grande do Sul State.

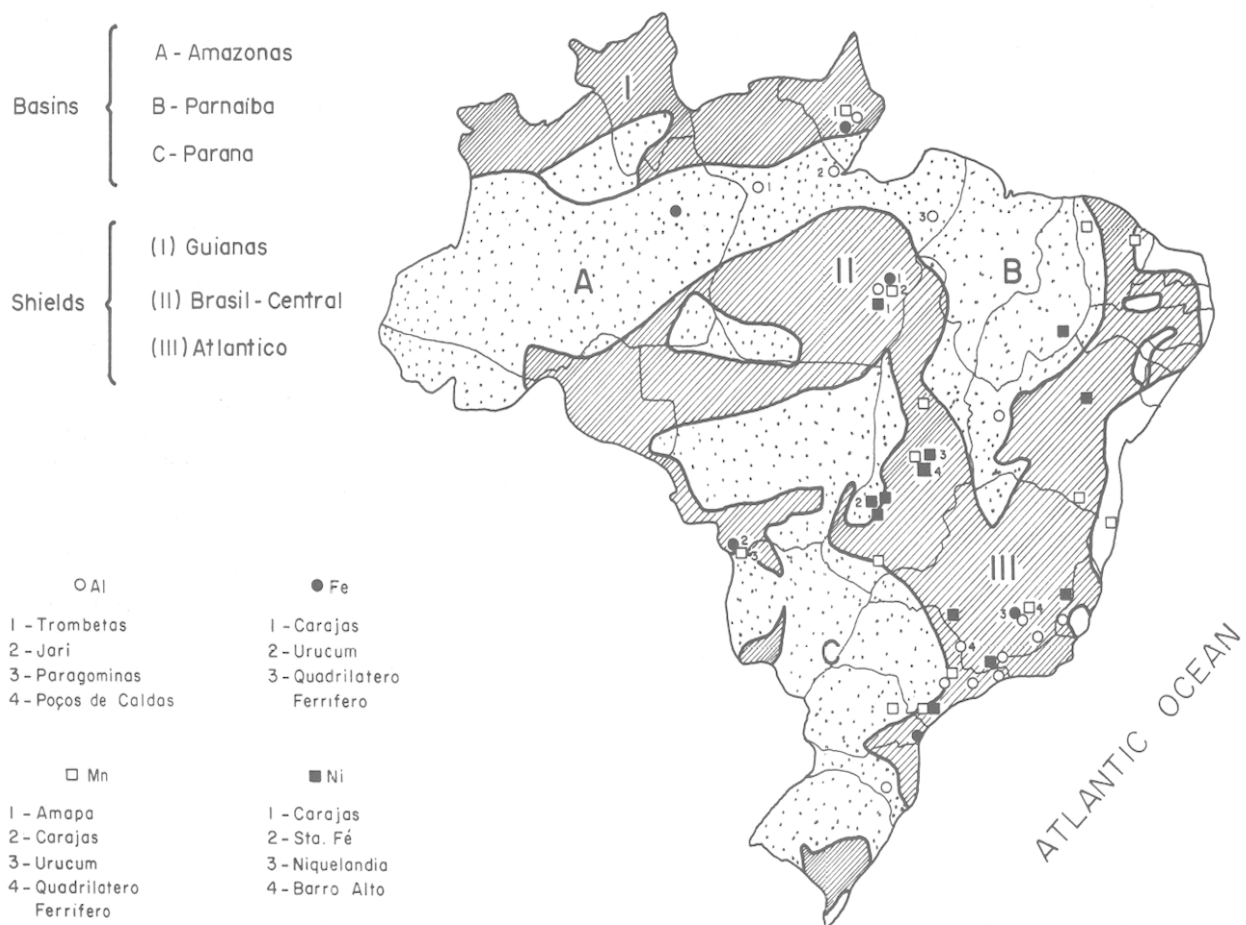


Fig. 1 — Tectonic map and location of the main lateritic ore deposits of Brazil.  
 Carte tectonique et localisation des principaux gisements latéritiques du Brésil.

## I — BASIC DATA ABOUT PHYSICAL ENVIRONMENT IN BRAZIL

This chapter will present briefly the lithological, climatic and morphological conditions in Brazil.

### A — GEOLOGIC OUTLINE OF LATERITIC DEPOSITS

The Brazilian territory is situated in the South American Platform, having an Archean age basement with a very complex geological history. This basement presents metamorphic rocks of amphibolite to granulite facies which are associated with Proterozoic units represented by a greenstone fold belt and a volcano-sedimentary cover, either slightly or not metamorphosed at all (SCHOBENHAUS *et al.*, 1984). These rocks outcrop in three great shield areas identified by thick Phanerozoic sedimentary covers (fig. 1) : the Guyana shield in the north ; the Central-Brazilian or Guaporé in the interior of the country, and the Atlantic shield in the coast. As a whole, the three shield areas represent nearly 60 % of the country surface. From Ordovician to Silurian time, the development of a sedimentary and volcanic cover took place, under stable conditions of an orthoplatform, in the South American Platform, mostly in the three great basins of Parana, Parnaíba and Amazônia.

Geological and geochronological data have allowed to identify, in the Brazilian part of the South American Platform, several orogenic cycles and thermotectonic or tectono-magmatic events, with either a continental or a local importance.

Considering their role in the formation and consolidation of this platform, we can mention four cycles (table I) : Jequié cycle (2600-2700 Ma) ; Transamazonian cycle ( $\pm 2000$  Ma) ; Brazilian cycle (450-470 Ma) and South Atlantean cycle (190-30 Ma). The latter corresponds to an important tectonic reactivation in the platform.

Table I  
Main Brazilian lateritic ore deposits and their chronostratigraphic relationships (modified after SCHOBENHAUS *et al.*, 1984)  
Principaux gisements latéritiques du Brésil et leur situation chronostratigraphique (d'après SCHOBENHAUS *et al.*, 1984)

M.y.					Geodynamic cycles
65	PHANEROZOIC	Cenozoic	clastic sediments (Al)		South Atlantean
		Mesozoic	alkalic volcanism (Al)	ultramafic-alkaline complexes (Ni)	
235					
570	PROTEROZOIC	Paleozoic			Brazilian
		Upper	ferruginous jaspilites (Mn, Fe)		
1100		Middle			Transamazonian
1900			alpine type ultramafics (Ni)		
2600		Lower	itabirites (Fe)	Si-CO <sub>3</sub> protore (Mn)	Jequie
		Archean	itabirites (Fe)	volcanism sedimentary complexes (Mn)	
				mafic-ultramafic complexes (Ni)	

The South American Platform had its evolution during the Pre-Cambrian and was completely consolidated in the beginning of the Paleozoic.

\*The geological history of Brazil, from the Ordovician on, is characterized by the presence of intercratonic sedimentary basins. These basins, having up to 5000 m of sedimentary and associated magmatic rocks, have received a marine sedimentation during Ordovician, Silurian and Devonian times ; a mixed sedimentation in the Carboniferous ; and they have evolved to a continental environment from the Permian to the Jurassic times. At the end of the Jurassic period, when these basins were still active, an important tectono-magmatic event (South

Atlantean) has started, giving origin to several marginal basins. At the same time, an intense tholeiitic magmatic activity has occurred in all basins and particularly in Parana Basin, where it has covered more than 1 200 000 km<sup>2</sup> with 600 m average thickness.

This intense reactivation of the South American Platform has led to the formation of important depressions (grabens) as a result of faulting in the Brazilian coastal region, according to a tectogenetic pattern. From the Neoproterozoic-Albian, these depressions were filled up with marine sediments.

The basic tholeiitic magmatic activity was followed by an alkaline magmatism which was responsible for the formation of several alkaline massifs, with ages from 220 Ma (early phase of the South Atlantean) to 50 Ma, around Parana Basin.

Finally, a continental clastic sedimentation has covered a large part of the platform.

Associated with those events in the shield areas, rocks having a pre-concentration of iron, manganese, nickel and aluminum (proterites) may be found.

## 1. The Archean basement

An important group of rocks associated with Archean units is the large ultramafic complex with gabbros, pyroxenites and peridotites of Goiás State (Niquelandia, Barro Alto and Cana Brava). These massifs are very large in size (more than 20 km) and show a sequence of superimposed zones steeply dipping towards the west (FIGUEIREDO *et al.*, 1970 ; LEONARDOS *et al.*, 1982).

Four different zones can be distinguished : a basal zone, essentially noritic ; either a harzburgitic ultramafic zone (Barro Alto) or a zone having alternatively dunitic and pyroxenitic levels (Niquelandia) ; a central zone, constituted mainly of norites and anorthosites ; and a gabbroid summitless zone. The main nickel ore deposits of Brazil are associated with these rocks.

A second group of Archean rocks is the serpentinized basic-ultrabasic complex of Vermelho Area (Carajas, Pará State). This massif forms a small elongated body with 2.5 km wide and 5 km length, and SE-SW orientation. The massif is intrusive in the Archean basement rocks and contains serpentinized zones in the northern, central and southern part (dunites and peridotites) separated by gabbro and pyroxenite zones. A small lateritic nickel ore deposit is associated with this massif.

Another group is formed by the ferriferous rocks containing the itabirites (Banded Iron Formation) of Serra dos Carajas (Pará State). The itabirites are associated to Grao Para Group with 2600 Ma age. The itabirite constitutes an epicontinental sedimentary sequence, interlayered with several volcanic strata and intercalated between two layers of volcanic rocks (basalt sills). They are metamorphic rocks of amphibolite facies and are formed by a millimetric to centimetric alternation of quartz layers and iron minerals, being haematite the most common. The Carajas iron ore deposit, which is one of the largest iron reserves of the world, occurs associated with these rocks.

Finally, the Archean rocks include the manganiferous rocks of Serra do Navio (Amapá), which form the most important manganese ore deposit being exploited in Brazil. According to SCARPELLI (1973), these rocks constitute two kinds of protore ; a carbonatic one and a silico-carbonatic. The carbonatic protore (manganiferous marble) is characterized by a carbonate association (Ca-kutnahorite to Ca-rhodochrosite), plus olivine (tephroite), pyroxenoids, spessartite and also graphite as secondary constituent (BELLO *et al.*, 1981). The silico-carbonatic protore shows the same association, but with larger amounts of garnet and pyroxenoids, and less olivine and carbonates. These rocks are the result of metamorphism over a sedimentary sequence which is similar to the one found, metamorphosed or not, in the Proterozoic.

## 2. Proterozoic units

The itabirites of the « Quadrilátero Ferrífero » (Minas Gerais State), which constitute the protore of the most important iron ore deposit of the world (DORR, 1964), are found associated to the Lower Proterozoic units. These rocks belong to the Itabira Group with a Transamazonian age ( $\pm 2000$  Ma), consisting mainly of chemical

sedimentary rock with chert, iron oxides and dolomites. The regional metamorphism of amphibolite facies has changed chert into quartz, which is associated with haematite, magnetite and martite.

Haematite is dominant, except locally, when dolomite and amphiboles (cummingtonite or tremolite) replace quartz. In this case, martite and its alteration products are more abundant.

The manganiferous silico-carbonatic rocks of the « Quadrilátero Ferrífero » are also included in the Lower Proterozoic units, associated with Itabira Group and were formed by the regional metamorphism of pelitic sediments rich in rhodochrosite and chert, which were deposited in closed basins, under reducing conditions (ROY, 1968 ; MELFI and BITTENCOURT, 1975). Metamorphism has transformed those sediments either into a silicate rock with garnet (in the zones where the reaction between rhodochrosite and chert has formed silicates), or into a carbonatic rock (in the zones depleted in silica where only a recrystallization of rhodochrosite has occurred). These rocks gave origin to a relatively important lateritic ore deposit. Nowadays, the secondary ore is practically exhausted and the carbonatic protore is being commercially exploited.

Finally, the manganiferous rocks of Azul Formation occur in Serra dos Carajas (Para State) (VALARELLI *et al.*, 1978). The manganiferous protore is a carbonatic rock with rhodochrosite, clay minerals, pyrite and carbonaceous fragments with no metamorphism.

In the Medium Proterozoic units, serpentized ultramafic massifs of « alpine-type » are found in close association (BERBERT, 1977). They present different ages ; some of them reaching the Brazilian cycle (600 Ma). They form small massifs situated in long alignments in the States of Goiás, Para, Bahia and Minas Gerais. Some of them contain lateritic nickel ore deposit with small size (Liberdade, Ipanema, Morro do Niquel and São João do Piauí).

In the Upper Proterozoic units, the large « jaspilite » body of Urucum (Mato Grosso do Sul State), to which the important reserves of iron and manganese are associated, is found (PUTZER, 1959). It constitutes a « Banded Iron Formation » type, like itabirite, although with the silica occurring as small lenses of chert, with a higher proportion of haematite (70 to 80 %) and with detritic levels (arkoses, conglomerates). Two manganiferous layers are associated with the detritic levels.

### 3. Meso-Cenozoic units

Alkaline ultramafic massifs of Cretaceous age occur associated with Meso-Cenozoic units. These massifs are generally small and they surround the Parana Basin from Rio Grande do Sul State up to Goiás and Mato Grosso do Sul States. They are circular, with a dunitic nucleus, and sometimes they have also carbonatite, for instance, Jacupiranga (MELCHER, 1954). Nickel lateritic ore deposits can be associated with these ultramafic massifs (Santa Fé, Ipore, Jacupiranga, etc.).

The alkaline massifs of southern Brazil which normally form bauxite deposits are also associated with the Meso-Cenozoic. These massifs present different sizes, with ages ranging from the Upper Cretaceous to the Lower Tertiary (ULBRICH and GOMES, 1981). The massifs are constituted of a syenitic sequence with subsaturated to saturated terms, being either intrusives or extrusives.

Finally, clay-sandy sediments of Amazônia occur also within these units, bearing the largest bauxite ore deposits of Brazil and one of the largest in the world. These sediments are rich in quartz, kaolinite and iron-oxides, and are considered as Tertiary (Barreiras Group). They are constituted alternatively by clay and sandy layers and change gradually from a conglomeratic sandstone in the base to a claystone in the top.

## B — RECENT MORPHOLOGICAL AND CLIMATIC CONDITIONS

It is well known that the morphological and climatic conditions existing when the lateritic ore deposits were formed are not necessarily the same as the recent ones. However, it is quite important to know the recent conditions, since they can give peculiar characteristics to each deposit.

