BRAZILIAN BAUXITES

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PREFACE

Among geologists, geochemistis, soil scientists, working on old and deep weathering mantles, questions are constantly arisen: what was the nature of the past climates that formed the ancient soil covers, and how could certain relicts of them, buried or not, have escaped subsequent erosions, dissolutions and geochemical reworkings? The answer lies on the careful study of old bauxitic profiles with thicknesses ranging for tens to hundreds of meters which form high residual and dissected plateaus. Every method starts with a few simple concepts through a time of growth, with increasing sophistication, and, finally, reaches a time of synthesis when case histories can be brought together. This book is an attempt to connect all facets of the complex problems involved in bauxitic profiles and bauxitic relicts of Brazil and permits to answer to part of questions arisen.

Each chapter is written by an expert or experts in their respective fields to define their present understanding of the process of weathering and bauxite formation throught geological times, and so, this book contributes to the advancement of geological, geochemical, geomorphological understanding of Brazil. This country has large, extensive land areas which have been subject to weathering for tens to hundreds of millions of years and allowing us to approach rates of weathering, landform changes and bauxite differenciation. As analogous bauxitic formations occur in other continents, particularly Africa and Australia, the analysis of brazilian bauxites and some of their counterparts elsewhere is particularly timely.

This collection of chapters will provide a comprehensive statement of problems and present understanding of Brazilian bauxites investigations, which will be an indispensable foudation for the world's old lands evolution.

This book may help students and researchers, who are concerned with basic concept and recent trends of research on the processes of bauxite formation. Despite the appearance over the past two decades or so of a wealth of literature relating to mineralogy, geochemistry and geomorphology of bauxites, text books dealing specifically with all facets of Brazilian bauxites were singularly lacking.

I greatly congratulate the authors for such a piecce of good work.

Aix-en-Provence, July 8, 1996

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CONTENTS

INTRODUCTION

A . BRAZILIAN BAUXITE DEPOSITS: A REVIEW

B . PETROLOGICAL AND GEOCHEMICAL CLASSIFICATION OF BAUXITES AND IRON-RICH LATERITIES

A . BRAZILIAN BAUXITE DEPOSITS: A REVIEW

A.J. Melfi

Introduction

Despite presenting a great variety of morphological and structural features, the bauxite deposits of Brazil are all of lateritic origin. They are constituted essentially by gibbsite and are formed by intense tropical weathering of different rock types. The climatic and geomorphological conditions, together with the time, were the most important factors of the formation of these deposits. The lithological aspects seems to be less important, considering that bauxite occurs on various types of rocks.

The bauxite deposits are widely spread in the Brazilian territory, occurring from the north hemisphere down to 35° south latitude. Nevertheless, the most part of these deposits (97 %) is concentrated in the Amazon region where, except for Carajás, they are developed from sedimentary rocks. The rest of the deposits (3 %) occurs in different regions and were formed on other kind of rocks.

I. State of knowledge of Brazilian Bauxite

The huge reserves of bauxites in Brazil, one of the largest of the world, has played a very important role on its economy. No matter, very few studies were carried out on these deposits during the last decade. Most of these studies were quite isolated, without any integration that could give a global understanding of its genesis and a better knowledge of the prospection and exploration aspects.

The very first information about the occurrence of brazilian bauxites goes back to 1920, when the Quadrilátero Ferrífero deposits were found in Ouro Preto (MG). During a long time, these deposits were the only source of aluminium in Brazil.

However, the first known study on Brazilian bauxite was carried out in Poços de Caldas many years later by Barbosa (1936). He described these deposits, based on field observations and chemical analysis, as a weathering material developed from phonolites and phoyaites, through a process similar to the one occurring in Arkansas (USA). Due to the importance of these deposits, this first study was followed immediately by some others, either dealing with the economical aspects (Pinto, 1937) or trying to present a genetic interpretation on the basis of the current knowledge (Souza Santos, 1937; Pinto, 1938).

A few years later, the deposits of Poços de Caldas was already quite known, specially after the detailed studies of Harder (1952) and Weber (1959). Harder (1952) presented a very detailed description of the profiles and the physical characteristics of these deposits. Weber (1959) described the bauxite types of Poços de Caldas and presented a discussion on the bauxitization process and its factors of formation. He identified two ways of bauxitization, controlled by the pH conditions: in the first one, bauxite would be formed directly from the parent rock and in the other one, through a clay horizon. He suggested that bauxite could have been submitted either to a secondary gibbsite enrichment or to resilicification process, originating a clay layer. He also stated that bauxitization was a recent process, being active up to the present time.

Later on, Moniz (1969), following partially the ideas of Weber (1959), described the bauxitization and the argillization processes in Poços de Caldas, emphasizing the action of hydrothermal solutions in the origin of halloysite.

However, the most complete study on the bauxite of Poços de Caldas was carried out much later by Almeida (1977). The author classified the bauxites, according to their topographic situation, as ridge deposit and plateau deposit. He presented a detailed characterization of the two types of deposits and a discussion on the involved processes and forming factors. The author suggested that the bauxitization in Poços de Caldas was a direct and continuous process in the ridge deposits and is active up to the present time. He considered also that topography, rock nature and the climatic conditions were the most important factors in its formation.

More recently, some studies were carried out on bauxite deposits formed on alkaline rocks, in other regions rather than Poços de Caldas, but with no significant changes in the basic knowledge accumulated so far (Szubert & Vergara, 1976; Sigolo, 1979; Toledo-Groke, 1982; Toledo-Groke & Melfi, 1982; Sigolo & Toledo-Groke, 1984; Sigolo & Boulangé, 1987). It has to be mentioned also Melfi & Carvalho (1984), who tried to present a new interpretation for the genesis of the Poços de Caldas deposits, emphasizing the role of the kaolinization front in the bauxitic profiles situated in the slope.

As for the deposits of the Quadrilátero Ferrífero, despite being the first to be discovered, very few studies were done and most of them refers to the parent material. Thus, initially, Guimarães(1945) and Guimarães & Coelho (1946) suggested an autochtonous origin for these bauxites, that would be formed on phyllite of Minas Group. Later, Fleischer & Oliveira (1969), based on geological, geomorphological and geochemical data, suggested an allochtonous origin, with the bauxite formed on sediments coming from the basement rocks and deposited in lakes of karstic origin existing within the Itabira Group. The more important work in this region is by Varajão (1988) that made a good comparative study of Quadrilátero Ferrífero bauxite.

The bauxite of the Amazon region, discovered more recently (in the years 50's), has changed completely the geographical and economic picture of the brazilian bauxites. As a consequence, the attention of brazilian and foreign specialists was drawn to this region, resulting in more than 20 published papers in this period. The studies of Denen & Norton (1977), Grubb (1979), Assad (1978), Aleva (1981), Kotschoubey & Truckenbrodt (1981), Kronberg et al. (1982) and Boulangé & Carvalho (1989) are among the more important ones, since they allowed to obtain a consistent model for the evolution of these deposits. This model is based on a polygenetic origin, including various steps of evolution.

However, an aspect that is still a matter of controversy, among the specialists working on the amazonic bauxites, refers to the clay layer that covers the deposits. This layer, named Belterra Clay, was considered initially, by Sombroeck (1966), as a lacustrine deposit of Pleistocene age. Lately, Klammer (1971) considered it as the upper part of the Barreiras Formation, so including it in the bauxitic profile. This idea was accepted and followed by some authors as Dennen & Norton (1977), Aleva (1981) & Kronberg et al. (1982). On the other hand, some others, as Grubb (1979) and Kotschoubey &Truckenbrodt (1981), suggested a sedimentary origin for the clay layer. More recently, the studies of Lucas (1989) brought a more solid evidence of an autochtonous origin. In any case, the problem is far from been solved and only a more detailed micromorphological analysis would bring any progress to the discussion.

Finally, it has to be mentioned the deposits associated with metamorphic rocks of gneissic, granitic and basic composition. These deposits occur in a large zone, extending from Espírito Santo State down to São Paulo State, covering the hill tops of Mar and Mantiqueira ranges and are included in the so called Brazilian Atlantic Bauxitic Belt of Suzsynski (1978). Most of these deposits are of low economic value and, as a consequence, not very much attention has been paid to them. Among the few studies carried out, it has to be mentioned, Toledo-Groke (1982), Toledo-Groke & Melfi (1982) and Beljavskis et al (1984). Considering the economical aspects, the bauxite of Cataguazes region (MG), presenting very important reserves, is an exception. The genesis of these deposits was initially studied by Roeser et al. (1984) and it was suggested that the excellent drainage conditions was able to change, even unfavourable rocks, into quite thick deposits of bauxite of good quality (40 to 45% available alumina). More recentelly, Valeton & Melfi (1988) and Valeton et al. (1991) have given more detailed data about these deposits genesis.

This short review on the existing knowledge on the Brazilian bauxite, evidenced that up to now, the lack of study of synthesis, where the different parameters involved in the formation of these deposits would be considered. As a matter of fact, that was the main reason that led to the organization of an integrated project, involving Brazilian universities (Universidade de São Paulo e Universidade Federal do Rio Grande do Sul) and ORSTOM (France), with the cooperation of some other groups from abroad (University of Hamburg).

II. Basic data on physical environment in Brazil

In the tropical zones, the occurrence of supergenic metallic ore deposits associated with lateritic-type formations is very common. It is well known that the formation of the so-called lateritic deposits, mainly by rock weathering processes, depends on the convergence of a series of conditions, without which economical concentrations would never happen (Lelong et al., 1976). Among these conditions, it can be mentioned the lithological, the climatic and morphotectonic ones.

In the Brazilian territory, these conditions have existed and still exist in some regions and, as a consequence, metallic deposits and specially bauxites deposits are quite abundant.

Brazil, having continental dimensions extending from 4°N down to 32°S latitude, shows a large variation in its bioclimatic and geodynamic conditions, with direct effect on the bauxitization process.

1. Geologic Outline

The Brazilian territory, situated in the South American Platform, has an Archean age basement, with a very complex geological history. This basement is constituted by metamorphic rocks of amphibolite to granulite facies, associated with Proterozoic units, represented by greenstone fold belt and a volcano-sedimentary cover, either slightly or not metamorphosed at all (Schobbenhaus & Almeida Campos, 1984). These rocks outcrops in three great shield areas covered by thick Phanerozoic sedimentary layer (Fig. A.1): the Guyana Shield in the north; the Central-Brazilian or Guaporé shield, in the interior of the country, and the Atlantic shield in the coast. As a whole, the three shield areas represent 60% of the country surface.

From Ordovician to Silurian time, the development of a sedimentary and volcanic cover took place, under stable conditions of orthoplatform, in the South American Platform, mostly in the three great basins of Paraná, Parnaíba and Amazon.

Geological and geochronological data 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, it can be mentioned four cycles (Table A.1): Jequié cycle (2,600-2,700 my), Transamazonian cycle (2,000 my), Brazilian cycle (450-470 my) and South Atlantean cycle (190-30 my). The latter corresponds to an important tectonic reactivation in the platform (Schobbenhaus & Almeida Campos, 1984).

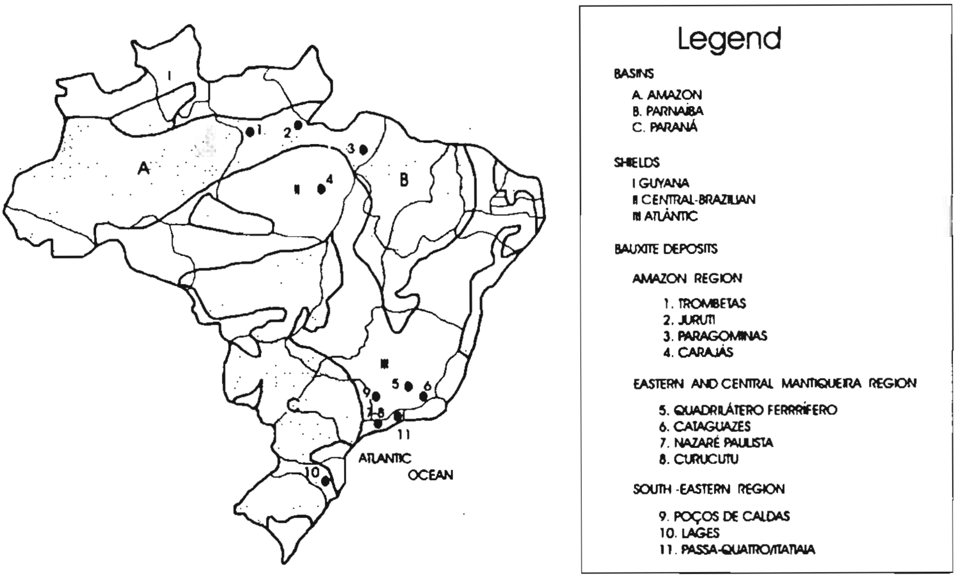

Figure A.1 - Tectonic map and location of the main bauxite are deposits of Brazil (based on Melfi et al., 1988).

Table A.1 - Main Brazilian lateritic ore deposits and their chronostratigraphic relationships (modified after Schobbenhaus et al., 1984).

M y.						Geodynamic cycles
65	Cenozoic	Clastic sediments (Al)				South Atlantean
235	Mesozoic	alkalic volcanism			ultramafic alkaline complexes (Ni)	
570	Paleozoic					Brazilian
1100	Upper		ferruginous jaspilites (Mn, Fe)			South Atlantean
1900	Middle				alpine type ultramafics (Ni)	Transamazonian
2600	Lower		Itabirites (Fe)	Si-CO$_3$ protore (Mn)		Jequié
	Archean		Itabirites (Fe)	volcanism sedimentary complexes (Mn)	mafic-ultramafic complexes (Ni)	

PHANEROZOIC
PROTEROZOIC

The South American Platform had its evolution during the Pre-Cambrian and was completely consolidated in the beginning of the Paleozoic (Almeida, 1966).

The geological history of Brazil, from the Ordovician upwards, was mainly characterized by the presence of intercratonic sedimentary basin. These basins, having up to 5,000 m of sedimentary and associated magmatic rocks, were submitted to a marine sedimentation during the Ordovician, Silurian and Devonian time; a mixed sedimentation in the Carboniferous and changed to a continental environment from the Permian to the Jurassic times. At the end of this period, the basin being still active, an important tectono-magmatic event, related to South Atlantean cycle, gave rise to several marginal basins. At the same time, all the basins were affected by an intense basic tholeiitic magmatic activity which was particularly important in the Paraná basin, where it reached 600 m of average thickness, and covered 1,200,000 km^2 of its area.

The intense reactivation of the South American Platform, during this period, results on taphrogenic pattern faults, in the coastal region. These faults led to the formation of important depressions (grabens), that were filled up with marine sediments during the Neoaptian-Albian (Almeida, 1966).

The basic tholeiitic magmatic activity was followed by an alkaline magmatism which was responsible for the formation of several alkaline massifs around the Paraná basin, with ages from 220 my (early phase of the South American cycle) to 50 my.

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

2. 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 one. However, it is quite important to know the recent conditions, since they can give peculiar characteristics to each deposit.

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 on five great bioclimatic zones (Fig. A.2), as follows:

(1) Warm and humid equatorial climate with equatorial forests. It is the dominant climate in the northern Brazil, in the Amazonic region. It

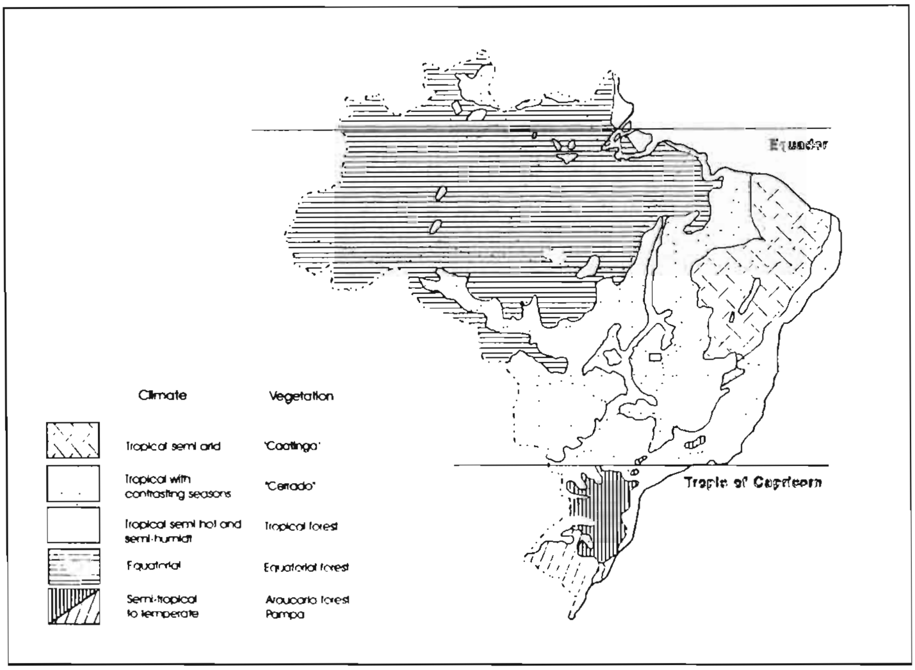

Figure A.2 - Simplified distribution of the main bioclimatic Zones in Brazil (after Melfi et al., 1988).

is very wet, with average rainfall of more than 1,800 mm and generally around 2,000 mm, a very short dry season of 2 or 3 months and with a mean temperature over 26°C and constant throughout the year. The Al deposits of Serra dos Carajás and the huge reserves of Al of Pará state are found in this climatic region.

(2) Semi-arid and tropical climate with "caatinga" vegetation. It 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" has low density of trees and shrubs, normally xerophilous and thorny, and with no permanent herbaceous cover.

(3) Warm and humid to sub-humid tropical climate with contrasting seasons and savanna vegetation. It is the dominant climate of the middle-western Brazil and is characterized by a mean temperature between 22 to 25°C, with slight annual variation and rainfall around 1,200 to 1,800 mm, well distributed at least within 6 months. The dry season does not exceed 3 to 4 months. The vegetation is mainly of Savannah type ("cerrado"), containing a gramineous stratum and a shrub stratum with individuals well scattered. A gallery forest occupies the main valleys.

(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 a rainfall between 1,500 to 1,900 mm, well distributed throughout the year. The typical vegetation is a slope humid tropical forest (Romaris, 1974), called "Mata Atlântica" (Atlantic Forest), presenting a great density of high trees and arborecents. All the metallic ore deposits of the Quadrilátero Ferrífero of Minas Gerais, as well as other small Al occurrences in states of Minas Gerais, São Paulo and Santa Catarina are related to this climatic zone.

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

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, leveling the Brazilian landscape into a huge peneplane named South American Surface or South American cycle ("Ciclo Sulamericano") by King (1956).

In the lower Tertiary, during the aggradation phase of this 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 1,000 m. Rests 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 again submitted to weathering that affected also the Velhas Surface, leading to a new alteration cover 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 aluminium oxides (over ultrabasic rocks silica is also common). On the other hand, Velhas Surface (Plio-Pleistocene) is divided into different compartments that correspond roughly to the great hydrographic basins and 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, they are much thinner and less clayey. In the southern Brazil, the cover is rather thin and 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;

3. Distribution of the Brazilian bauxite deposits.

According to the Brazilian literature and particularly based on the studies of Almeida (1977), Dennen & Norton (1977), Grubb (1979), Sigolo (1979), Aleva (1981), Melfi & Carvalho (1984) and Valeton et al. (1991), it is possible to identify the various types of bauxites and to know its distribution. It was shown that, as concerning the parent rock, three main types of bauxitic deposits occur in Brazil.