### 1. Present-day climatic conditions

A great variety of climates can be found in Brazil as a consequence of its continental dimensions. These different climatic types are distributed in five great bioclimatic zones (fig. 2).

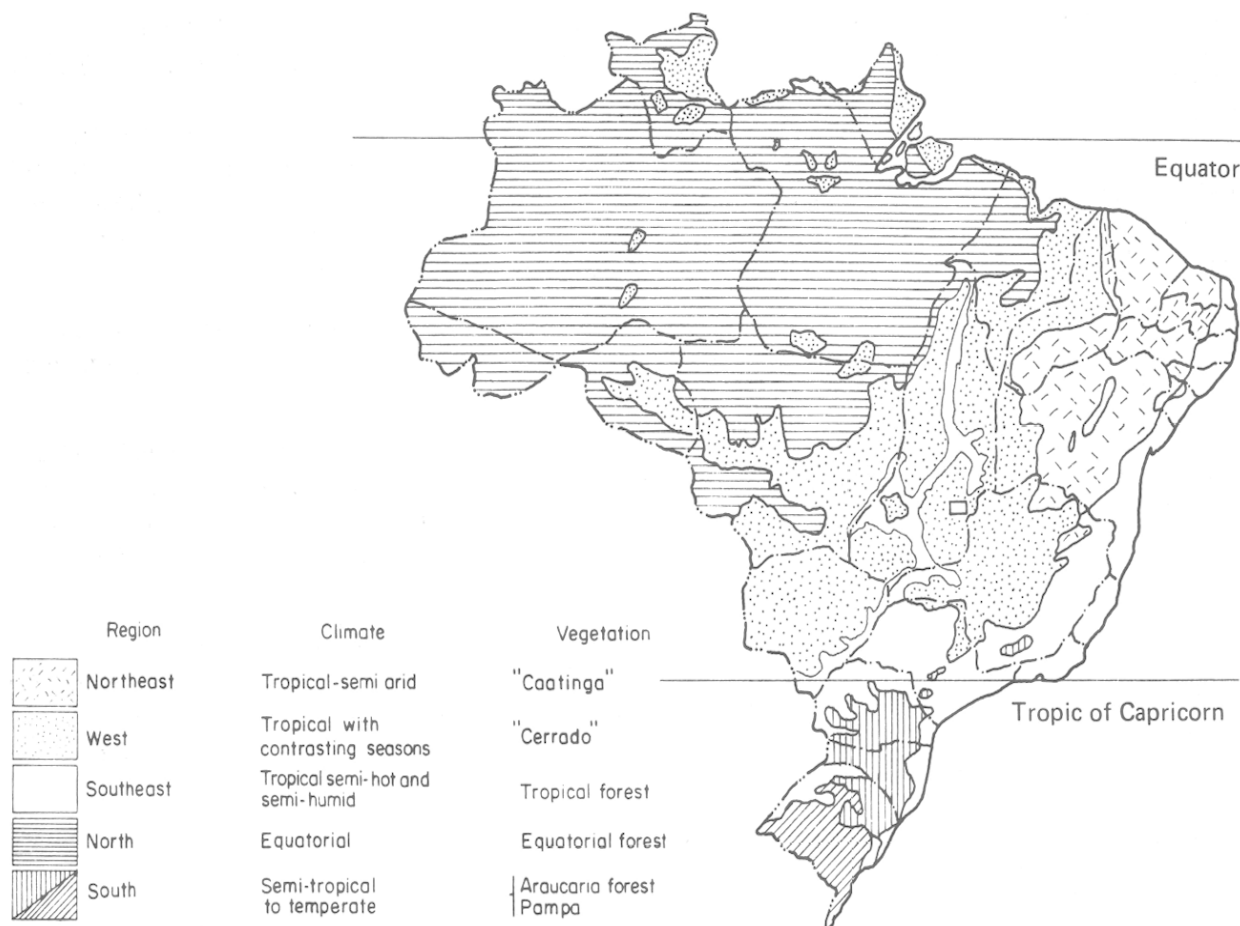


Fig. 2 — Simplified distribution of the main bioclimatic zones in Brazil (modified after ROMARIS, 1974).

*Distribution simplifiée des principales zones bioclimatiques du Brésil.*

(1) Warm and humid equatorial climate with equatorial forests. It is the dominant climate in the northern part of Brazil, in the Amazonic region. It is very wet, with average rainfall of more than 1800 mm and generally around 2000 mm. It presents a short dry season of 2 to 3 months, a mean temperature over 26 °C and very constant throughout the year. The ore deposits of Al, Fe, Mn and Ni of Serra dos Carajas (Para State) ; Fe and Mn of Amapa and the huge reserves of Al of Para are associated with this type of climate.

(2) Semi-arid and tropical climate with « caatinga » vegetation. This climate dominates in northeastern Brazil and is characterized by a mean temperature ranging from 24 to 26 °C with slight annual variations. The annual rainfall is lower than 800 mm and concentrated within 3 to 4 months, being the rest of the year completely dry. The « caatinga » vegetation is characterized by a low density of trees and shrubs, normally xerophilous and thorny, and by the absence of permanent herbaceous cover. Besides the small deposits of Mn and Ni of the States of Bahia, Ceara and Paraiba, the most important in the semi-arid zone is the nickel ore deposit of Sao Joao do Piaui.

(3) Warm and humid to sub-humid tropical climate with contrasting seasons and savanna vegetation. It is the dominant climate of middle-western Brazil and it is characterized by a mean temperature between 22 and 25 °C with slight annual variations and rainfall around 1200 to 1800 mm, well distributed at least within 6 months. The dry season does not exceed 3 to 4 months. The vegetation is of savanna type (« cerrado »)

containing a gramineous stratum and a shrub stratum with the individuals well scattered. A gallery forest occupies the main valleys. The most important nickel ore deposits of Goias as well as the deposits of Mn, Al and Fe of the States of Bahia, Goias and Mato Grosso do Sul are associated with this type of climate.

(4) Sub-warm and sub-humid tropical climate with tropical forest vegetation. This climate dominates the Atlantic coast and the southern part of the country. It is characterized by a mean temperature of 20 °C and rainfall between 1500 to 1900 mm well distributed throughout the year. The typical vegetation is a slope humid tropical forest (ROMARIS, 1974) or Atlantic Forest, with a great density of high trees and arborescent. All the metallic ore deposits of the Quadrilátero Ferrífero of Minas Gerais (Al, Fe, Mn and Ni), as well as other small occurrences of the same metals in the States of Bahia, Minas Gerais, São Paulo and Santa Catarina are related to this climatic zone.

(5) Sub-tropical to temperate climate with vegetation either of Araucaria Forest (Paraná Plateau) or Prairie (Rio Grande do Sul). It is the dominant climate in southernmost Brazil. No lateritic deposits are known up to now in this part of the country.

## **2. Topographic conditions**

It can be said that the Brazilian topography is a result of an evolution started in the Upper Cretaceous with the uplift of the South American Continent (BRAUN, 1971). A very long erosional period was established, levelling Brazilian landscape into a huge peneplane called South American (Sulamericano) by KING (1956).

In the Lower Tertiary, during the aggradation phase of the South American Surface, the weathering led to the formation of important alteration covers.

A new uplift of the continent, in the Upper Tertiary, has enhanced the development of a new erosional cycle named « Velhas Cycle » (KING, 1956). The South American Surface was mostly dismantled but some well preserved remnants can be found in the interior of the country, forming the essential part of the Central Brazilian Plateau with altitudes around 1000 m. Remnants of this surface are also found in the northeast and in the Amazonic region, but with lower altitudes (200 to 500 m).

The South American Surface was then submitted to weathering activity that was effective also on the Velhas Surface leading to a new alteration of lateritic type.

Thus, the South American Surface (Eocene) constitutes a nearly continuous geographical compartment in the interior of Brazil. Its cover materials are thick and rich in iron and aluminum oxides (over ultrabasic rocks silica is also common). Velhas Surface (Plio-Pleistocene) is divided into different compartments that correspond roughly to the great hydrographic basins. Its cover materials have peculiar characteristics. In the Amazon Basin the superficial formations are thick and clayey (kaolinitic), while in the Araguaia-Tocantins and São Francisco Basins it is much thinner and less clayey. In Urucum, the « jaspilitic » massif forms a group of plateaus covered by materials that, except for a ferruginous superficial indurated layer, exhibit a low degree of alteration when compared to other iron ore deposits of Brazil. They have a higher content of silica (~ 20 %), reason why they are not exploited yet. In southeastern Brazil, the cover is rather thin and it is characterized by the presence of kaolinite and aluminous vermiculite.

These lateritic deposits as a whole cover nearly 75 % of the Brazilian surface and have very few indurated layers.

## **II — LATERITIC ORE DEPOSITS OF BRAZIL**

### **A — ALUMINUM DEPOSITS**

The aluminum deposits of Brazil (bauxites) are all of lateritic origin and they are formed by the supergenic evolution of different rocks. In figure 1, showing the bauxite distribution in Brazil, we can observe that they are

concentrated in three large regions :

- *northern region* (Amazônia), with an equatorial climate, where the bauxite is formed from clastic sediments of Pliocene age ;
- *middle-eastern region*, with a tropical humid climate with contrasting seasons, where the bauxite is originated from the alteration of different lithological types of Pre-Cambrian age (migmatites, granites, granite-gneisses, schists, amphibolites, etc.) ;
- *southeastern region*, with a subtropical climate and with deposits associated with the evolution of alkaline rocks.

Aluminum reserves in these three regions are shown in table II.

Table II  
*Bauxite deposits of Brazil. Gisements de bauxite du Brésil*

GEOGRAPHICAL REGION	DISTRICT	LITHOLOGY	RESERVES (x 10 <sup>6</sup> ton)	CONTENT % Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>
SOUTHEAST	Poços de Caldas	alkaline rocks (K - Tertiary)	65	54-50	2-5
	Itatiaia		10	45-50	2-6
	Lages		5	48-51	4-6
	Passa Quatro		20	48-50	2
MIDDLE-EAST	Quadrilátero Ferrífero	different lithologies (Precambrian basement)	20	36-42	1-4
	Serra do Mar		5	42	2
	Serra da Mantiqueira		120	38-45	3-6
	Carajas		50	38-40	1-2
NORTH	Trombetas	detritic sediments (Tertiary)	1126	49	3-5
	Jari		369	50	3-5
	Almeirim		639	48-50	4-6
	Paragominas		2460	48-52	4-6

### 1. Bauxites of the southeastern region

Several small deposits of bauxites related with alkaline massifs are found in the Brazilian southeastern region (Poços de Caldas, Lages, Passa Quatro, Itatiaia, Redondo, etc.) (fig. 3). These massifs form generally high plateaus, sometimes with more than 2000 m above the surrounding area.

The alkaline massifs are generally formed by a subsaturated to saturated syenitic sequences (syenites, phonolites, trachytes, foyaites, tinguaite, etc.). These rocks are constituted mainly of K-feldspar, nepheline, aegirine-augite, sodalite, cancrinite and other feldspathoids. Quartz and micas may also be present in small amounts.

Normally, two different topographic compartments, easily identified in the landscape, are associated with those massifs. One of them, situated on the border of the massifs, shows an undulated to hilly topography with steep slopes. The other one, associated with the internal plateau of these massifs, presents a slightly undulated topography. Those plateaus, except for the one in the Passa Quatro massif, have always a structural origin.

Two types of bauxitic alteration profiles related with the two different topographic compartments can be found in the different alkaline massifs (ALMEIDA, 1977 ; MELFI and CARVALHO, 1984).

#### a) Ridge alteration profile

In the steepest slopes of Poços de Caldas, Itatiaia and Passa Quatro massifs, the excellent drainage conditions are responsible for the strong alteration of the alkaline rock. The result is the formation of a bauxitic layer directly in contact with the rock and very rich in aluminum (gibbsite) and poor in silica (clay) and iron (goethite). Despite the well developed alteration, these profiles are always rather thin, due to the erosive mechanism that is very active in the zone of steep slope. Consequently, in these slopes alkaline rock outcrops are common.

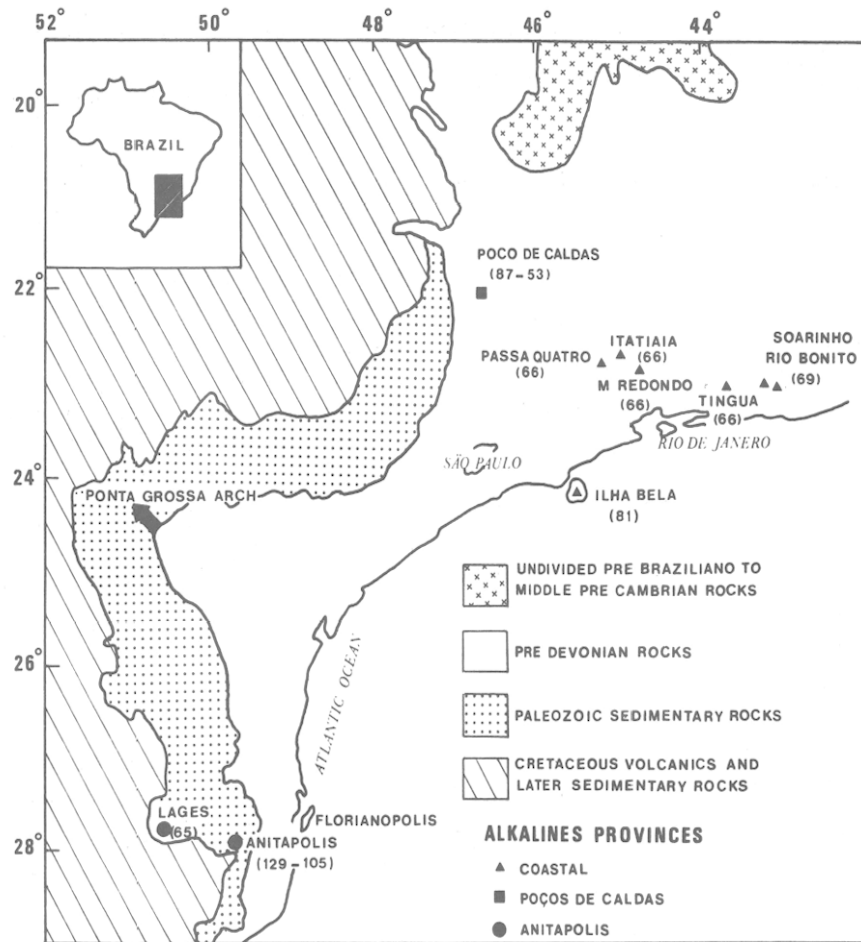


Fig. 3 — Location of alkaline massifs of southern Brazil.  
*Localisation des massifs alcalins du Sud-Est du Brésil.*

These bauxitic profiles present, from bottom to top, three main horizons :

- *a friable horizon*, with preserved structure, formed by a homogeneous, light yellow bauxite with 2 to 6 m thickness. Its density is quite low (nearly 1 g/cm<sup>3</sup>) and the porosity is high ( $\pm 60\%$ ) ;
- *a coherent dense horizon*, constituted also by bauxite with preserved structure, usually overlying the previous one, but locally lying directly on the rock. It is a more coherent and harder horizon, with a higher density (1.2 to 2.0 g/cm<sup>3</sup>) and lower porosity (10 to 50 %). The thickness of this horizon, which may attain 10 m, is generally around 3 m ;
- *a nodular superficial horizon* which when present, may have 1 m of maximum thickness. Its structure is nodular or concretionary, with the structural elements embedded either in a clay matrix of reddish color or in a bauxitic matrix of reddish-yellow color.

The chemical and mineralogical composition along the ridge alteration profile is shown in figure 4. It can be noticed that the transition between the fresh rock and the bauxite is quite sharp. The primary minerals are quickly altered, undergoing a total loss of silica and bases. At the same time gibbsite, goethite and halloysite associated with small amounts of kaolinite, boehmite and lithiophorite are formed. Concerning the chemical composition this bauxite corresponds to a very rich ore of high grade type (BARDOSSY, 1982) with alumina content higher than 55 %.

#### *b) Plateau alteration profile*

This profile type is associated with the most important bauxite reserves related to alkaline rocks. It is found in all the studied massifs, related to a less undulated and smoother topography. In these areas, the internal

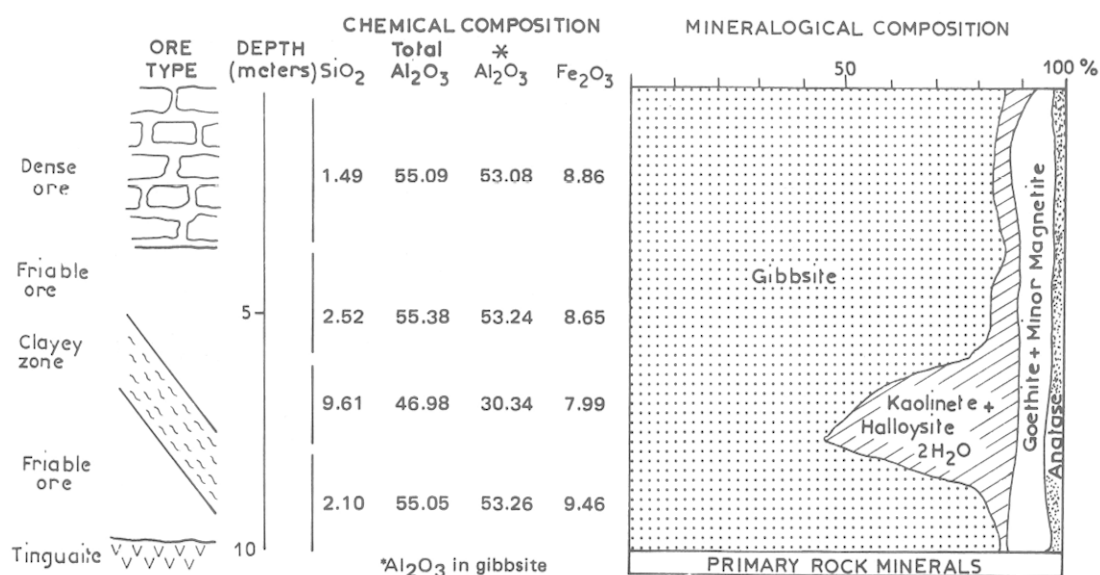


Fig. 4 — Chemical and mineralogical composition along the bauxitic ridge alteration profiles, Poços de Caldas (after ALMEIDA, 1977).  
 Variation de composition chimique et minéralogique le long d'un profil d'altération bauxitique de versants en secteur montagneux, Poços de Caldas (d'après ALMEIDA, 1977).

drainage is less important than in the previous one, and a less developed and more heterogeneous alteration profile is formed. Nevertheless, it presents a higher thickness related to the lower erosional activity.

The plateau profile, like the previous one, shows three main horizons, as follows :

- a kaolinitic clay horizon that lies directly on the bedrock. The present thickness ranges from a few centimeters up to 4 meters, and it shows a massive structure, clay texture and reddish color ;
- a bauxitic horizon with preserved structure, presenting a spongy or compact structure and thickness varying from 2 to 7 m. Its color is light yellow or reddish brown. The density ranges from 1.6 to 2.0 g/cm<sup>3</sup>, while the porosity varies from 16 to 50 %. The friable horizon with preserved structure, which is dominant in the ridge deposits, appears scarcely in the plateau profiles ;
- a nodular horizon that covers all the plateau alteration profiles. Its thickness is generally around 2 m and the characteristics are very close to the one in the ridge profiles.

The chemical and mineralogical composition of the plateau alteration profiles is shown in figure 5. It is noteworthy that the mineralogical composition here is quite similar to that of the ridge profiles, the difference

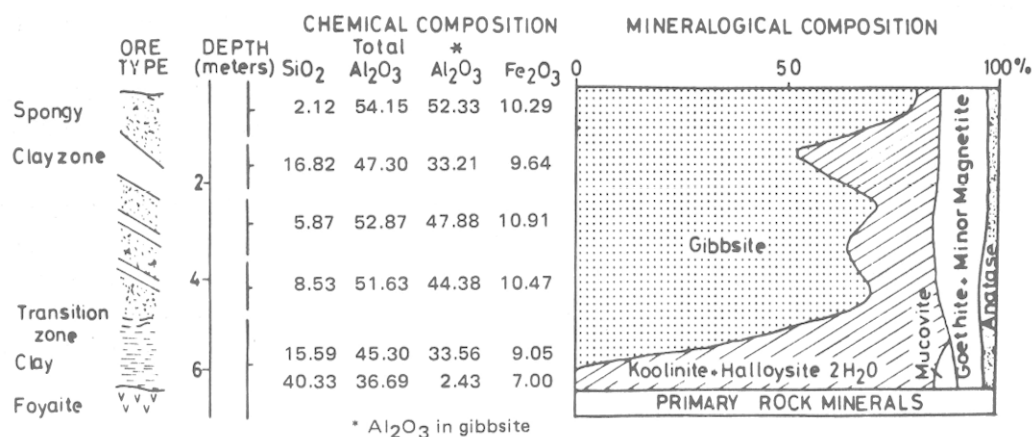


Fig. 5 — Chemical and mineralogical composition along the bauxitic high plateau alteration profiles, Poços de Caldas (after ALMEIDA, 1977).

Variation de composition chimique et minéralogique le long d'un profil d'altération bauxitique du plateau central du massif alcalin de Poços de Caldas (d'après ALMEIDA, 1977).

being the presence of a kaolinitic clay horizon between the bauxite and the parent rock and a rather important mica content. The clay horizon is constituted mainly of kaolinite, 7 Å halloysite, illite and traces of gibbsite. Considering the chemical composition, this profile type has less aluminum and more silica than the previous one.

**c) General interpretation of the alteration profiles evolution developed on alkaline rocks**

The study of the alteration profiles developed from alkaline rocks shows that bauxitization is a direct process and is characterized by a rapid hydrolitic evolution of feldspars and feldspathoids (GROKE *et al.*, 1983). This evolution starts at the borders and discontinuities of crystals, giving origin to a gibbsitic network preserving the original rock structure. Later on, the central part of the minerals are dissolved and partially leached forming aluminous products, that are ill-crystallized at the beginning, and that may either change into gibbsite (second generation) or be eliminated leaving empty cavities. The result is a porous material, with preserved structure, low density, and high porosity. This material may undergo a gibbsite recrystallization which fills the cavities (third generation) and which may change into a hard and dense one.

The pyroxene, which alters almost simultaneously with the feldspar, is completely dissolved, forming a ferruginous residue which evolves into goethite. Haematite may also be formed later on.

The occurrence of a clay layer between the bauxite and fresh rock may suggest an indirect origin for the bauxite. Nevertheless, when in this situation, the preserved structure in the bauxite overlying a clay layer with no preserved structure seems to support a direct genetic process. The study of a topographic sequence (fig. 6) shows a close relationship between the local drainage conditions and the development of both types of profiles. In the zones of steep slope, the intense internal drainage leads to the formation of homogeneous bauxitic profiles. In the lower ones, where drainage is not as good and where the silica lateral migration is rather important, an essentially kaolinitic profile is developed. It is suggested that the formation of this material in the lower part reduces the water flow and, consequently, the zone of kaolinitic alteration moves upwards. Thus, the so-called kaolinitic profile migrates towards the top, leading to the formation of a clay horizon underlying the older bauxitic layer. In this case, bauxitization is no more an active process at the present.

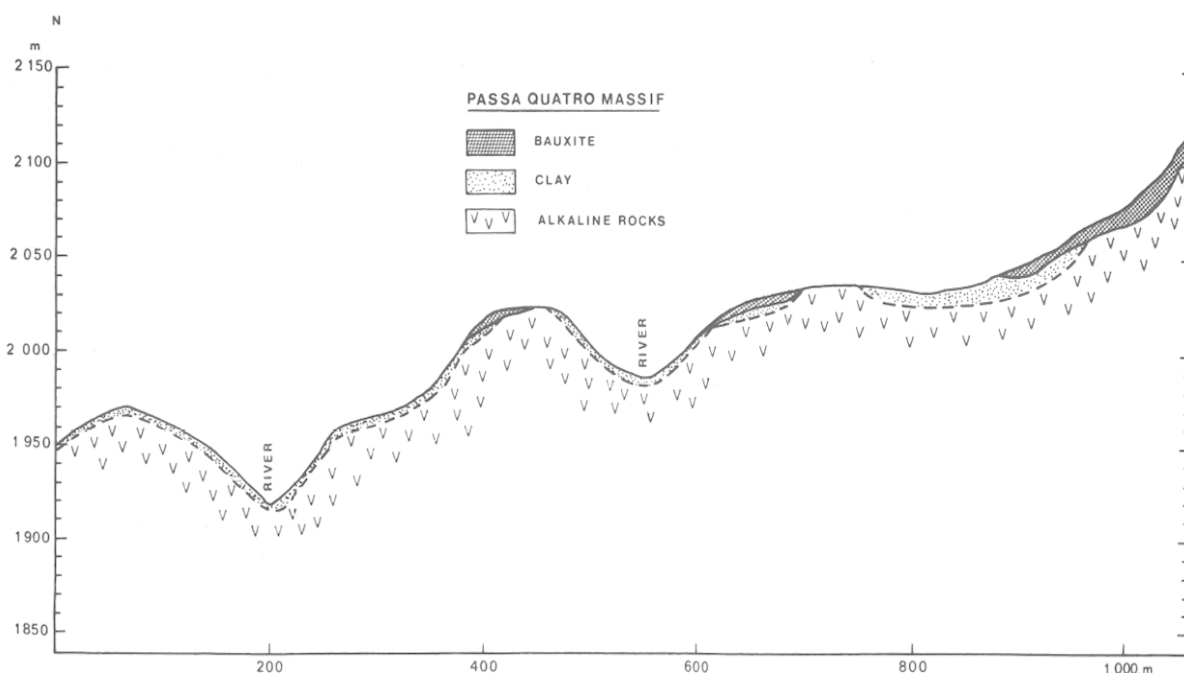


Fig. 6 — Cross-section of high plateau bauxitic deposit, Passa Quatro alkaline massif.  
Coupe à travers un gisement bauxitique de hauts-plateaux, massif alcalin de Passa Quatro.

## 2. Bauxites of the middle-eastern region

Important bauxite ore deposits occur in the middle-eastern part of Brazil, associated with the superficial evolution of different rocks of Pre-Cambrian age ; like granites, micaschists, amphibolites, charnockites, metavolcanic rocks (phyllites), gneisses, etc. These deposits are distributed over great geographical extensions and within different altitudes. Nevertheless, they always occupy the high positions of Serra do Mar and Serra da Mantiqueira and are associated with old erosional surfaces developed in the Eocene.

Considering their importance for the Brazilian mineral economy, two different areas, included in this region, may be mentioned : Quadrilatero Ferrifero, due to its proximity to the siderurgical center, and Cataguases, due to the important reserves recently found.

### a) Quadrilatero Ferrifero

In the Quadrilatero Ferrifero there are about 26 bauxitic deposits that have been studied since 1945 by GUIMARÃES, and more recently by POMERONE (1974), FLEISCHER (1968), FLEISCHER and OLIVEIRA (1969). Nevertheless, these deposits are not yet very well known.

The bauxite deposits are associated with rocks belonging to Itabira Group, consisting mainly of itabirites and dolomites with intercalations of phyllites. These phyllites are indeed metavolcanic rocks with basic, intermediate, or even acid character, that could concentrate aluminum by weathering.

The existence of metavolcanic rocks has been recognized rather recently so that FLEISCHER and OLIVEIRA (1969) have suggested an allochthonous origin for these deposits, considering that the itabirite could not be a source of aluminum.

The studies that have been carried out in the area (VARAJÃO, personal communication) have shown that field observations do not support the previous ideas and that the bauxites of Quadrilatero Ferrifero seem to be related to *in situ* evolution of volcanic intercalations.

### b) Cataguases

The Cataguases bauxite deposits are associated with the so-called « Charnokite Complex » of Paraíba do Sul, consisting of migmatites, garnet-gneiss, amphibole-gneiss, granulites.

The observation of prospecting pits opened by Companhia Brasileira de Alumínio (CBA) in the area of Mirai, Miradouro, Astolfo Dutra, Rio Pomba, Nepomuceno, etc., has allowed to establish a typical profile for this kind of deposit (fig. 7).