The first and most important, corresponding to 97% of the known deposits, refers to the bauxites developed on clastic sedimentary rocks. The rest 3% includes other types of deposits formed on Precambrian crystalline rocks (granites, gneisses, schists, amphibolites), metasedimentary rocks (phyllites) and alkaline rocks.

It was also observed (Melfi et al., 1988) that these deposits occur nearly in the whole country, extending from 3°N to 27°S latitude, being absent only in the northeast and in the extreme south (Rio Grande do Sul), due to unfavourable morphoclimatic conditions. (Figs. A.1,2).

On the other hand, it is noteworthy (Fig. A.1) that the different types of bauxitic deposits are concentrated in different regions: Amazon, Quadrilátero Ferrífero and Mantiqueira Province, and South-Southeastern region. Each one of these regions has distinct lithological and bioclimatic characteristics.

Amazon Region. In the Amazon region most of the bauxitic deposits are associated with clastic sedimentary rocks, contained within the Amazon Basin. The geological history of this basin is well known, particularly due to the studies of Santos (1984), Bahia & Abreu (1985), Montalvão & Beserra (1985) and Caputo (1985).

The Amazon Basin covers an area of 1,000,000 km^2 and it is limited by the Guyana Shield to the north and the Central Brazilian Shield to the south. Its formation goes back to the Paleozoic period, at the time of the fracturation and separation of the African and South America continents. This separation, marked by important volcanic activities (pyroxenites and tholeiitic diabases), extended from the Paleozoic up to the Cretaceous.

The Amazon Basin, from the Ordovician up to the Devonian, was an unique elongated basin, with E-W direction and was submitted to a homogeneous marine sedimentation related to an east to west transgression. The process lasted up to the Carboniferous and the resulting sediments may reach 2,000 m.

During the Westphalian, the area was tilted towards the west leading to an inversion of the sedimentation that occurred from west to east. The result of the whole process was the subdivision of the basin into three sub-basins, each one characterized by a different type of sedimentation:

-Upper Amazon sub-basin or Acre Basin, situated in the western part and characterized by a marine and purely chemical sedimentation (limestone and evaporites) that went up to the Andes Ridge uplift (Cretaceous-Tertiary) and end up with the deposition of clays and sands (Mio-Pliocene).

-Middle Amazon sub-basin or Solimões basin, with a chemical and continental sedimentation, ending with the deposition of the Solimões Formation during the Plio-Pleistocene, represented by 1,000 m of shales, claystones and sandstones.

-Low Amazon sub-basin, that together with the Marajó basin, was characterized by a continental and terrigenous sedimentation, with age up to Pleistocene and originated from the alteration of the Brazilian and

Guyana shields. It has to be pointed out that the Marajó basin, at this time separated of the Amazon basin by the Gurupá arch, was an extension of it during the Paleozoic.

The known bauxitic deposits are only located in the Low Amazon basin and at the border of the Marajó basin and were formed on the continental formations.

The topography of the Amazon region is constituted in its most part (40%) by the Amazonic plain, being the rest occupied by the crystalline shields and in a less extent, by the coastal plain. The Amazonic plain, where the bauxitic deposits are situated, is formed by the flood plain and the mainlands (firm lands ?).

The flood plain form a zone of variable wideness (16 to 50 m), alongside the Amazon river and the lower part of its tributaries, extending over more than 65,000 km^2, i.e., 1.5% of the whole basin.

The mainlands are constituted by Tertiary sediments that cover the most part of the Amazon basin. They present a monotonous topography, formed by low plateau, that rises up to the north and to the south and towards the crystalline shields. Near the river, they show altitudes of 30 to 40 m, reaching 80 to 100 m in the interfluves and rise up (80 to 100 m) close to the shields. The highest altitude attained is around 300 m.

These plateau are remnants of the Velhas surface (Plio-Pleistocene), showing an inclination of 1 to 2° toward the Amazon river that was cut down after the epeirogenic event started in the Pleistocene (Lucas, 1989).

The Amazon region, having an excessive smooth topography and being placed under the equatorial line, presents quite homogeneous climatic conditions.

The region have mean annual temperature over 24°C, generally between 24 and 26°C. The high temperature is maintained all over the year and particularly during September-October and November-December when it can reach 26 to 28°C. As a consequence of the high humidity and nebulosity very high temperatures are not common, but it can happen to reach 40°C in certain regions in September and October. During June and July, the temperature is milder but not lower than 22°C, except for some areas in the south where it can attain 12°C. Considering these characteristics, the region can be considered as a domain of warm climate.

The rainfall is rather high and presents not the same uniformity. In the region of Amapá and Amazon mouth the pluviosity is very high (over 3,000 mm) and in the central zone is lower, within 1,500 and

1,700 mm.

On the other hand, these rains are not equally distributed throughout the year and the difference between the more humid months and the dryer ones is the highest of Brazil. As considering the rainfall, there exist two different types of climate: a super humid (> 2,500 mm), having no more than one dry month, and a humid (1,500 - 2,500 mm), with a dry season lasting up to three months (August, September and October).

The Amazon region is covered mainly by the equatorial, hygrophile rain forest ("Hileia Amazonica") that developed on mainland (firm land ?) and by evergreen forest submitted to periodical or permanent flooding, in the valley bottoms.

There exist also a vegetation other than the forest, that includes the Savannah (cerrado) and the prairie which occurs scarcely in isolated areas.

The bauxite deposits of Carajás District, included in the Amazonic region, present different conditions as compared to the described ones. These bauxites were formed by alteration of Precambrian basic rocks. These deposits, situated in the central-east of Pará State, are associated with the rocks of Grão Pará Group, that lay on older rocks of the Xingú Group and Salobo-Pojuca Sequence. They are covered by the rocks of Rio Fresco Formation, all of them of Precambrian age. In Carajás ridge, the Grão Pará Group is constituted by three units, called Lower Paleo-volcanic Sequence Carajás Formation and Upper Paleo-volcanic Sequence. The two volcanic sequences are formed by basalts, while in the Carajás Formation the itaberites are dominant. The regional metamorphism effects in these rocks are quite clear, despite the intensive and localized action of hydrothermal alteration.

In the bauxitic area, a huge plateau of 600 m high, limited by steep slo-pes, that were cut by erosion following the formation of the Carajás ridge planation surface (South-American Surface), is the outstanding geomorphological feature.

Quadrilátero Ferrífero Region. The Quadrilátero Ferrífero Region is situated in the central part of Minas Gerais State and covers an area of 7,000 km^2. It is a mountainous region, of pre-Precambrian age and is included in the folded belt of São Francisco shield. It is limited by the folds of Minas Supergroup layer, that contains very important iron ore deposits.

The stratigraphic series overlie a granite-gneiss basement, which is the central outcropping in the southern part of the Quadrilátero Ferrífero.

The series initiate with the Rio das Velhas Supergroup sediments (5,800 m thick), considered as Archean and including from the top to the bottom:

- Nova Lima Group, predominantly metavolcanic and clastic metasedimentary rocks (greenschist facies). It is unconformably overlain by.
- Maquiné Group, which is predominantly clastic with conglomerate, conglomeratic quartzite and phyllite.

The series follow with the Minas Supergroup (3,500 m thick), laying unconformably on the previous one and include three groups:

- Caraçá Group, constituted of clastic sedimentary rocks, with conglomerates, quartzites, sericitic and graphitic schists and oxide-facies iron formations;
- Itabira Group, formed in the lower part by itabirite, dolomitic itabirite, sericitic schists and dolomite (Cauê Formation) and in the upper part by magnesian dolomite, limestone, dolomitic and sericitic schist with interstratified thin layers of itabirite (Gandarela Formation),
- Piracicaba Group, overlying unconformably the previous one, is formed by ferruginous quartzite, quartzite, sericitic schist, dolomite (Cercadinho Formation); quartzitic or dolomitic sericitic schist, dolomite (Fecho do Funil Formation); orthoquartzite (Tabões Formation); sericitic or graphitic schist (Barreiro Formation).

The Sabará Formation, which may be considered as a group, consists of mica-chlorite schists, intercalated with mafic volcanic rocks and quartzite. It has a basal conglomerate resting with unconformity on the top of the Minas Supergroup.

Finally, the Itacolomy Group overlies the Minas Supergroup with a strong erosional unconformity and closes the Precambrian series. It is formed by coarse quartzite and grit, micaceous or ferruginous quartzite and conglomerate.

It can also be found, in the Quadrilátero Ferrífero, metagabbros and metadiabases dykes, that do not cut the Minas Supergroup, and younger diabases dykes (probably Cretaceous). Semi-consolidated sedimentary accumulations appear in some small basins as Gandarela and Fonseca.

The region shows a folded and dissected topography, being flattened in the central part and higher in the edge, giving rise to ridges.

Among the topography that surrounds the Quadrilátero, the Caraçá ridge, having altitudes higher than 1,900 m, presents on its summit, evidences of an old planation surface, that has been considered as elaborated in the Mesozoic (King, 1956).

The Moeda and Ouro Branco ridges, with lower topography (1,300 to 1,400 m) would correspond also to a Cretaceous planation, but a little younger, i.e., Post-Gondwana (King, 1956).

The central depression shows different forms, changing from convex to tabular, at 1,000 m of altitude. Despite the intense dissection, it is possible to notice leveled tops, that has been interpreted as evidence of a younger planation surface identified as Cristas Medias (De Martonne, 1943) or South American (King, 1956) of Terciary age and also to Neogenic Surface (De Martonne, 1943) or Velhas (King, 1956) of Plio-pleistocenic age.

The present climate shows a mean annual temperature of about 24°C, excepted for the regions of higher altitudes, when it is lower than 22°C. During the warmest month (January), the average can reach 30-32°C in the most part of the region and slight lower (<29°C) in the high altitudes. During the winter the temperatures are milder, normally around 14°C and could go down to 6-8°C in the higher altitudes.

The mean annual rainfall is around 1,500 to 1,900 mm, with a maximum in the summer and a minimum in the winter, characterizing a typical seasonal regime of the tropical regions.

The original vegetation was the Tropical Semi-deciduous Forest (RADAM, 1983), also named Tropical Broadleaf Forest. It is not very well known and nowadays it is practically completely cut down.

Central Mantiqueira Province. The region refers to a large and extensive zone, nearly parallel to the coast, that goes from the northeast of São Paulo State up to Espírito Santo, reaching also the south of Bahia State and including the southeast of Minas Gerais and Rio de Janeiro State.

The region corresponds to the central part of the so-called Mantiqueira Geomorphological Province, which includes the Juiz de Fora and the Coastal Complexes (Hasui & Oliveira, 1984). Both units are geologically constituted of a great variety of metamorphic rocks of amphibolitic and granulitic grades, associated with granitic-gneissic rocks.

The Coastal Complex presents different grades of migmatization and granitization. The more common rocks are banded and augen gneisses and migmatites, interlayered with calci-silicatic and metavolcanic rocks, iron formations and quartzites. The granulitic facies form preferentially bands and isolated pockets of charnockites, kinsigites, letnites and enderbites.

The Juiz de Fora Complex presents a clear dominance of the granulitic facies, represented by enderbites, charnokites, granitoids, quartz-diorites, diorites, gabbros and norites, associated with ganulitic gneisses and migmatites.

South and southeast region. In the south and southeast of Brazil, during the Precambrian basement, it was cut by alkaline intrusive rocks, associated with the volcanic rocks of Paraná Basin and with the opening of the South Atlantic.

These alkaline rocks were classified in different associations, grouped into several provinces (Ulbrich & Gomes, 1981). In the south of Brazil three of these provinces were submitted to bauxitization: Anitápolis, Poços de Caldas and Coastal Provinces. They are constituted mainly by unsaturated to saturated sienitic series, practically with the same mineralogical composition.

These alkaline massifs form generally high plateaus, with altitudes between 1,200 and 2,500 m and most of them is roughly circular in shape.

Generally, these massifs show two different topographic compartment. One refers to its border, with a topography having undulated hills with steep slopes and the other is associated to the depressed central part, having a rolling topography with smooth slope.

Due to its latitudinal situation the region, as a whole, presents a mean annual temperature around 24°C, except for the higher parts where it is lower than 22°C. During the warmest month (January) the average can reach 30-32°C in most part of the region and slight lower in the highlands (<29°C). During the winter, the temperatures are milder, being around 14°C and going down to 6-8°C in the highlands.

As concerning the precipitation, the region has a typical seasonal regime. The mean annual rainfall varies from 1,500 to 1,900 mm, with a maximum during the summer and minimum in the winter.

In the area of the alkaline massifs, as a consequence of the high altitudes, the mean annual temperature ranges from 12 to 18°C. On the other hand, the climate is always humid, with rainfall varying from 1,300 to 2,000 mm, well distributed throughout the year, with one or two dry months (July -August) according to the region.

The natural vegetation is the Tropical Semi-deciduous Forest (RADAM, 1983) or Tropical Broadleaf Forest (Azevedo, 1960), associated with a tropical forest with Araucária further south and with a denser forest in the more humid areas.

III. Types of deposits and reserves

Taking into account either the different lithologies associated with the bauxitic deposits or the regions where they occur, it is possible to group them into 3 different types:

- Amazonian bauxite: formed mainly on sedimentary rock, but including also the deposits formed on basic rock of Carajás,
- Bauxite of the Central Mantiqueira Province: developed essentially from Precambrian basement rocks. The bauxite of QF, formed on metasedimentary, metavolcanic and sedimentary rock are included here due to its situation in the vicinity of the Province.
- Bauxite of the south-southeastern region: refers particularly to the deposits formed on alkaline rocks that are widespread in this part of the country.

In each one of these regions, the most representative bauxites deposits were selected to give an idea of their characteristics (Table A.2).

These deposits present a total reserve of 1,7 billion tons of bauxite, distributed in the various regions of the Brazilian Territory.

It can be observed that the biggest deposits are those ones in the Amazon Region, with a total of 1,5 billion tons.

Previously to the discovery of the Amazonic deposits, the baux-

Table A.2 - Distribution and reserves of the bauxite deposits in Brazil.

REGION	STATE	DEPOSITS	PARENT ROCK	RESERVE (Mt)$^+$
AMAZONIA	PARA			1500
		Almeirim	sediment	(72,5)
		Porto Trombetas (Oriximina*, Faro) Juruti*	sediment	(1002)
		Paragominas* (Ourem,Irituia)	sediment	(316)
		Carajas (Maraba, N5*)	basalt	(49)
	AMAPA	Mazagão	sediments	24,5
CENTRAL MANTIQUEIRA PROVINCE AND QUADRILATERO FERRIFERO	ESPIRITO SANTO	Mimoso do Sul	gneiss	0,5
	MINAS GERAIS			183
		Quadrilátero Ferr. (24 deposits) - Batatal* - Fraga * - Nova Lima (V. dos Oculos*) - Macaquinho*	phyllite phyllite rhyodacite? sediment	(0,27)
		Cataguases*	gneiss	(3,95)
	SÃO PAULO			5
		Nazare Paulista*	amphibolite	
		Curucutu*	diabase	
		Mogi das Cruzes*	granit	
	RIO DE JANEIRO	Resende, Rio Bonito, Pirai, Macacu	alkaline rocks	4,7
SOUTHEASTERN	MINAS GERAIS	Poços de Caldas* (Andradas, Caldas, Poços)	syenite	(47)
		Passa Quatro (Itamonte,Ithanandu, Lavrinhas*, Passa Quatro*)	syenite	(6,5)
	SANTA CATARINA	Lages*, Coreia Pinto	basalt, diabase phonolite	2,7

$^+$ Data issued from Brazilian Mineral Yearbook 1990. The total by state does not correspond to the sum of deposits, because all the deposits are not registred here, and deposits studied have not allways an quantittative evaluation.
* Deposits studied in this work

ite on alkaline rocks were the main aluminium source. Nowadays, their reserves are around 100 million tons and the most important deposit is Poços de Caldas, with 65 million tons.

The bauxite of Quadrilátero Ferrífero, with an estimated reserve of 10 million tons, is distributed in 24 small deposits and the more important are Morro do Fraga, Vargem dos Óculos and Faria, which are the only ones being exploited.

It has already to be mentioned the deposits occurring on the Precambrian rocks of the region of Mar and Mantiqueira ranges, with an estimated reserve of 100 million tons.

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B . PETROLOGICAL AND GEOCHEMICAL CLASSIFICATION OF BAUXITES AND THEIR ASSOCIATED IRON-RICH LATERITES

Y. Tardy, J.L. Boeglin, C. Roquin

Abstract

Lateritic bauxites are accumulations of aluminium developed, in situ, from quartz-free or poorly quartzitic parent rocks under humid tropical climates. Iron in goethite or hematite also accumulates in bauxitic profiles, associated with or dissociated from aluminium, occurring in gibbsite, boehmite or kaolinite.

Four major types of lateritic bauxites: protobauxites, orthobauxites, metabauxites and cryptobauxites are defined as function of the nature of iron and aluminium minerals, as well as their relative distribution in profiles.

Protobauxites are lateritic soils where gibbsite and goethite are formed together under very humid climates.

Orthobauxites are gibbsitic and do not exhibit a concretionary structure. Iron as goethite or hematite is concentrated with aluminium. Conakrytes (non-nodular iron-rich accumulations) close to the top of the bauxitic profiles are, thus, frequently associated with orthobauxites. The presence of kaolinite at the bottom of the profiles is not necessary.

Metabauxites are boehmitic and show a concretionary or pisolitic structure; iron is dissociated from aluminium and is frequently concentrated as hematite in a kaolinitic ferricrete, located at the bottom of the bauxitic profile. Kaolinite appears always at the bottom of metabauxites profiles and, less frequently, at the base of orthobauxites.

In cryptobauxites, kaolinite is abundant at the top and at the bottom of the profiles, so that the gibbsitic layer is interbedded between two kaolinitic horizons.

Protobauxites are immature, while ortho-, crypto-, and above all metabauxites are old and mature formations. Proto- and orthobauxites are formed under a continuously humid tropical climate. Metabauxites are ancient orthobauxites, later transformed under warmer and less humid climate, whereas orthobauxites or cryptobauxites could have been kaolinitic ferricretes, later transformed into red or yellow latosols and further later into bauxites under more humid conditions. The lateritic bauxite classification is based on reactions of hydration-dehydration and of silication-desilication, regulated by temperature, water activity and chemi-

cal composition of the parent material.

Lateritic bauxites are witnesses of the paleoclimates which have been succeeding through the last 150 million years, since the Atlantic opening.