A schematic profile presents, from top to bottom, the following sequence :

- *clay soil* with reddish brown color, and thickness up to 1 m ;
- *nodular bauxite*, presenting elements with an average diameter of 2 to 3 cm that may reach 10 m. The nodules are embedded in a brownish matrix ;
- *transitional zone* where the concentration of nodules decreases, while the amount of larger bauxite blocks increases ;
- *dense bauxitic horizon* of yellow color (« breccia-like ») with preserved structure. Downwards, the bauxite becomes denser and may contain blocks of weathered rock. The color here is redder, showing a yellow hue ;
- *weathered rocks* (saprolite), sometimes intercalated with bauxitic blocks, in the upper part.

In many profiles the dense bauxitic horizon overlies a very fine red yellow matrix (clay size) containing some fragments of bauxite.

Bauxite deposits are always situated at the top of hills presenting very undulated topography. The bauxitic layer is rather thick in the hill top, thinning down towards the valley, where only the fine matrix is found over the rocks.

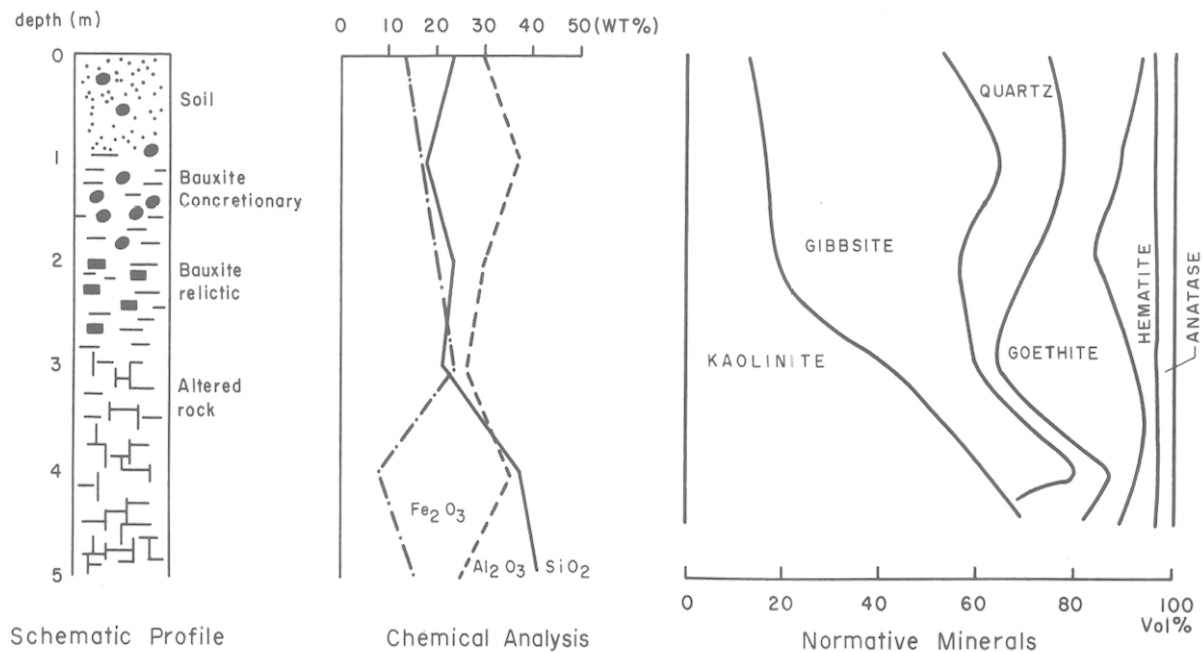


Fig. 7 — Chemical and mineralogical composition along a typical bauxite profile, Mirai (Cataguases).  
*Variation de composition chimique et minéralogique le long d'un profil bauxitique typique, Mirai (Cataguases).*

### 3. Bauxites of the northern region (Amazônia)

The bauxite deposits of the Amazon region are quite homogeneous and they are generally characterized by only one type of profile, with slight variations in thickness (ALEVA, 1981 ; SOARES *et al.*, 1984). The only exception is the bauxitic deposit of Serra dos Carajas, developed from a basic metavolcanic rock of Pre-Cambrian age. Many deposits, totalizing a reserve of 4000 million tons, are found in the region, being Trombetas, Paragominas and Almerim the most important ones.

Considering the lithological and morphological aspects, the region is very uniform. Thus, the Amazon bauxitic ore deposits are developed from detrital sediments of Barreiras Group, consisting of sandstones with cross bedding and intercalated clay. These are poorly sorted sediments and they normally present a gradation from coarse-grained material (conglomerates and coarse sand) in the base to fine-grained one in the top (fine sand, clay). The dominant minerals are quartz and kaolinite, associated with feldspars and mica that do not exceed 5 %. The Pleistocene age of these sediments is a matter of discussion.

The regional topography is characterized by the presence of a great plateau, rather dissected, having flat tops which evidenciate the existence of a large erosional surface between 160 and 200 m of altitude. This surface, developed on rocks supposed to be Pleistocene, was interpreted as corresponding to the Velhas Surface (KING, 1956) of Plio-Pleistocene age. Nevertheless, this age is not certain, first because the sediments could be older, Cretaceous for instance, and then because the correlative deposits present structural aspects related to older materials, with very long development. That is the case of the pisolitic bauxite, which in Africa is always associated with older surfaces Cretaceous-Eocene (GRANDIN and THIRY, 1983). Based on the fact that there is no deposit of that size in the world after the Medium Tertiary, GRANDIN and THIRY (1983) suggested that the age of this formation should not be Plio-Pleistocene.

#### a) Alteration profile

In all profiles, the bauxite layer is found in the upper part of the plateau, either outcropping directly on the surface or, more frequently, covered by a plastic clay layer 5 to 15 m thick (fig. 8).

Considering a typical profile, the following horizons can be observed from bottom to top :

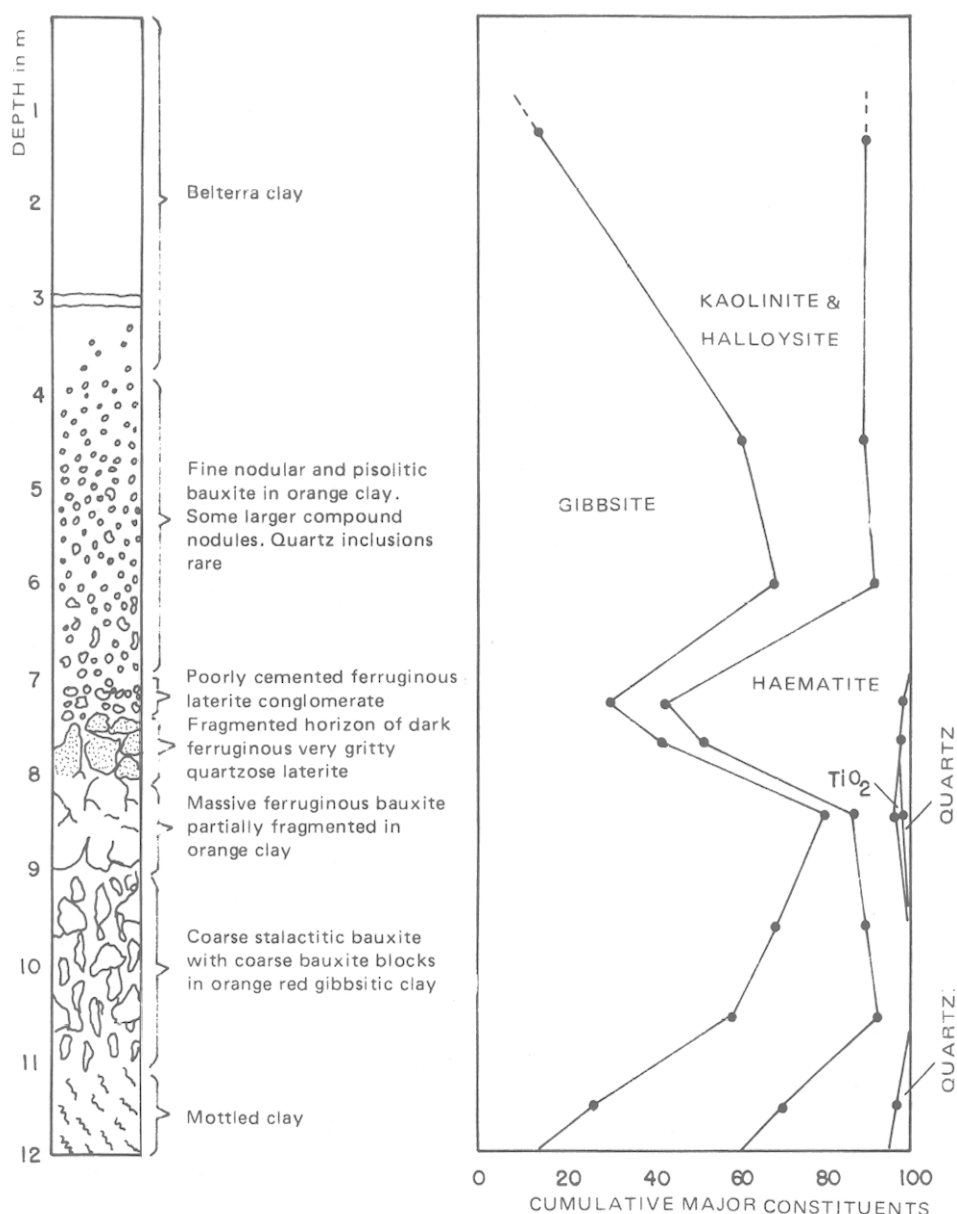


Fig. 8 — Profile section through Trombetas bauxite deposit (after GRUBB, 1979).

*Profil d'altération du gisement bauxitique de Trombetas (d'après GRUBB, 1979).*

**Mottled clay**, forming the lower horizon, directly in contact with the Barreiras sediments and characterized by a strong clay enrichment with decrease of quartz that starts to be dissolved. Neoformed kaolinite is found in this horizon, giving origin to horizontally oriented white lenses (CHAUVEL, personal communication). The presence of nearly colorless ferruginous concretions is common, giving a mottled aspect to the horizon. It represents the parent rock alteration.

**Bauxitic layer.** It is a horizon with average thickness of 10 m, consisting of three sub-horizons :

- **massive to granular bauxite.** This sub-horizon may attain 6 m depth and presents, near the base, pockets of yellow clay with up to 62 % kaolinite (SOARES *et al.*, 1984), vertically elongated and containing bauxite fragments in its interior. Here the bauxite shows cavities that may be filled with gibbsite or, more frequently, with clay. In the intermediate part, the bauxite becomes friable, alveolar, frequently showing irregular rock blocks in gibbsite and associated with kaolinitic clay. In the upper part, a hard and compact iron-rich layer occurs, characterizing a ferruginous bauxite, with high density and much quartz. In this layer, the iron starts to be replaced by silicon and aluminum ;

- *ferruginous laterite*. It is a sub-horizon of variable thickness (1.5 to 3.0 m) which grades into a ferruginous bauxite towards the top. In the upper part, the bauxite is pisolitic with aluminous pisolites cemented by iron oxide. Some crust of a white and very hard bauxite with colloidal aspect is found in this level ;
- *nodular or pisolitic bauxite*, consisting of bauxite nodules, very hard and with irregular shapes. The amount and size increase towards the underlying ferruginous layer. These nodules are embedded in a clay matrix of red color and kaolinitic composition. Coarser ferruginous pisolites are associated with gibbsitic nodules and their nuclei may consist of gibbsite or quartz.

*Yellow clay*. It is the cover of most bauxitic profiles. This layer is constituted by quartz and kaolinite (nearly 80 %), rather uniform and permeable. The thickness is maximum in the plateau center, decreases towards the border, and is absent in the eroded areas. Its interpretation is still a matter of discussion. SOMBROEK (1966) named it Belterra clay and suggested a lacustrine origin. Later on, DENNEN and NORTON (1977) considered this clay as part of the lateritic profile, i.e., formed *in situ*, based in the interpretations of WOLF and SILVA (1973).

Recently, TRUCKENBRODT and KOTSCHOUBEY (1981) suggested an allochthonous origin, related to the deposition by means of mudflow. This idea was not accepted by ALEVA (1981) that proposed *in situ* origin of a residual soil formed at the same time as the bauxites. More recent works carried out by CHAUVEL, BOULET and LUCAS (personal communication) seem to confirm a residual origin for the Belterra clay.

#### **b) Chemical and mineralogical characteristics**

As to mineralogy, the bauxitic layer is essentially gibbsitic (fig. 8), originating from the evolution of kaolinites, associated to small amounts of goethite, frequently of aluminous type, and haematite. Kaolinite is always present but in a very small amount. Boehmite, as well as quartz, is rare and frequently absent. Illite may occur as trace, while halloysite, associated with ill-crystallized gibbsite or amorphous (clachite), was detected in some profiles. The main heavy minerals are rutile, ilmenite, tourmaline, zircon and anatase. GRUBB (1979) pointed out the fact that ilmenite is present in a high content but its alteration product, leucoxene, is absent, which seems to indicate that the bauxitization has occurred under special Eh conditions.

Concerning chemical composition, the bauxite shows alumina content between 43 and 45 % that after treatment may reach 60 %. The silica content is relatively high (6-15 %), while the iron remains between 6 and 20 %.

#### **c) Genetic considerations**

Many authors have studied the genesis of these deposits. GRUBB (1979) suggested a polygenetic origin, with several evolution steps :

- lateritic alteration of clastic sediment and formation of massive bauxite under a humid climate, with contrasting seasons ;
- uplift of the base level and deposition of the Belterra clay ;
- modification of climatic conditions, favoring podzolization, with migration of aluminum and formation of ferruginous laterite ;
- lowering down of the base level and occurrence of a new bauxitization phase.

A similar interpretation was proposed by DENNEN and NORTON (1977), the difference lying on the Belterra clay that was considered as an *in situ* formation.

KOTSCHOUBEY and TRUCKENBRODT (1981) also confirmed the polygenetic model, suggesting five different phases in the deposit formation, controlled by climatic modifications. These authors also consider that the polygenetic formation of the bauxitic sequence required a very long period of time and they support the idea of its formation from the Eocene and not from the Upper Tertiary and Quaternary.