Introduction

Bauxites are formed under humid tropical climates They are associated with latosols (soft lateritic soils) and ferricretes (indurated iron accumulations) which are formed under contrasted tropical climates. Bauxites, latosols and ferricretes are widely distributed in North and South America, in West, Central or East Africa, as well as in Australia, India or in South-East Asia. Their geographic distribution is larger than the latitudinal zones of climates (humid tropical), under which they are normally formed or developed. Obviously, a part of bauxites and, particularly, the young profiles are, presently, developing under humid tropical climate, while another important part of them and, particularly, the old profiles are now evolving under more arid and warmer climates than those corresponding to their period of formation. Same kinds of considerations can be valid for ferricretes which are, normally, formed under contrasted tropical climates, drier and hotter than those requested for the formation of bauxite. Some ferricretes are, presently, evolving under more arid conditions; others are, presently, dismantled and are evolved under more humid climatic conditions than those strictly requested for their formation or conservation. Normally, bauxites and ferricretes are formed under tropical climates, differing by the rainfall and by the length of the dry season. Some bauxites, later evolving under a drier climate, may generate ferricretes, localized at the bottom of profiles, as well as ferricretes evolving later under a wetter climate may generate a new bauxitic horizon within a soft kaolinic horizon.

There are seven types of indurated or non-indurated laterites fundamentally distinguished by Tardy (1993). Latosols are soft and essentially kaolinic. Ferricretes, conakrytes and plinthites are indurated iron concentrations, and proto-, ortho-, meta- and cryptobauxites, stand for aluminium accumulations. Some bauxite formations are indurated, while others such as proto- and cryptobauxites are not.

I. Classification of iron-rich laterites

Tardy (1993) distinguishes three kinds of mechanisms of iron accumulations: concretion, incrustation and excretion, as well as three kinds of iron-rich lateritic formations: (1) mottled horizon and nodular ferricretes, (2) conakrytes of massive structures and (3) plinthites and petroplinthites of reticular organizations.

1. Ferricretes: nodular iron-rich accumulations

Ferricretes or “cuirasses ferrugineuses” *stricto sensu* are indurated iron concentrations, showing generally a noticeable nodulation. The words ferricrete, calcrete and silcrete are formed like concretion with “the formative crete” which etymologically comes from Latin *concrescere* meaning to cement or to grow together. Consequently, although these features may exhibit a concentric structure (Pettijohn, 1957), the definition of concretions does not include that they are concentric, as proposed by Brewer (1964), but are only indurated or cemented accumulations. After Tardy (1993), concretion designates also the mechanism of cementation and induration by centripetal accumulation of material in the pores of small size. In ferricretes, the mechanism of concretion leads to the formation of indurated nodules by accumulation of hematite in the very fine porosity developed by kaolinite crystal assemblages.

In a sequence of ferricrete development from mottles (diffuse accumulations) to subnodules (nodules with diffuse edges), nodules (with distinct edges), and metanodules (anastomosed), iron content increases, quartz content decreases drastically, while kaolinite amount decreases slowly or even increases moderately. In mottles, goethite dominates hematite but in well-developed nodules the contrary is observed. The ratio RHG (hematite/(hematite + goethite)) increases from the mottled zone to the ferricrete zone (Table B.1, Figs. B.1 and B.2).

In the process of ferricrete formation, kaolinite dissolves moderately but never disappears completely as long as the stability of hematitic nodules is insured. Concretion and nodulation in ferricretes are based on the association of hematite and kaolinite finely crystallized. This association of dehydrated or poorly hydrated minerals is very stable and develops under seasonally contrasted tropical climates. This paragenesis, when previously formed, is even stabilized in more arid conditions. On the contrary, nodules of hematite and kaolinite are destabilized in humid tropical conditions, and, particularly, under the great equatorial forest (Beauvais and Tardy, 1991).

Finally, ferricretes are formed under tropical climates which are warm, humid and seasonally contrasted ($1100<P<1700$ mm/yr; $T>25°C$)

Table B.1 - Chemical and mineralogical compositions of a serie of 190 samples of ferricrete developed from schists in Burkina Faso. Classes are determined by their iron content (after Mazaltarim, 1989 and Boeglin, 1990).

Fe_2O_3 %	20-25%	25-30%	30-35%	35-40%	40-45%	45-50%	50-55%	55-60%
	N=2	N=5	N=11	N=28	N=62	N=55	N=21	N=6
SiO_2	60.6 ± 1.9	53.9 ± 2.4	48.8 ± 4.1	39.1 ± 4.3	32.8 ± 3.8	26.8 ± 2.8	22.3 ± 2.1	19.7 ± 2.4
Al_2O_3	6.7 ± 0.5	9.7 ± 2.7	9.2 ± 2.6	11.9 ± 2.9	12.7 ± 3.0	13.6 ± 2.0	4.0 ± 1.9	12.0 ± 2.3
Fe_2O_3	24.2 ± 0.5	27.7 ± 0.6	32.6 ± 1.3	38.0 ± 1.4	42.8 ± 1.3	47.5 ± 1.4	51.6 ± 0.9	56.4 ± 0.7
H_2O	5.6 ± 0.5	7.0 ± 0.7	7.3 ± 0.8	8.7 ± 0.8	9.5 ± 0.6	1.0 ± 0.9	10.1 ± 0.5	10.2 ± 1
Qtz	57 ± 2	46 ± 6	42 ± 7	29 ± 8	22 ± 8	15 ± 5	10 ± 4	10 ± 5
Kaol	14 ± 1	21 ± 7	19 ± 7	25 ± 8	27 ± 8	29 ± 5	29 ± 5	22 ± 7
Goet	23 ± 2	22 ± 4	29 ± 5	32 ± 5	36 ± 7	36 ± 7	37 ± 7	44 ±10
Hema	6 ± 1	11 ± 3	10 ± 4	13 ± 5	15 ± 6	21 ± 6	24 ± 6	23 ± 8
Gibbs	0	0	0	t	t	t	1 ± 2	1 ± 1
RGH	20 ± 5	33 ±11	25 ±11	30 ±12	30 ±12	36 ±11	39 ±10	35 ±14

and break down under tropical climates, warm but more humid (P>1700 mm/yr; T>25°C), or under subtropical climates, humid but cooler (P>1300 mm/yr; T<25°C).

2. Conakrytes: non-nodular iron accumulations

Conakrytes are iron accumulations characterized by massive or crystalloplasmic structures and the absence of concretions and nodules. Kaolinite does not form in such weathering products, so that, according to Tardy (1993), nodulation is not possible. Reasons for a non-formation of kaolinite are twofold.

Conakrytes, in the first case, are develop under a very humid climate, and result of an active leaching on a parent rock poor in quartz, so that gibbsite is formed instead of kaolinite. Thus, aluminous conakrytes are the equivalent of ferruginous orthobauxites. Conakrytes are commonly associated with orthobauxites of which they tend to form the superficial part. In this case, conakryte is characteristic of a humid climate.

Conakrytes, in the second case, are non aluminous iron accumulations which are developed from non-aluminous parent rocks, such as dunites, similar to those described by Bonifas (1959), in Conakry (Guinea). They are widely distributed lateritic products formed by weathering of ultramafic rocks, under all kinds of climates. In this case, conakryte is equivalent either of a bauxite or of a ferricrete and, consequently, not

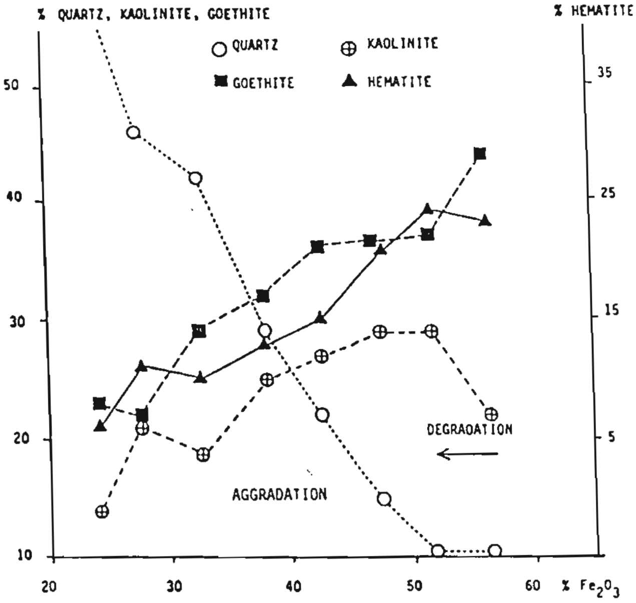

Figure B.1 - Chemical and mineralogical compositions of a serie of 190 ferricretes developed on schists, in Burkina Faso. Notice that hematite and kaolinite ponderal concentrations increase or decrease together, so that their fluctuations are used to discriminate two domains in the process of the ferricrete formation: dehydratation and aggradation (concretion) versus hydration and degradation (excretion) (from Tardy, 1993).

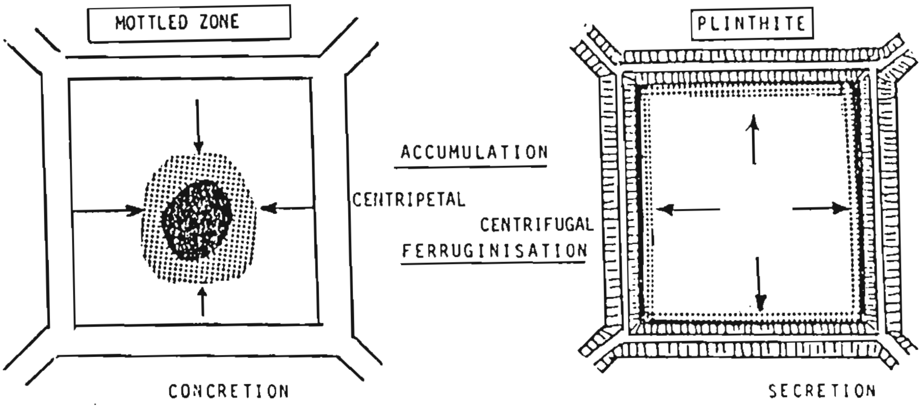

Figure B.2 - Concretion (mottle and nodule formation) versus excretion (reticular cutan formation): two processes of iron accumulation which may allow, if acceptable, to distinguish ferricretes from plinthites (from Tardy, 1993).

characteristic of a peculiar type of climate.

Conakrytes of the first type are gibbsitic; those of the second type are not. Relative amounts of goethite and hematite, which constitute together the major part of the laterite, are not yet used as criteria for conakrytes classification. Further investigations will say how to introduce subdivisions within this peculiar group of laterites, which is clearly separated from ferricretes. In fact, ferricretes show concretions of hematite, concentrated in very fine or subamorphous crystals, together with kaolinite. On the contrary, conakrytes exhibit crystallarias of large crystals of goethite or hematite associated with gibbsite, in pores of large size. These features which characterize conakrytes, approach *cutanic excretions* and differ totally from concretions and nodulations, which characterize ferricretes. Further researches should also be promoted to investigate another type of iron accumulation which we have called plinthite in a restricted sense.

3. *Plinthite: a cutanic and reticular iron-rich laterite?*

Tardy (1993) has shown that what he called *excretion* and *incrustation* which appear as cutanic and reticular accumulations have to be clearly distinguished and also separated from *concretions*. A cutan of excretion results of a centrifugal transfer from the argillaceous matrix with a porosity of small size, towards the voids and the porosity of large size. A cutan of incrustation results of a transfer of matter which goes from voids and the porosity of large size towards the soil matrix. *Excretion and concretion* are opposite in relation to features (cutan versus nodule) and to processes (centrifugal versus centripetal). *Excretion and incrustation* are similar in relation to features (cutans in both cases) but are of opposite polarity (centrifugal versus centripetal). *Incrustation and concretion* are opposite in relation to feature (cutan versus nodule) but similar in relation to the polarity of processes (centripetal towards the porosity of fine size). The process of excretion corresponds to the leaching of iron from kaolinitic domains and to the cutanic accumulation of hematite in the voids. Excretion is clearly distinguished from concretion which corresponds to a leaching in domains close to the voids and an accumulation of hematite in domains rich in kaolinite.

Chatelin and Martin (1972) and Chatelin (1974) have distinguished structichron and retichron. A retichron is a cutanic accumulation of iron (hematite or goethite) organized as a network reticulated which can be indurated. Retichron are mostly located downslope of the landscapes, where they can be mistaken for hydromorphic laterites or plinthites.

In fact, this definition converge with that one of Camargo et al. (1988), for whom a plinthite is an iron accumulation showing laminar, reticular or polygonal organization.

Thus, a plinthite differs from a mottled formation and petroplinthite differs from a nodular ferricrete. Plinthites and petroplinthites are localized downslope, while ferricretes are situated upslope in the landscape morphology.

The question which arises here is how to establish a distinction, at a level of classification, between an iron reticular accumulation specially made of cutans of hematite or cutans of goethite and iron accumulation specially made of hematitic-kaolinitic concretions. Other fundamental questions concern the distinction between cutans of incrustation and cutans of excretion, corresponding to opposite polarities of iron transfer.

These processes permit to classify the different types of iron accumulation. An iron accumulation specially characterized by mottles or nodules, which result from concretion, is classified as a mottled horizon (soft material) or a ferricrete (hardened material). An iron accumulation characterized by iron-rich cutans more abundant than nodules may be either a ferricrete or a plinthite: if the cutans result from incrustation, then it is classified as a ferricrete, if, on the contrary, cutans result from excretion, then it is classified as a plinthite (soft material) or petroplinthite (hardened material).

The vermiform facies of ferricretes in which iron-rich cutans are more abundant than nodules was considered (Eschenbrenner, 1987) as the result of incrustation (Tardy, 1993). Thus, these iron accumulations can be conserved as part of the group of ferricretes. If, on the contrary, cutans do not result of incrustation, but result of an excretion, vermiform iron accumulation should be classified as plinthites, if their specific definition is acceptable. Furthermore, if plinthites are mottled horizons and petroplinthite are nodular horizons, they have to be classified with ferricretes and then a terminological distinction is not justified. On the contrary, if they are not incrustations, but cutanic excretions, thus, the distinction of the term plinthite is entirely justified (Tardy, 1993).

Finally, if confirmed, plinthites and petroplinthites defined as iron cutanic and reticular accumulations resulting from a process of excretion have to be clearly separated from mottled horizons and ferricretes which are iron accumulations, resulting from a process of concretion (Fig. B.2). Climates and conditions of development are distinct.

Mechanisms of formation are different.

II. Classification of lateritic bauxites

The bauxitisation of very thick lateritic profiles requires a lot of time and, eventually, millions of years or even tens of millions of years to be formed. This is the reason why bauxitic profiles have been evolving under different types of climatic and morphological situations which do not necessarily correspond to their conditions of formation.

1. Protobauxites

It is rather difficult to determine with precision what is the type or what are the types of soils which could be the precursors of thick bauxitic profiles. It is also difficult to evaluate the time required for transforming a protobauxite (gibbsitic soil) into a well characterized bauxite. Tardy (1993) admitted that among the different types of oxisols (latosols, in the Brazilian classification or sols ferrallitiques, in the French classification) the most sensitive profile is the "sol ferrallitique jaune" or the yellow oxisol in which gibbsite and goethite dominate and where kaolinite, hematite and quartz are, at least originally, subsidiary. They are envolving towards cryptobauxites. However, products of ferricrete dismantlement, red latosols, oxisols or "sols ferrallitiques rouges desaturés" originally rich in haematite and kaolinite but poor in quartz may be progressively enriched in gibbsite and may naturally evolve towards orthobauxites. In Tables B.2 and B.3, chemical and mineralogical data are presented, characterizing a red gibbsitic oxisol (sol ferrallitique rouge fortement désaturé) developed over the basalts of Adamaoua (Sieffermann, 1973). Gibbsite appears at the top and close to 250 cm, while kaolinite minerals are abundant in the whole profile, but dominate at the bottom. Halloysite (very hydrated) and metahalloysite (hydrated) are in higher proportions in the deeper part, while kaolinite (poorly hydrated) is more abundant in the higher part of the profile. Similarly hematite (dehydrated) dominates at the top, while ferrihydrite (hydrated) is represented all over the profile. In the upper part of the profile, desilication and dehydration reactions are prevailing. Dehydration of ferruginous minerals develops more easily than for aluminous minerals: for the aluminous minerals the desilication is easier when hydration is possible. Dehydration seems very easy for ferruginous minerals, so that gibbsite and hematite can coexist together. These

Table B.2 - Chemical composition of a red gibbsitic oxisol profile developed over the basalts of Adamaoua, Center-Cameroon (from Sieffermann, 1973).

Horizons	Nº	Depth (cm)	Granulometry %<2µm	Granulometry %>2µm	Chemical analysis (%) SiO_2	Al_2O_3	Fe_2O_3	H_2O	Ratio SiO_2/Al_2O_3	Ratio Fe_2O_3/Al_2O_3
A	231	8	42	58	29.4	26.7	21.6	11.7	1.87	0.51
B_{1ox}	232	25	70	30	28.2	29.2*	21.9	12.9	1.64	0.47
B_{1ox}	233	55	69	31	27.8	29.6	22.7	13.0	1.60	0.48
B_{2ox}	234	100	70	30	26.8	28.9	23.7	14.9	1.58	0.51
B_{2ox}	235	200	65	35	26.7	28.3	23.6	13.8	1.60	0.52
$B_{3ox, Cn}$	236	250	43	57	26.2	30.0	22.8	13.9	1.48	0.47
B_{4ox}	237	300	67	33	27.4	29.6	24.4	13.2	1.57	0.51
BC	238	350	31	31	29.3	28.4	23.6	12.5	1.75	0.52
BC	239a	460	70	30	30.1	27.4	24.3	11.5	1.87	0.56
CG	239b	600	66	34	30.0	26.0	25.4	11.4	1.92	0.59
CG	239c	800	59	41	31.2	27.1	25.3	11.2	1.96	0.58
RM	239d	950	0	100	45.7	11.8	11.9	0.7	6.60	0.63

Table B.3 - Mineralogy of a red gibbsitic oxisol profile developed over the basalts of Adamaoua, Center-Cameroon (from Sieffermann, 1973).

Horizons	Nº	Depth cm	Kaolinic clays (%) T	K	M	H	G	Quartz Q	Ratio SiO_2/Al_2O_3	Ratio Gib/Kaol	Al_2O_3 Am/Gib	Kaolinites M/K	H/K
A	231	8	39	24.6	14.6	0	15.5	11.8	1.12	0.62	0.11	0.59	0
B_1ox	232	25	43.4	26.	17.4	0	13.2	7.5	1.20	0.51	0.21	0.67	0
B_1ox	233	55	39.8	23.9	15.9	0	16.0	9.0	1.08	0.67	0.17	0.67	0
B_2ox	234	100	37.7	22.6	15.1	0	16.1	9.3	1.03	0.74	0.13	0.67	0
B_2ox	235	200	35.7	21.4	14.3	0	17.3	10.1	1.00	0.81	0.15	0.67	0
B_3ox, Cn	236	250	41.8	18.6	23.3	tr	18.7	6.8	1.20	1.01	0.07	1.25	0
B_4ox	237	300	50.4	22.1	27.6	0.7	16.8	3.0	1.31	0.45	0.20	1.25	0.0
BC	238	350	60.3	18.6	38.2	3.5	3.3	0.6	1.54	0.17	0.52	2.05	0.2
BC	239a	460	62.1	9.1	43.5	9.5	1.4	0.6	1.72	0.15	0.50	4.78	1.0
CG	239b	600	64.0	6.4	48.8	8.8	0	0.2	1.85	0.0	2.00	7.62	1.4
CG	239c	800	65.3	6.5	48.4	10.4	0	0.2	1.94	0.0	1.60	7.44	1.6
RM	239d	950	0.0	0.0	0.0	0.0	-	-	-	-	-	-	-

T: Total; K: Kaolinite; M: Metahalloysite; H: Halloysite; Q: Quartz; G: Gibbsite

Ratios: SiO_2/Al_2O_3 of secondary minerals; Gib/Kaol: Gibbsite/Kaolinite; Am/Gib: Al_2O_3 amorphe/Gibbsite; Kaolinite: M/K: Metahalloysite/kaolinite; H/K: Halloysite/Kaolinite.

two minerals are essential in orthobauxites.