## B — IRON ORE DEPOSITS

### 1. General features

The lateritic iron ore deposits show a geographical distribution controlled by the occurrence of a ferruginous parent rock of itabirite-jaspilite type (Banded Iron Formation, BIF) (DORR, 1964 ; PUTZER, 1959 ; TOLBERT *et al.*, 1971). Consequently, the main Brazilian iron deposits (fig. 1 and table III) are situated in Pre-Cambrian areas where the « BIF » are common, like Serra dos Carajas Amazonia), Quadrilatero Ferrifero (Minas Gerais) and Urucum (Mato Grosso do Sul).

Table III  
*Iron deposits of Brazil. Gisements de fer du Brésil*

STATE	DISTRICT	KIND OF BIF MINERALOGY	ASSOCIATED ROCKS	RESERVES (x 10 <sup>9</sup> ton)	CONTENT % Fe
Minas Gerais	Quadrilatero	haematite-magnetite	sedimentary and volcanic	13	30-66
Para	Carajas	haematite-martite magnetite	volcanic	18	63-66
Mato Grosso	Urucum	haematite-quartz (crypto)	sedimentary	(50)	50-64

In these deposits with no doubt, lithology is the main genetic factor, climate being of subordinate importance. Nevertheless, time seems to play an important role, mainly with respect to ore quality, as can be evidenced in the deposits of Serra dos Carajas and Quadrilatero Ferrifero. These two deposits, the most important iron ore deposits of the world, are associated to old Eocene surface (South American Surface), where itabirites are deeply weathered, showing an alteration profile with hundreds of meters (fig. 9). On the other hand, the deposit of Urucum, developed more recently on Plio-Pleistocene surface (Velhas Surface), in spite of having an iron-rich protore, is not a good iron ore, since the alteration does not remove all the silica (quartz dissolution is partial).

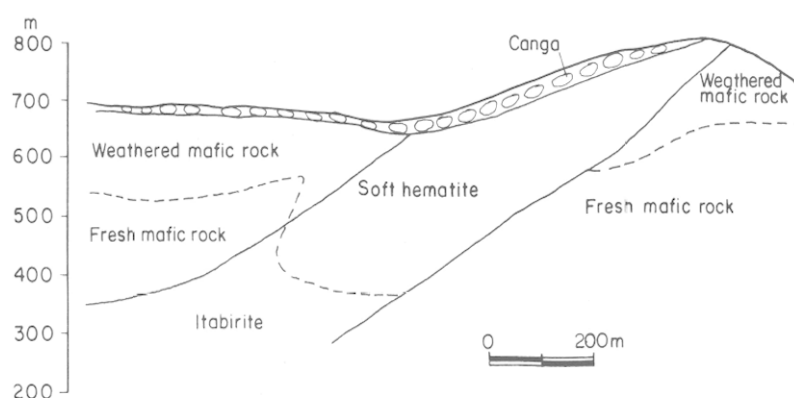


Fig. 9 — Cross section of Carajas iron deposit.  
*Coupe du gisement de fer de Carajas.*

In all Brazilian deposits, the first iron accumulation is of sedimentary origin, either chemical, as in Quadrilatero Ferrifero, or detritic, as in Urucum. The sedimentation occurred in the Pre-Cambrian, in large geosynclinal or volcano-sedimentary basin. Both in Carajas and Quadrilatero Ferrifero, these sedimentary

rocks were lately affected by successive orogenic phases. These processes have originated the metamorphic rocks (itabirites) characterized by a very singular mineralogical composition, where nearly 95 % of its volume is formed by quartz, haematite and martite and the 5 % left, made of accessory minerals, mainly magnetite and wavellite,  $(\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O})$ . As a consequence of metamorphism, these rocks show a coarse, well developed and oriented texture. The haematite, interlayered with quartz, consists of elongated lamellae, with 500  $\mu\text{m}$  average length, which may reach some millimeters. Quartz is slightly smaller.

In Urucum, the ferruginous sediments were not affected by metamorphism and the iron deposit was developed on a thick sedimentary sequence (Jacadigo Series), having in its upper part a more than 300 m thick layer of jaspilite. This rock is formed by the intercalation of fine layers of haematite and silex.

The landscape in these three regions is dominated by levelled surfaces, covered with thick ferruginous crusts (« canga ») which attain more than 20 m thickness. In Carajas, where the itabirite is intercalated with metavolcanic rocks (greenstones rocks), the surface shows two different levels : a higher one, which corresponds to the itabirite rocks and which is covered by a ferruginous crust, while the other one is 150 m lower, and is related to the greenstones, less resistant to weathering and erosion, and covered by a bauxitic crust.

## 2. Itabirite alteration profile

The Quadrilatero Ferrifero and Carajas deposits can be characterized by a single profile type. They are rather similar, the difference lying on the thickness of the alteration zone. The representative schematic profile shows, from bottom to top, the following sequence of horizons (fig. 10 after EICHLER, 1967).

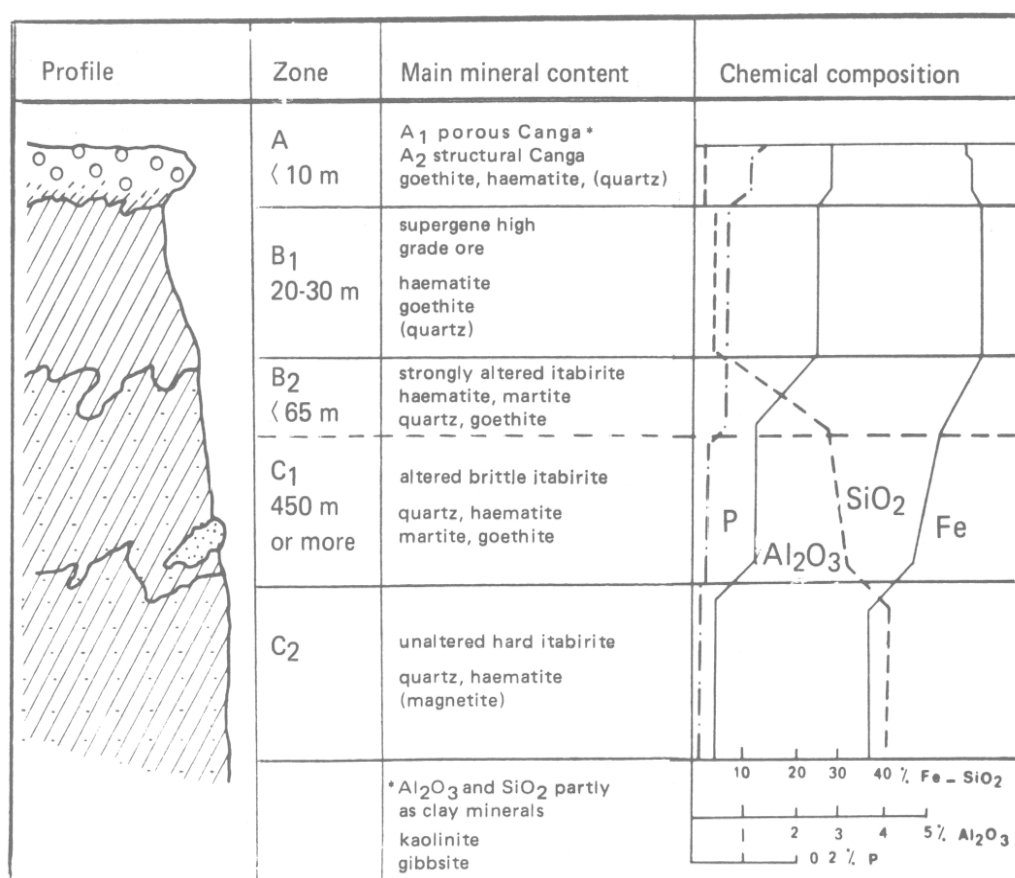


Fig. 10 — Chemical and mineralogical composition along a typical schematic itabirite alteration profile. Quadrilatero Ferrifero (modified after EICHLER, 1967).

*Variation de composition chimique et minéralogique le long d'un profil d'altération schématique développé sur itabirites. Quadrilatère ferrifère (d'après EICHLER, 1967, modifié).*

**Fresh itabirite** : compact and hard rock made of iron oxide layers (dominantly haematite with subordinate magnetite and martite), with dark grey colors alternated with quartz layers.

**Slightly altered itabirite**. In this horizon the rock shows evidences of disaggregation, but the structure is still visible. The quartz layers present an important porosity, related to an incipient dissolution. The haematite is still fresh, loosing only its characteristic brightness. Ferruginization processes are active in the quartz layer.

**Weathered itabirite**. In spite of the layered rock structure still visible, the rock is already friable and easily disaggregated, isolating its constituents. The colors change into a reddish hue.

**Soft haematite**. The horizon has nearly no quartz and is formed mainly of free haematite. Secondary iron oxides give a red color to this material. In its upper part, cementation of primary haematite by ferruginous products occurs.

**Ferruginous crust**. The so-called « canga » is characterized by its hardness, a red-yellow color and a 5 m thickness, which locally may attain 20 m. It presents different structural facies : vacuolar, nodular, breccia-like, alveolar and mottled.

As to chemical composition, the itabirite alteration profile is characterized by an intensive desilicification with consequent iron accumulation. Thus, from the beginning of the alteration, silica content decreases and in the altered rock it is already 50 % less than in the original rock. On the other hand, there is relative accumulation of iron that changes from the original 40 % into more than 60 %. EICHER (1967) showed that the itabirite evolution occurs nearly with constant iron.

As to mineralogy, quartz is very clean and with well defined crystal faces in the fresh rock. In the alteration horizons, it is nearly rounded at the beginning and totally fractured with fissures filled with ferruginous products. Crystal corrosion is well evident. Haematites, with polished and bright faces in the fresh rock, loose their brightness in the first stage of alteration and give support to the development of goethite (MELFI *et al.*, 1976). This goethite may have two different shapes. The first one, as elongated particles forming disordered, nearly round aggregates made of micro-crystals. It is a result of an *in situ* re-organization of haematite into goethite. The other one is acicular and develops perpendicular to the primary crystals, enveloping them. The crystals can be haematite or quartz and the goethite is formed by redistribution of iron which is carried on farther and which promotes particle cementation. This process occurs in the upper part of soft haematite and in the ferruginous crust, where part of the haematite evolves to goethite by pseudomorphose. In the crust, the development of goethite is particularly abundant.

## C — MANGANESE ORE DEPOSITS

In Brazil there are several manganese deposits of different importance and with a wide geographical distribution (fig. 1, table IV). The main deposits are located in the State of Mato Grosso (Urucum) and in the Amazon Region (Azul, Serra do Navio and Buritirama).

Table IV  
Manganese deposits of Brazil. Gisements de manganèse du Brésil

STATE	DISTRICT	RESERVES (x 10 <sup>3</sup> ton)	CONTENT % Mn	PROTORE
Mato Grosso	Urucum	100 000	46-52	primary oxide
Para	Azul	45 000	39-46	carbonate
	Buritirama	12 000	47	
Minas Gerais	Lafaiete	4 400	35	Si-carbonate
	Quadrilatero	13 100	27-35	Si-carbonate
Bahia	Various	15 000	38	primary oxide and carbonate
Amapa	Serra do Navio	20 000	39	Si-carbonate
Ceara	Various	20 000	28	primary oxide and Si-carbonate
Goiás	Various	1 500	36-51	Mn-slate

The deposits of Minas Gerais, despite the small sizes, have been exploited for a long time, due to their proximity to Quadrilátero Ferrífero iron deposits. As a consequence, they are better known when compared with the small deposits of the Northeast and Goiás.

In all Brazilian deposits, the first manganese accumulation is of sedimentary origin. These sedimentary rocks, normally fine grained, are rich in Mn-carbonate (rhodochrosite) and are formed under reducing conditions. Frequently, they have undergone a metamorphism which led to the recrystallization of the rhodochrosite and/or the formation of spessartite. When rhodochrosite is very abundant, these rocks themselves can be exploited as ore (as in Lafaiete, where Mn = 42 %). Nevertheless, the exploitable ore is generally a result of a protore lateritic alteration (carbonatic, silico-carbonatic or silicatic protore, according to the metamorphic processes). Contrary to what was observed in other lateritic deposits, the manganese ores are mainly controlled by lithology, with no association with particular levelling surfaces or recent climatic conditions.

### 1. Carbonatic protore alteration

The Azul deposit, in Serra dos Carajas (PA) was recently studied by VALARELLI *et al.* (1978) and BEAUVAIS (1984). The protore is constituted by the upper levels of Rio Fresco Formation that occupies the middle portion of a great syncline of volcano-sedimentary rocks and Carajas Itabirite (Grão Para Group). The protore was observed only from drill-holes and it presents two manganeseiferous levels intercalated with a Mn-poor layer (fig. 11 and table V) :

- the upper unit, with 33 to 54 m thick, comprises rhodochrosite (30 %), quartz (35 %), micas (20 %), K-feldspars (10 %) and pyrite (5 %) and has an average content of 14 % Mn ;
- the intermediate silty unit (quartz and micas) is 60 to 100 m thick and has 4 % Mn ;
- the lower unit, 18 to 40 m thick, is constituted by rhodochrosite (65 %), quartz (15 %), micas (15 %) and pyrite (5 %), and presents a 26 % Mn content.

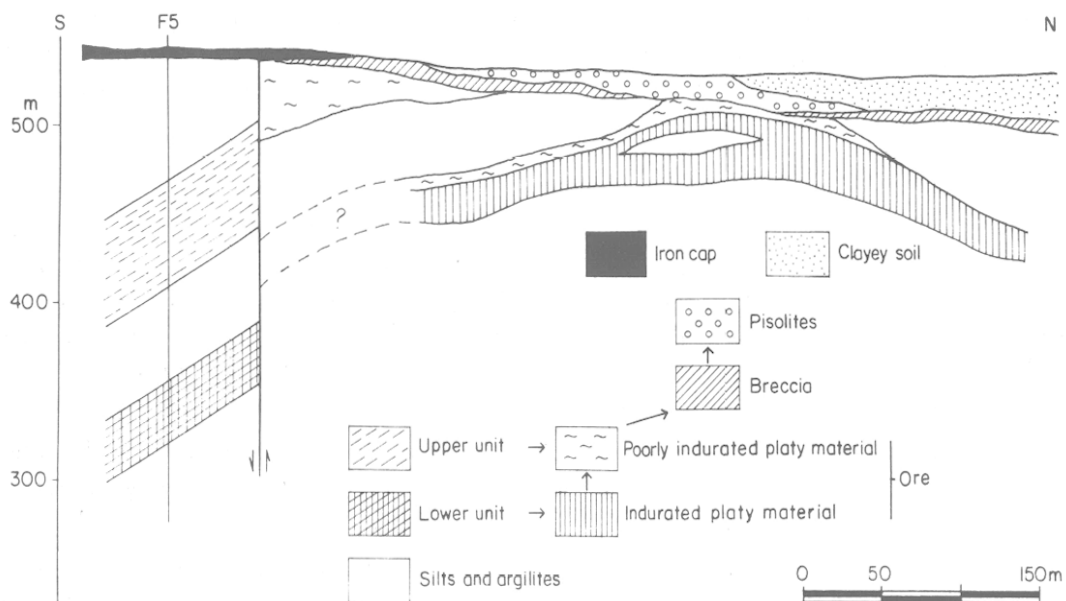


Fig. 11 — Schematic cross-section of the manganeseiferous Azul deposit, Serra dos Carajas.  
Coupe schématique du gisement de manganèse d'Azul, Serra de Carajas.