2. *Orthobauxites*

The prefix *ortho* in Greek means normal. Orthobauxites are developed normally and they are supposed to have been forming continuously under a tropical humid climate with annual rainfall greater than 1700 mm/year. They are products of evolution of gibbsitic goethitic and hematitic protobauxites.

Typical orthobauxitic profiles. What is called here a typical orthobauxitic profile is made of three major horizons (Valeton, 1972, 1981; Aleva, 1979, 1981, 1982, 1989; Bardossy, 1989; Bardossy and Aleva, 1990). From the top to the bottom one finds:

- a ferruginous, hematitic and gibbsitic horizon, red in color, located close to the surface;
- a bauxitic horizon, less colored, less ferruginous and more aluminous, with gibbsite and hematite;
- an argillaceous horizon, rich in kaolinite, poorly ferruginous and red-yellowish color.

Typical orthobauxitic profiles are those of Mounts Bakhuis, Surinam (Aleva, 1981), Jarrahdale in the Darling Range, Australia (Grubb, 1971), Mount Tato at Lakota in Ivory Coast, Africa (Boulangé, 1983, 1984) and some profiles of Famansa in Mali, Africa (Tardy, 1993).

The profile of Jarrahdale (Fig. B.3) (Grubb, 1971) shows a decrease of quartz and kaolinite and an increase of goethite and hematite from the bottom to the top.

Towards the surface, the ratio hematite/goethite increases. Typical orthobauxitic profiles show an increase of iron from the bottom to the top, where iron content can be greater than aluminium (Table B.4).

The orthobauxite of Famansa (Mali). The plateau of Famansa, South-Mali, is located close to the border of Guinea at an altitude of 800 m. The morphological surface of the plateau is supposed to have been formed during the Cretaceous (Michel, 1973).

There are two types of bauxites in Famansa: orthobauxites and metabauxites. Orthobauxites are homogeneously red, do not exhibit nodules, concretions or pisolites. Over about 10 m., they are constituted of gibbsite, hematite and goethite (Table B.5, Fig. B.4). The ratio hematite/goethite also increases towards the surface.

Conakrytes: ferruginous hard caps over orthobauxites. It is frequent to find in the literature a distinction introduced between bauxites and laterites for horizons belonging to the same profile. The use of the term laterite to designate an accumulation of iron at the surface of bauxitic profiles (Balasubramanian, 1989) is confusing, simply because bauxites are also laterites. It is also frequent to find in descriptions the term ferricrete to indicate these superficial ferruginous horizons. After Nahon (1976), it is impossible to call ferricrete all the ferruginous accumulations and particularly those which do not present an important nodulation. Grubb (1971) used to call these iron accumulations: ferruginous hard cap. Tardy (1993) has chosen to nominate them conakrytes.

Finally, an orthobauxite, developed from a parent rock sufficiently ferruginous, is normally capped by a conakryte. An orthobauxite is also dominantly gibbsitic in the thick intermediate horizon and it does not show boehmite, pisolites nor concretions.

Isalteritic orthobauxites. There are several orthobauxitic profiles which do not exhibit a kaolinitic layer at the base of the bauxitic intermediate horizon. Thus, the bauxite develops down to the contact with the unaltered parent rock. The volume and the architecture of the parent rock are preserved and that is the reason why Boulangé et al. (1973, 1975) and Boulangé (1984) call these formations isalteritic bauxites. They are formed in well drained areas high above the water table level and they are very frequent at the base of orthobauxite profiles.

3. *Cryptobauxites*

In Amazonia, bauxites are widespread. Lucas et al. (1986) and Lucas (1989) have presented an interesting synthesis concerning the ore deposits of Juriti and Trombetas. The parent rocks are sandstones and argillites of Alter-do-Chão from the later Cretaceous or the early Tertiary (Daemon, 1975). All bauxitic profiles are capped by an argillaceous horizon, very rich in kaolinite and poor in quartz, called Clays of Belterra and considered by Sombroeck (1966) and Tricart (1978) as a quaternary sedimentary lacustrine formation; as a Pliocene lacustrine or desertic deposit by Grubb (1979), Truckenbrodt and Kotschoubey (1981); and, finally, as a sedimentary cover by Aleva (1981, 1989). Chauvel et al. (1982) and Lucas et al. (1984) firstly called our attention on a pedogenetic origin, while Tardy (1993) proposed that the pedogenetic phase takes place in a biogenic formation. The peculiarity of this type of bauxites comes from the fact that a gibbsitic horizon is interbedded between two horizons rich in kaolinite (Fig. B.5). It is also interesting to remark that hematite is associated with gibbsite in the bauxitic horizon, while goethite is the iron mineral dominant in the superficial layer. We can certainly admit with Lucas (1989) that bauxites of Amazonia are polygenic. They are similar to gibbsitic soils of Cameroon, such as those

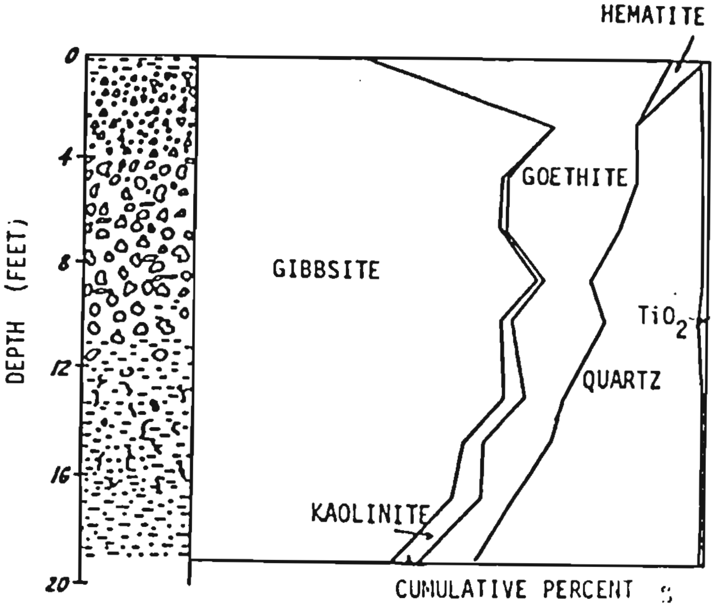

Figure B.3 - Mineralogy of the bauxite of Jarrahdale in Australia (from Grubb, 1971).

Table B.4 - Ferruginous bauxite of Bakhuis in Surinam (from Aleva, 1979). This profile is considered as characteristic of an orthobauxite (from Tardy, 1993).

Depth (m)	Fe_2O_3 (%)	Al_2O_3 (%)	SiO_2 (%)	Gibbsite (%)	Kaolinite (%)
1	45	35	0	55	0
2	25	48	0	75	0
3	21	51	0	79	0
4	18	53	0	82	0
5	12	55	2	85	3
6	12	44	9	68	20
7	11	37	30	24	65
8	8	41	35	17	75
9	5	41	43	3	92

Table B.5 - Chemical and mineralogical analyses of the samples collected in the red orthobauxite of Famansa, South-Mali, (from Tardy, 1993).

Depth	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	H_2O	Kaolinite	Boehmite	Gibbsite	Hematite	Goethite	Sum	RHG
0.00	12.61	9.57	70.51	1.23	5.57	31.90	0.00	0.00	9.57	0.00	99.49	1.00
0.50	40.68	33.80	1.26	2.77	21.00	2.71	0.83	59.49	33.80	0.00	99.59	1.00
1.00	36.86	37.87	0.86	2.13	20.79	1.85	0.00	55.24	25.25	14.04	98.51	0.64
1.50	41.72	32.02	0.36	2.13	22.85	0.77	0.00	63.32	24.61	8.24	99.08	0.75
2.00	37.29	37.51	0.81	2.56	20.71	1.74	0.00	55.97	27.69	10.92	98.88	0.72
2.50	41.52	32.48	0.33	1.97	22.95	0.71	0.00	63.06	23.28	10.23	99.25	0.69
3.00	33.83	42.65	0.72	2.21	19.38	1.55	0.00	50.79	28.49	15.75	98.79	0.64
3.50	34.07	42.23	0.58	2.01	19.33	1.25	0.00	51.34	29.84	13.79	98.22	0.68
4.00	35.86	38.55	0.76	2.36	20.77	1.63	0.00	53.84	21.53	18.93	98.30	0.53
4.50	48.63	19.15	0.82	2.83	26.90	1.76	0.00	73.29	7.62	12.83	98.33	0.37
5.00	43.09	27.97	0.42	3.81	24.27	0.90	0.00	65.34	14.29	15.21	99.56	0.48
5.50	44.54	26.67	0.49	2.81	24.88	1.05	0.00	67.47	14.30	13.76	99.39	0.51
6.00	37.81	35.45	0.52	4.71	20.56	1.12	0.00	57.14	29.80	6.28	99.05	0.83
6.50	36.62	37.52	0.53	2.76	20.45	1.14	0.00	55.31	27.23	11.44	97.88	0.70
7.00	34.63	41.16	0.68	1.65	20.04	1.46	0.00	52.07	24.95	18.03	98.16	0.58
7.50	43.93	29.50	0.28	2.14	23.86	0.60	0.00	66.81	23.62	6.55	99.71	0.78
8.00	41.38	31.83	0.36	3.13	23.04	0.77	0.00	62.80	21.13	11.90	99.74	0.64
8.50	37.91	36.43	0.48	2.10	21.04	1.03	0.00	57.34	27.03	10.45	97.96	0.72