#### a) The alteration profiles

These are originating from *in situ* alteration of the lower and upper units and are characterized by the platy shape, which is related with the protore sedimentary structure. These plates are harder or even more cemented in the ore originated from the lower units, which is more manganeseiferous (granular, platy or massive facies, with average content of 46.5 % Mn), than the ore formed on the upper unit (pelitic facies with plates less hardened and

Table V  
Azul manganese ore deposit : contents and tons. Gisements de manganèse d'Azul : teneurs et tonnages des minerais

PROTORE		ORE		BRECCIA		PISOLITE
UPPER UNIT Mn = 14-16 % thickness = 33-54 m	→	ILL-INDURATED PLATES pelitic ore Mn = 38 % (washed) tons = 16 mt	→	BLOCKS + Mn PLATES + matrix Fe Al + blocks Fe Al Mn = 38 % (washed) tons = 22 mt	→	PISOLITES Mn + Al pisolites Mn + Al + matrix Fe Al Mn = 18 %
MEDIUM UNIT Mn = 4 % thickness = 60-100 m		↑ ↑				
LOWER UNIT Mn = 21-26 % thickness = 18-40 m	→	INDURATED PLATES ( ore — grained — platy — massif ) Mn = 46.5 % tons = 12 mt				

with average content of 38 % Mn after washing). In the upper part of the hardened platy horizon (lower unit), the plates are fractured into smaller elements embedded in a reddish matrix. This disaggregation goes on, affecting afterwards the breccia-like material, which covers the *in situ* altered levels : the plates size decreases while the amount of matrix increases. The presence of fragments of iron crust and bauxite evidentiates the occurrence of mechanical transport. Nevertheless, this material presents 38 % Mn after washing.

In the surface, the destruction of the plates is accelerated and pisolites are formed. The pisolites have a manganesiferous core, several Fe-Al-Mn cortex and are embedded in a reddish-brown clay matrix (pisolitic material — which may locally attain 10 m). The pisolitic material contains centimetric plate fragments, badly rounded, with a very thin cortex up to spheric pisolites (5 mm diameter), where the nuclei are entirely taken by the cortex. Even after washing, the Mn content does not exceed 18 % and this level is not exploitable.

#### b) Chemical and mineralogical evolution

The gradation from rock to ore can not be observed. In the lower part of the platy horizon, quartz is dissolved, sulfides are oxidized, micas are slightly altered and rhodochrosite changes into cryptomelane (locally todorokite), preserving the micronodular structure of the carbonate. This plasmic cryptomelane is recrystallized pseudomorphically at the beginning, afterwards into nsutite, ramsdellite in the pores and, finally, into polianitic pyrolusite. This evolution is followed by an increased oxidation of the manganese up to Mn<sup>IV</sup>, with the successive phases being progressively enriched in MnO<sub>2</sub> (up to more than 96 % MnO<sub>2</sub> in the pyrolusite).

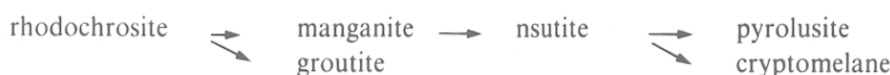
As soon as the plates start to be destroyed, the micas are altered into kaolinite, liberating their K content. The previous manganesiferous mica phases undergo a retrometamorphic evolution, changing into secondary cryptomelane which corresponds to a partial reduction of Mn<sup>IV</sup> into Mn<sup>II</sup>.

In the breccia-like level, and mainly in the pisolites, nsutite and pyrolusite disappear and the secondary cryptomelane is formed in the center of the pisolites, while in their border the cryptomelane changes into lithiophorite, which represents a partial reduction of Mn<sup>IV</sup> to Mn<sup>II</sup> and an important gain of aluminum. The lithiophorite of the cortex is associated to kaolinite, goethite and gibbsite which are also the constituents of the matrix enveloping the pisolites.

The geochemical balance data of each phase of alteration show that the final retrometamorphism of MnO<sub>2</sub> to cryptomelane and later to lithiophorite is related to a loss of H<sup>+</sup>, a reduction of Mn<sup>IV</sup> and a loss of Mn<sup>II</sup>, which is remobilized towards the profile bottom. This evolution is controlled by the conditions of the superficial horizons, rich in organic matter, that favours the mobility of aluminum incorporated to lithiophorite. The migration of Mn, from surface to bottom, where it takes part as first-generation cryptomelane which pseudomorphoses rhodochrosite, is the origin of the high Mn content of the exploitable ore deposits.

## 2. Metamorphosed silico-carbonatic protore alteration

The evolution of recrystallized rhodochrosite in the metamorphosed carbonatic protore is similar to that described for Azul deposit. Thus, in Serra do Navio deposit (DORR *et al.*, 1950 ; VALARELLI, 1967), the protore is at first oxidized *in situ* (cryptomelane, pyrolusite) and later destroyed and transported, forming cryptomelane, lithiophorite, goethite and gibbsite. The same process occurs in Conselheiro Lafaiete (BITTENCOURT, 1973 and MELFI and BITTENCOURT, 1975), where the following sequence has been found :



The initial formation of  $\text{Mn}^{\text{III}}$  compounds was not described in Azul deposit, since this first stage of alteration has not yet been observed in this deposit. In Moanda (Gabon), WEBER (1968) shows that the alteration of a protore similar to that of Azul deposit starts with the formation of manganite. The later evolution to  $\text{MnO}_2$  phases (nsutite and pyrolusite) and afterwards the retrometamorphism to cryptomelane are identical to those of Lafaiete and Azul.

In the metamorphosed silico-carbonatic protore the rhodochrosite is associated with manganiferous silicates : spessartite, rhodonite and tephroite. These silicates undergo the same evolution as the rhodochrosites as it was shown by BITTENCOURT (1973) in Conselheiro Lafaiete : progressive oxidation of the manganese in  $\text{MnO}_2$  (nsutite and cryptomelane) after a manganite phase and final retrometamorphism in cryptomelane.

## 3. Urucum ore deposit

The deposit of Urucum, located near Corumba town, in Brazil-Bolivia frontier, represents a very different kind of manganese accumulation.

The associated iron and manganese deposits correspond to six plateaus with undulated tops, very steep slopes and altitudes about 1000 m. These plateaus are formed by a thick sedimentary sequence, Jacadigo Group (1000 Ma) (DORR, 1946 and PUTZER, 1959). The lower part of the sequence is conglomeratic and arkosic, while the upper part, with more than 300 m thickness, is a haematitic jaspilite. This jaspilite shows alternatively centimetric to decimetric layers composed of fine lamellae of haematite and narrow lenses of siliceous 1 cm thick. Its difference from the itabirites (Carajas and Quadrilátero Ferrífero) is the existence of detritic characteristics, like the presence of ilmenite, micas and zircon.

At the base of the jaspilitic level, two manganiferous layers of metric thickness occur separated by 40 m of jaspilite and embedded in detritic rocks (arkoses and conglomerates). The manganiferous layers are constituted mainly of cryptomelane and occasionally pyrolusite and haematite, with several fine intercalations of chert. The texture is generally fine lamellar, very porous, and may be locally nodular in the pyrolusite-rich phases.

The average chemical composition of the manganiferous layers is the following :

$\text{SiO}_2 = 1.26 \%$  ;  $\text{Al}_2\text{O}_3 = 1.74 \%$  ;  $\text{Fe} = 11.1 \%$

$\text{Mn} = 45.6 \%$  ;  $\text{MgO} = 0.13 \%$  ;  $\text{CaO} = 0.20 \%$  and  $\text{K}_2\text{O} = 3.53 \%$

Initially, this deposit was considered as originated by primary chemical sedimentation. Recently, WALDE *et al.* (1981) observed that haematite, as well as silica and cryptomelane, could pseudomorphose rhombohedral crystals, which seems to indicate that the primary minerals were iron and/or manganese carbonates, which actually could never be found. (A rhodochrosite layer in the middle of an itabirite level is known in Conta Historia Mine, Minas Gerais). Consequently, the paragenesis existing in Urucum represents a result of a partial alteration of a certain protore. The low silica content in the jaspilite (20 %  $\text{SiO}_2$ , 70-80 % haematite) seems to indicate also that this rock is partially altered.

## D — NICKEL ORE DEPOSITS

The action of tropical climates on ultrabasic rocks (with olivine and eventually pyroxene, with variable grade of serpentinization), under favorable morphological and tectonic conditions, leads to the accumulation

of thick ferruginous alteration covers, where nickel can be concentrated — *nickeliferous laterite*.

In Brazil, the ultramafic massifs are abundant ; they comprise different types and are scattered throughout different climatic zones. The lateritic nickel ore deposits are associated preferably with certain kinds of massifs and certain climatic zones. As for the parent rocks, they consist of large Archean massifs followed by the Cretacic ultramafic-alkaline massifs. As for the climatic conditions, there is no doubt that the most favorable are those of tropical climate with contrasting seasons found in the central part of the country, and, secondarily, the more humid zones of the Atlantic coast (Sao Paulo and Minas Gerais) or of the Amazon region (Para). Only one ore deposit is known in the semi-arid northeastern region (Piaui) and none in the sub-tropical to temperate southern region, below the 25° parallel.

Table VI summarizes the main characteristics of the most important Brazilian ore deposits, which total reserve of lateritic nickel exceeds  $4 \times 10^6$  ton of Ni.

Table VI  
*Nickel deposits of Brazil. Gisements de nickel du Brésil*

STATE	DISTRICT	RESERVES (x 10 <sup>3</sup> ton)	CONTENT % Ni
Goiás	Niquelandia	60 000	1.45
	Barro Alto	73 000	1.67
	Canabrava	9 500	1.3
	Santa Fé	61 000	1.5
	Serra Água Branca	60 000	1.3
	Morro do Engenho	18 000	1.03
	Morro dos Macacos	10 000	1.3
	Rio dos Bois	?	?
	Montes Claros (Salobinha)	15 000	1-1.5
	Sao Luiz Montes Belos	?	?
Minas Gerais	Morro do Niquel	2 300	1.7
	Liberdade	7 900	1.7
	Ipanema	7 300	1.24-1.59
Sao Paulo	Jacupiranga	2 250	1.47
Piaui	Sao Joao do Piaui	20 000	1.57
Bahia	Serra das Marrecas	900	1.5
Para	Sao Félix do Xingu	13 000	2.1
	Quatipuru	13 000	1.3
	Carajas	40 000	1.56

## 1. Central Brazil (Goiás) ore deposits

In Goiás State, as in most of the regions in Brazil, the ultramafic massifs comprise hills that look down on broad levelled plains corresponding to the country rock (fig. 12). The higher points are generally tabular and frequently capped by a silcrete layer. They are interpreted as remnants of an ancient level of planation, the South American Surface formed in the Lower Tertiary.

The surrounding lowlands are related to a more recent (Late Tertiary) erosion cycle (Velhas) as a result of the south american continent uplift. In areas of ultramafic rocks, the silicification related to the South American cycle, has protected the remnants of the older surface. Depending on the dimensions of the massif and on the nature of the rocks, the erosion of this surface was more or less important.

— In the ultramafic zone central part, at Barro Alto, the South American Surface is partially preserved (fig. 12 A) : this plateau is just dissected by transversal valleys, and its rims have convex slopes ; in contrast, the altitude of the southern and northern parts of the ultramafic zone is lower and corresponds to Velhas level (TRESCASES and OLIVEIRA, 1981).

— In the ultramafic zone southern part, at Niquelandia, Serra da Mantiqueira (fig. 12 B), the South American remnants are well preserved on dunites and peridotites. The pyroxenites correspond to large U suspended valleys, without silcrete and about 50 m lower than the silicified plateau (PECORA, 1944). In the

northern part of Niquelandia and in Santa Fé, the erosion has been more intense and just few hills capped by silcrete have been left as remnants of South American Surface ; the landscape is dominantly flat, corresponding to Velhas level (OLIVEIRA and TRESCASES, 1980) (fig. 12 C).

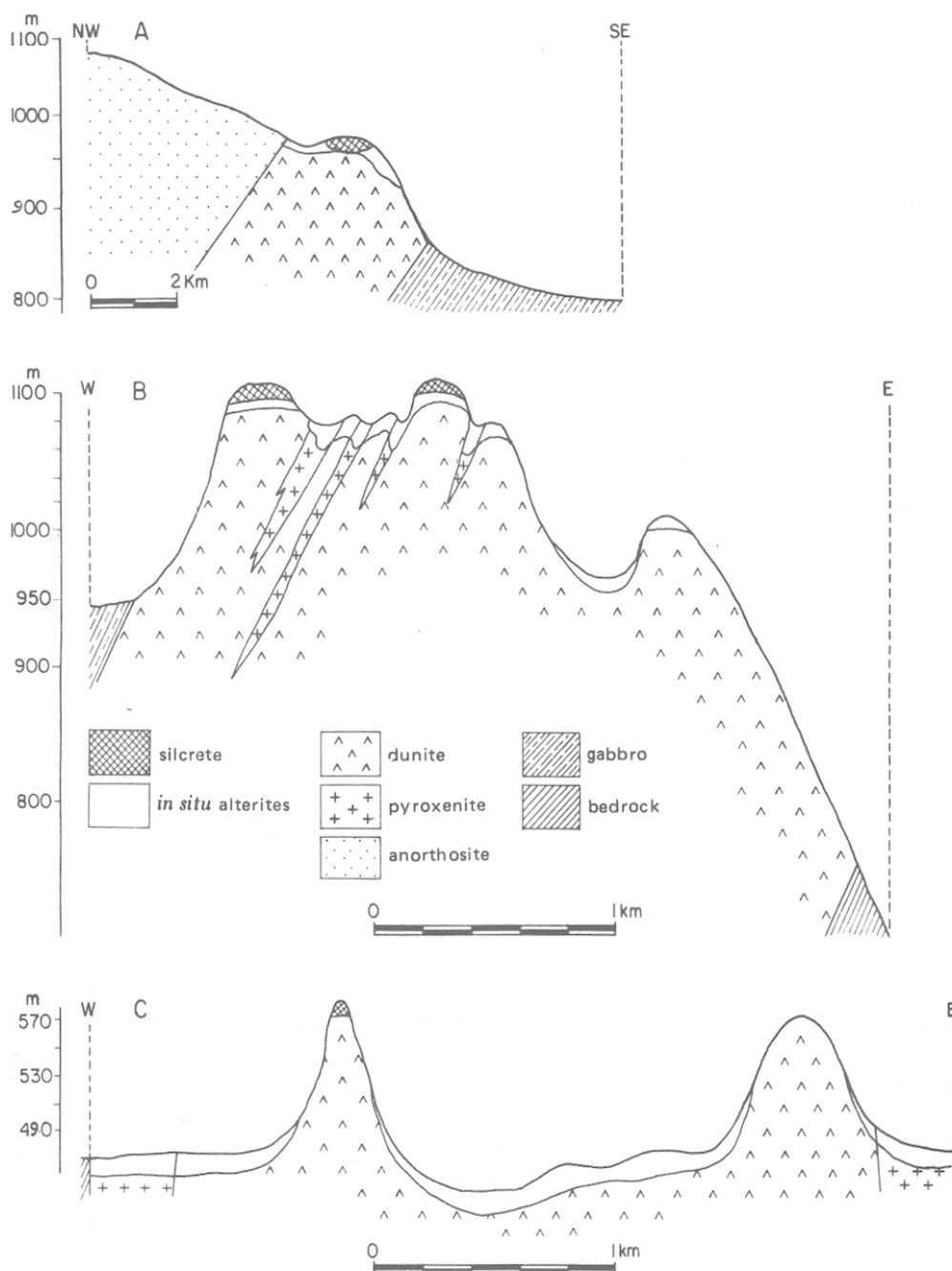


Fig. 12 — Cross-sections of nickeliferous deposits in Central Brazil : A, Barro Alto, central part ; B, Niquelandia, southern part ; C, Santa Fé.  
 Coupes de divers gisements nickélifères du Brésil central : A, Barro Alto, partie centrale ; B, Niquelandia, partie Sud ; C, Santa Fé.

#### a) The alteration profiles

Figure 13 shows the different types of alteration profiles in a topographic sequence.

On the tops, the profiles are not well developed, the silcrete (accumulation of silicified blocks) covers

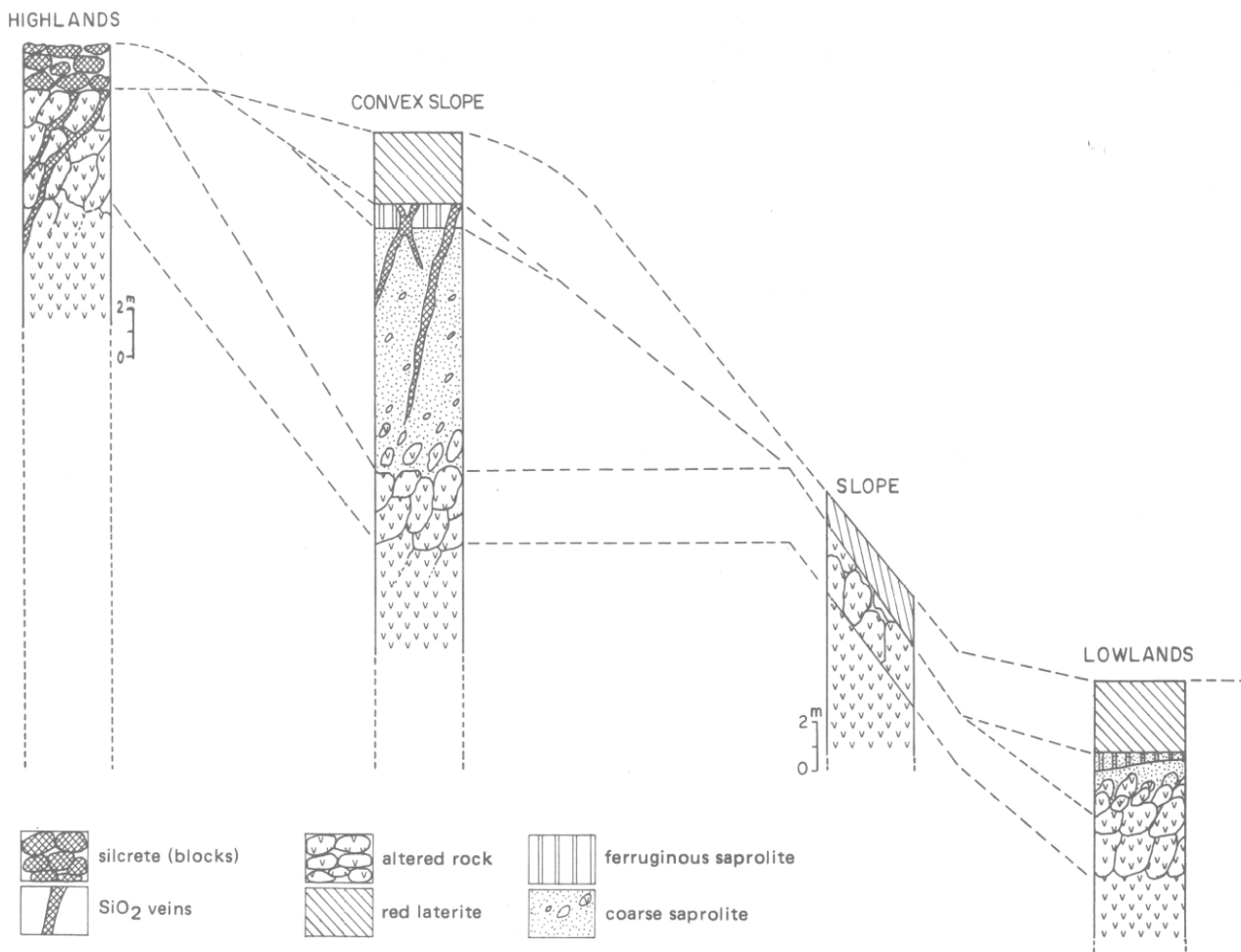


Fig. 13 — Ultramafic rocks alteration profiles morphological characteristics in highlands, slopes and lowlands in Central Brazil.  
*Caractéristiques morphologiques de profils d'altération de roches ultrabasiques en zones hautes, sur les versants, et en zones basses, dans le Brésil central.*

partially a slightly weathered hard rock and sometimes underlies 1 to 2 m of saprolite.

*On some depressed zones in highlands*, without silcrete (in Barro Alto convex slopes and in Niquelandia suspended valleys), the profiles are 15 to 30 m thick and show the following sequence of horizons :

- *at the bottom*, a slightly altered hard rock (density 2) with the fractures filled with siliceous and/or garnieritic veins (total thickness between 6 and 10 m) ;
- *saprolite*, is coarse grained in its lower part, with islands of hard rocks embedded in a greenish-brown clay matrix. It changes upwards into a clay saprolite, without residual rocks, with preserved original structure (total thickness around 10 m) ;
- *ferruginous saprolite* (or yellow laterite), yellowish-brown material, with evidences of compaction of the original texture (thickness between 1 to 5 m) ;
- *red laterite*, lateritic material with gravels in the upper part (thickness 2 to 5 m).

*On the steep slopes*, a thin layer of colluvial red laterite covers the slightly altered hard rock.

*In the lowlands*, the profile is of the same type as those described for the depressed areas of the highlands. The profile is well developed, with a saprolitic horizon at the bottom and with a lateritic one at the top (generally thicker than those of the highlands). This profile is typical of the nickeliferous laterite (TRESQUES, 1975 and LELONG *et al.*, 1976), but generally with a less developed ferruginous saprolite. It can be noticed that on the steep slopes or underlying the silcrete, only the first stages of the lateritic profile are present (hard rock and eventually saprolite).

### b) Mineralogical and chemical composition

In the first stage of alteration, at the level of the slightly altered rock, olivine is gradually hydrolyzed, with nearly total removal of magnesium and partial removal of silica. In this oxidizing environment, iron and nickel have very low solubilities, and together with the residual silica they give origin to secondary products which replace olivines : ill-crystallized iron hydroxides (« limonites ») bearing nickel and silica or smectites (saponites) when the drainage is not good. Pyroxenes are partially altered into smectites (Ni-saponites, COLIN *et al.*, 1985). Despite being stable, serpentine presents part of octahedral magnesium replaced by nickel or iron. In the fissures, part of the evacuated silica, locally with nickel, precipitates forming quartz and garnierites (mixture of 10 Å and 7 Å, Mg-Ni-silicates ; BRINDLEY, 1978). Thus, the liberated nickel from olivine undergoes many microtransfers towards the surrounding minerals or fissures.

When olivine is completely dissolved, the solutions of alteration become more diluted, pyroxenes change totally into smectites, that are more ferruginous and less magnesian than the former. The previously formed smectites may also change into a more ferruginous and less nickeliferous smectite (PAQUET *et al.*, 1983). Serpentine is slowly dissolved, leaving behind a residual nickeliferous goethite, while garnierite disappears and is replaced, in the fissures, by Mn-Ni-Co oxihydroxides (asbolanes). These transformations which start in the fissures, give origin to a more clayey material enveloping the residual blocks of hard rock (coarse saprolite). Gradually, the size and quantity of these residual islands decrease and the whole material becomes clayey (clay saprolite). These first horizons, where silicates are still present, constitute the nickel silicate ore (1-4 % Ni).

When serpentine disappears, it leaves behind a goethitic ghost, epigenic on the previous crystal lattice, and the texture is compacted (ferruginous saprolite). The iron hydroxides previously formed evolve into goethite and the asbolane remains stable. The smectite originated from pyroxenes changes into kaolinite and goethite (particularly on Niquelandia pyroxenites). Nickel is more soluble in this horizon and part of it migrates to the underlying saprolitic level. The nickel content is generally higher than 1 % and this horizon constitutes the lateritic or oxidized nickel ore.

In the upper part of the profile, the texture is no longer preserved, goethite changes into haematite, nickel is leached and pisolites are formed. It is the *red laterite* with a reddish-brown color. In the lowlands or in some depressed areas of the highlands (Niquelandia), the evolution may reach the state of indurated ferruginous crust. This evolution is similar to that of most of other ore deposits (TRECASSES, 1979).

Table VII shows the average chemical composition for each of these horizons in the massifs of Barro Alto, Niquelandia, and Santa Fé. Nickeliferous laterite profiles from New Caledonia (TROY *et al.*, 1979) and Philipines (OGURA, 1977) were also included for comparison. It can be observed that the sequence of alteration horizons for the Brazilian nickeliferous laterite is similar to those from other places. On the other hand, despite the difference in thickness, their chemical characteristics are quite similar. The magnesium and afterwards the silica are progressively leached, promoting a relative concentration of residual elements — Fe, Al, Cr, Ni, Co, Mn. The high nickel contents found in the coarse grained and clay saprolites indicate an absolute accumulation of this element as we can see from the high Ni/E (E = residual elements) ratio and from the isovolumetric balance.

### c) General interpretation

The cover alteration history begins at the Lower Tertiary, with the South American cycle. Two main mechanisms were important :

- intensive silicification alteration profiles, probably related to semi-arid climatic conditions
- lateritization of these profiles with nickel concentration, certainly following the silicification phase.

Later, in the Upper Tertiary, this South American Surface was dismantled and a lower surface was formed. The previous South American profiles were eroded down to the silicified zone that protected the ultramafic massifs. Part of these ancient profiles has been moved down and can be found as « red laterite » that covers the slopes and the alteration profiles developed in the lowlands. This fact could explain the average nickel content

Table VII  
Average chemical composition of the different horizons of nickeliferous laterites  
Composition chimique moyenne des différents horizons des latérites nickélistes

	H <sub>2</sub> O <sup>+</sup>	SiO <sub>2</sub>	MgO	Fe <sub>2</sub> O <sub>3</sub> *	Al <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	NiO	CoO	MnO <sub>2</sub>
ROCK									
New Caledonia	nd	44	45	8	0,4	0,4	0,38	0,01	nd
Philippines	12,8	37,0	35,9	8,5	0,9	0,38	0,30	nd	0,15
Barro Alto (Brazil)	2,7	42,2	44,3	9,2	0,8	0,44	0,35	nd	0,12
Niquelandia (Brazil)	12,8	37,1	40,6	8,2	0,3	0,56	0,30	0,01	0,15
Santa Fé (Brazil)	9	39,4	40,2	9,0	0,4	0,39	0,29	0,02	0,22
Carajas (Brazil)	15	32	36	12	1	0,4	0,3	nd	nd
ALTERED ROCK									
New Caledonia	nd	43	33	12	0,6	0,7	3,8	0,02	nd
Philippines	12,4	38,2	31,8	12,7	1,0	0,39	0,58	nd	0,21
Barro Alto	15,5	35,7	31,5	12,2	2,9	0,77	1,18	0,03	0,29
Niquelandia	12,8	41,0	28,1	14,5	1,5	0,75	1,14	0,02	0,25
Santa Fé	12,8	41,0	33,4	10,4	0,5	0,44	0,33	0,02	0,20
Carajas	15	37	34	14	1,0	0,7	0,4/0,1	nd	nd
COARSE SAPROLITE									
New Caledonia	nd	39	28	17	1	1	3,2	0,06	nd
Philippines	10,1	33,1	23,0	25,4	1,45	1,26	2,66	nd	0,20
Barro Alto	14,7	34,0	28,8	15,1	2,9	1,06	2,13	0,03	0,26
Niquelandia	14,8	36,3	25,4	17,4	1,67	0,57	3,07	0,09	0,45
Santa Fé	12,2	40,8	28,3	15,5	0,7	0,64	0,3/1,9	0,03	0,28
Carajas	15	34	27	22	1,0	1	0,5/3,0	nd	nd
ARGILLACEOUS SAPROLITE									
New Caledonia	nd	30	16	32	2	2	2,5/3,8	0,19	nd
Philippines	8,9	26,2	2,9	51,2	4,2	1,97	2,12	nd	0,51
Barro Alto	11,5	34,3	13,3	27,9	7,0	1,55	2,68	0,09	0,62
Niquelandia	14,4	36,9	16,7	21,2	4,6	1,6	1,8/5,0	0,08	0,50
Santa Fé	8,9	30,9	16,4	34,6	1,9	2,21	1,72	0,06	0,44
FERRUGINOUS SAPROLITE									
New Caledonia	nd	3	2	70	5	2	1,8	0,13	nd
Philippines	9,8	3	1,7	74,1	6,4	0,96	1,07	nd	0,48
Barro Alto	8,5	14,8	1,62	60,4	9,7	1,66	0,83	0,19	1,29
Niquelandia	11,6	4,3	1,0	70,6	7,4	2,87	0,90	0,10	0,70
Carajas	10	5	0,7	69	4	2	0,4/0,5	nd	nd
RED LATERITE									
New Caledonia	nd	1	0,6	72	6	3,5	1,0	0,10	nd
Philippines	10,4	2,8	0,6	73,1	7,6	2,0	0,9	nd	0,43
Barro Alto	7,3	12,5	1,4	57,0	13,9	3,2	1,30	0,11	1,0
Niquelandia	7,6	13,1	0,2	64,4	9,9	2,4	1,00	0,08	0,84
Santa Fé	5,2	10,1	1,6	70,8	3,5	6,2	1,2	0,14	1,0

\* Total iron

(generally greater than 1 %) of this horizon, which is higher than the one normally observed in the upper part of the nickeliferous laterites in the world ( $\leq 1$  %).

Afterwards, the alteration was active both in the highlands, mainly where there was no silcrete (suspended valley in Niquelandia and convex slope in Barro Alto) and in the lowlands. This alteration was lateritic and happened together with a lateral migration of nickel, from highlands towards lowlands. This migration was more or less intense according to the higher surface degree of erosion. Figure 14 (MELFI *et al.*, 1979/1980) summarizes the sequence of phases in this evolution.

## 2. The more humid coastal zone deposits (Sao Paulo and Minas Gerais)

There are no important variations in the deposits characteristic of the more humid coastal zones (ESSON and SURCAN, 1978 ; TRESCASES and OLIVEIRA, 1978) and those of Central Brazil (tropical zone with contrasting seasons).

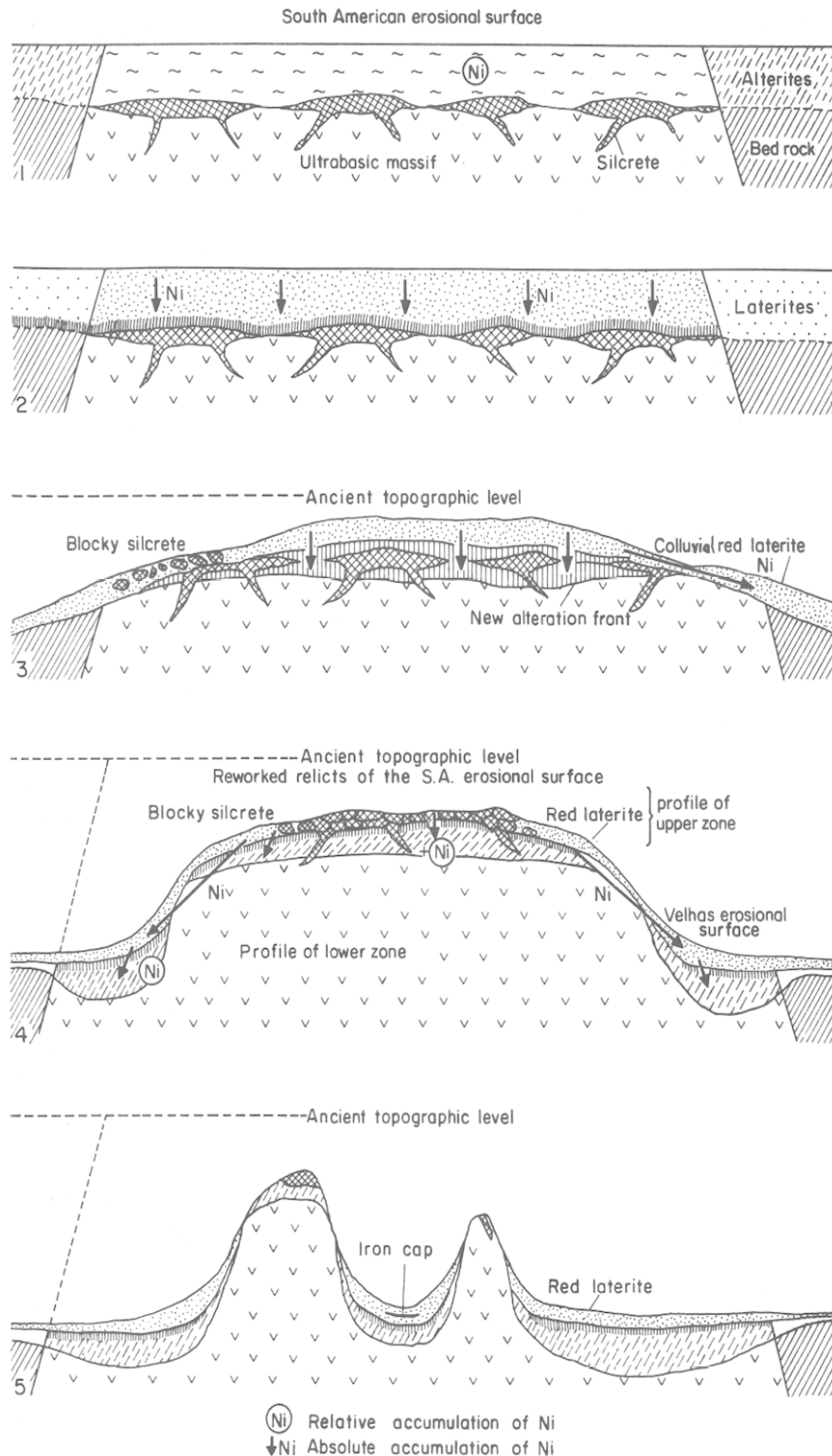


Fig. 14 — Schematic sequence of the different morphotectonic phases of the evolution of the Ni ore deposits in Central Brazil.

*Séquence schématique des différentes phases morphotectoniques de l'évolution des gisements de nickel du Brésil central.*

The ultramafic massifs are of small size and consequently the landscape has no highlands and lowlands. Here, either the whole massif corresponds to one hill covered by a thick silcrete (Morro do Niquel, MG) ; or the primitive silicified plateau is gently undulated, giving rise to a landscape of half-oranges (Jacupiranga, SP).

Everywhere, under the silcrete, the alteration profiles are similar to those developed in Goiás, in zones with no silcrete. The ferruginous saprolite is always thin in Minas Gerais (< 1 m in Morro do Niquel), where the parent rock is a serpentinite; and very thick in Jacupiranga (5 to 10 m), where the parent rock is a dunite located at lower altitude. In the silicated saprolite with more than 10 m thick, the development of smectites from pyroxenes and olivines is widespread, and at the bottom the garnierite veins are abundant.

There the evolution scheme is simpler than in Goiás, because no nickel migration occurs from an older levelling surface to a more recent one. All the evolution is *in situ* by deepening of the alteration under the silcrete which is very rare in Goiás.

### 3. Very humid equatorial zone (Para State)

In the Amazon region, only a few nickel deposits are known, probably due to the difficulties in geological mapping, except for the areas of known mineral districts like Serra dos Carajas. Besides the Quatipuru ore deposit (CORDEIRO and McCANDLESS, 1976), only the Vermelho deposit (Carajas) has been prospected and is well studied in the latest years (BERNARDELLI *et al.*, 1983).

In the Vermelho deposit, the parent rock is a serpentinite with pyroxenite intercalations. The massif is tabular and covered by a silcrete (up to 60 m thick). Like in Minas Gerais and São Paulo, the post Tertiary evolution went on *in situ* under the silcrete, with no development of lowlands. The alteration profile under the silcrete is typically lateritic. The silicated saprolitic horizons are 10 to 15 m thick, but here the smectites formed from pyroxenes and garnierite veins are absent. The ferruginous saprolitic horizon may attain 30 m thick which is the maximum that can be observed in Brazil. The chemical composition of the different horizons (table VII) is comparable to those from less humid regions. The lateritic evolution is more intense than in the humid tropical zone and in Central Brazil. Nevertheless, the silicated ore is slightly more abundant than the oxidized ore as in all the Brazilian deposits.

### 4. Semi-arid zone (Piauí State)

The recent climatic conditions of Brazilian northeastern region are not favorable for a lateritic evolution of ultramafic rocks, since rainfall rates are very low. Consequently, there is no true nickeliferous laterite in this region. However, one nickel ore deposit of supergenetic origin is found in São João do Piauí (SANTOS, 1974 and DINO, 1984).

The deposit is situated on a serpentinitic massif, having a central plateau, covered by a few meters thick silcrete, surrounded by a lowland. Under the silcrete, in the highland, as well as under the colluvial material covering the lowland, the serpentinite is altered *in situ* up to 10 m deep, with the original rock structure preserved. The serpentine is changed into smectite with progressive leaching of Mg and conservation of silica, as opposed to the lateritic evolution. Part of the dissolved silica from the silcrete is reprecipitated as quartz or chalcedony in the saprolitic smectitic horizons of the plateau and of the back slopes. The nickel content of these saprolites is generally higher than 1 % and may attain 3 %, forming an ore rich in silica.

The landscape similarity, the occurrence of silcrete on the higher surface and the existence of Tertiary laterites in the region suggest that São João do Piauí massif has had, in the Early Tertiary, an evolution process similar to that of other ultramafic massifs occurring from Pará to São Paulo, with silicification and lateritization phases. A certain amount of nickel was concentrated in the laterites overlying the silcrete and related to the South American Surface. This amount was redistributed in the younger profiles, either through vertical migration under the silcrete, or through lateral migration towards the lowland. Were it not for the previous concentration during the Tertiary lateritization, the recent evolution would never have formed a nickel ore deposit, since the conservation of silica would have avoided the relative concentration of nickel.

## CONCLUSIONS

The study of the main supergenic ore deposits in Brazil enabled the evaluation of the relative importance of the *formation factors* (parent rock, climate, topography and time) essential for the origin of these deposits, as well as the identification of the main mechanisms involved in the process.

It was observed that, in spite of the deposits being considered as lateritic, in a broad sense, their genesis implies different geochemical mechanisms that lead to the alteration of a rock (sometimes a protore) into an exploitable ore deposit. Under this point of view, the Brazilian supergenic deposits can be classified into three great categories.

### Deposits originated by the preservation of stable minerals

This category includes deposits formed by residual accumulation of minerals that are stable to weathering, and consequently are concentrated in the alteration profiles. That is the case of haematite in itabirites, where the main formation factor is of lithological character. It can be said that the huge iron deposits do not present, actually, a climatic control in Brazil, and if they are associated with *Eocene levelling surface* this is simply the result of the slowness of the total desilicification mechanism.

Other Brazilian deposits, not considered in this paper, belong also to this category : eluvial chromite concentration on ultrabasic rocks, cassiterite and niobium-tantalite on acid rocks or gold lateritic deposits.

### Deposits formed by the concentration of low chemical mobility elements

This category includes deposits formed by the relative concentration of elements during weathering, as, for example, Al in bauxites.

In this last case, lithological control is not very important (a parent rock containing 10-15 %  $\text{Al}_2\text{O}_3$  is sufficient), as well as there is no strong climate control. Although the biggest deposits are concentrated in equatorial zone, bauxites occur in a large variety of climates in Brazil, presenting, obviously, only minor different characteristics, typical of each region.

On the other hand, the role of topography is well marked. The bauxitization is a slow phenomenon and the deposits are, in general, associated with *Eocene levelling surfaces*. Nevertheless, in the particular case of alkaline rocks, bauxitization occurs even under rather unfavourable morphological and climatic conditions.

### Deposits formed by the concentration of a slightly higher chemical mobility elements

This category includes Mn and Ni deposits. These elements, despite having a lower mobility as compared to silica and bases, in the lateritic weathering, have mobilities higher than Fe and Al.

Concerning the Mn deposits, the climatic control is absent and the genetic mechanisms are relatively identical for all regions of Brazil. This is due to the fact that the main source of Mn is a carbonate, that can easily be dissolved. The lithological control, on the contrary, is rather important, since the protores enriched in rhodochrosite are a geological rarity. On the other hand, a clear relation between lateritic Mn deposits and a generalized levelled surface is not observed in Brazil. The Mn concentrations are located mainly in the levelled zones resulting from the incision of the original Eocene surface.

Concerning the nickel deposits, the lithological control is restricted mainly to the ultrabasic characteristic of the parent rock, being sufficient the existence of minerals as olivine and/or serpentine. The pyroxenites are not good protores, because of the low Ni content of the pyroxenes, but on the contrary, these rocks may be good Ni reservoirs. That is the case of Niquelandia (COLIN *et al.*, 1985), where the neighbouring dunite alteration provides Ni. The climate control in these Ni deposits is weak and produces simply a variation in thickness and the relative amount of the two main types of ore : *silicated* and *oxidized*. On the other hand, the morphoclimatic control is very important as clearly shown by the constant association of the Ni lateritic deposits with the Eocene and

Plio-Pleistocene levelling surfaces, and by the lateral downwards migration of Ni from an older upward Ni pre-concentration.

The role of Ni and Mn mobilization (from the top of the profile or from the upper parts of the deposit), and the absolute income (at the bottom of the profile or at the lower part of the deposit) is particularly important. In fact, such processes are evidently of fundamental importance since they allow to counterbalance the initial low contents of Ni and Mn in the uppermost part of the crust, generating the lateritic ore deposits.

Finally, it must be emphasized that the genesis of all lateritic ore deposits involves a very slow process, which occurs during a long period of time, and typically since the Early Tertiary.

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