RHG = hematite (%)/(hematite (%) + goethite (%))

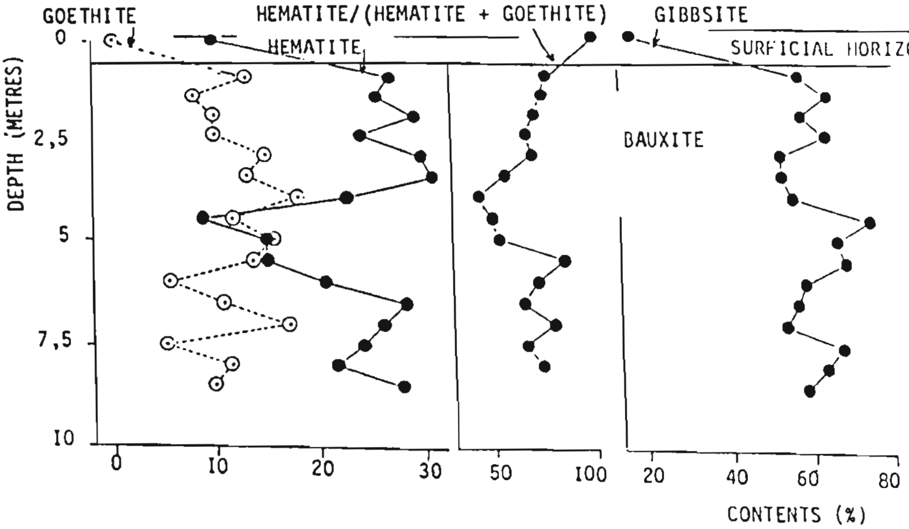

Figure B.4 - Mineralogical evolution in a red orthobauxitic profile of Famansa, South-Mali, Africa, (from Tardy 1993).

described by Muller (1987). Both were considered by Tardy (1993) as ancient ferricretes, formed under seasonally contrasted tropical climates and later dismantled under a more humid tropical climate.

Gibbsite is formed in the place of the ancient ferricrete, and continues to develop in situ, close to the water table (Lucas, 1989) but below a thick kaolinic soft horizon, so that the bauxite layer is hidden and called cryptobauxite. This peculiar distribution implies a strong necessity of supplying silica from the lower to the upper part of the profile. Several biological processes can be responsible for that: termites (Truckenbrodt et al., 1991) or phytolites (Lucas et al, 1993).

Cryptobauxites are frequent in equatorial forests and, if really polygenic, characterize a paleoclimatic succession, which has been changing from arid to humid. The contrary is observed for the metabauxites evolution.

4. Metabauxites

Metabauxites are orthobauxites, initially formed under a tropical humid climate and after transformed under warmer and drier climates. *Meta* in Greek means which comes later. Metabauxites are diagenetized bauxite (Tardy, 1993).

Typical metabauxite profiles. Some of the most typical profiles, that we can classify as metabauxites, are those of Weipa and Pera Head, in the Cape York peninsula, N.E. Australia. They were described by Loughnan & Bayliss (1961) and Loughnan (1969). Over a thickness of 10 m, a quartz-argillaceous sandstone is transformed into an aluminium-rich bauxite. From the bottom to the top of the profile, quartz and kaolinite, always present, diminish, while gibbsite and boehmite increase. In the lower part, goethite dominates, while in the higher part, hematite becomes the unique iron mineral.

The metabauxite profile of Famansa, in South Mali, was studied by Bourdeau (1991). This so-called white bauxite profile exhibits, over 10 m of thickness, an increase of aluminium, gibbsite and bohemia and a decrease of silicium and aluminium towards the profile surface.

Ratios RBG: boehmite/(boehmite + gibbsite), RHG: hematite/(hematite + goethite) and RGiK: gibbsite/(gibbsite + kaolinite) all three rise constantly from the bottom to the top of the profile. In this profile, iron does not accumulate in the superficial horizon but at depth, between 6 and 8 m., forming a typical kaolinite-hematite rich nodular ferricrete (Table B.6, Fig. B.6).

Metabauxites are deferruginized at the top, but ferruginized at

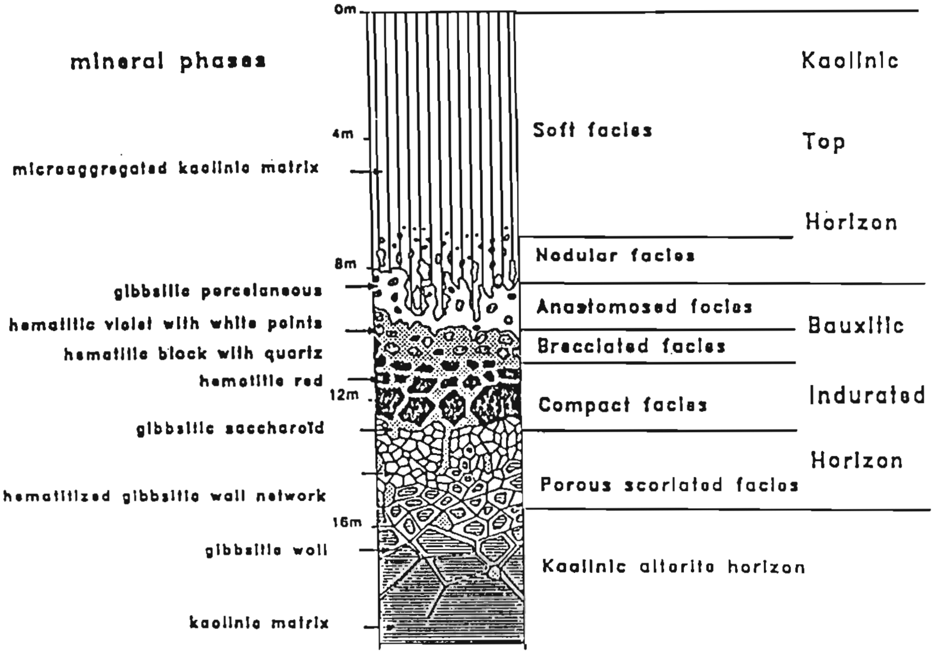

Figure B.5 - Cryptobauxite profile from Juriti in Amazonia, Brazil. Three horizons are distinguished: a soft kaolinic layer at the surface; a bauxitic layer in an intermediate position within a dismantled ferricrete; a kaolinic lithomarge in the lower part of the profile (adapted from Lucas, 1989).

the bottom of profiles. The massive gibbsitic structure is replaced by a boehmitic and pisolitic structure. In orthobauxites, iron in hematite and aluminium in gibbsite are associated at the top of the profile, forming conakrytes of massive structure. In metabauxites, at the surface of profiles, iron and aluminium in boehmitic pisolites are separate, while, in the ferricrete located at the bottom, iron in fine grained hematite and aluminium in kaolinite are again associated.

Local distribution of orthobauxites and metabauxites in Famansa (South Mali). In South Mali, orthobauxitic profiles, red in color, and metabauxitic profiles, white in color, are mixed. Where a conakryte outcrops, the water content of the orthobauxitic red profile is higher. If the pisolitic bauxite outcrops, the water content of the metabauxitic white profile is lower (Fig. B.7 and B.9).

Regional metabauxitisation. Balkay and Bardossy (1967), firstly, have pointed out that the amounts of boehmite in bauxites of Western Africa increase from the South to the North.

Table B.6 - Chemical composition and mineralogy of a white metabauxitic profile in Famansa, South-Mali, Africa, (from Tardy, 1993).

Depth (m)	Al_2O_3 (%)	Fe_2O_3 (%)	SiO_2 (%)	TiO_2 (%)	H_2O (%)	Kaol. (%)	Boeh. (%)	Gibb. (%)	Hema. (%)	Goeth. (%)	Anat. (%)	Sum (%)	RHG (%)	RBG (%)
0.00	58.00	17.03	0.20	4.79	18.32	0.43	30.86	48.30	17.03	0.00	4.79	101.41	1.00	0.39
0.50	64.00	4.07	0.29	6.40	23.68	0.62	25.36	64.52	4.07	0.00	6.40	100.97	1.00	0.28
1.00	58.20	13.59	0.51	4.80	21.28	1.10	23.60	57.64	13.59	0.00	4.80	100.73	1.00	0.29
1.50	41.95	30.77	0.58	3.45	21.30	1.25	2.01	60.77	30.77	0.00	3.45	98.25	1.00	0.03
2.00	46.92	24.89	0.81	5.26	20.11	1.74	11.48	55.76	24.89	0.00	5.26	99.13	1.00	0.17
2.50	99.90	12.35	0.51	4.69	21.20	1.10	26.05	57.06	12.35	0.00	4.69	101.24	1.00	0.31
3.00	54.40	15.68	0.27	4.22	24.41	0.58	10.83	68.75	15.68	0.00	4.22	100.06	1.00	0.14
3.50	55.70	13.26	0.41	4.80	24.72	0.88	11.72	69.40	13.26	0.00	4.80	100.06	1.00	0.14
4.00	57.70	10.22	0.37	3.35	26.91	0.80	8.90	78.17	10.22	0.00	3.35	99.44	1.00	0.10
4.50	55.50	13.81	0.47	3.10	26.03	1.01	8.15	73.65	13.81	0.00	3.10	99.72	1.00	0.10
5.00	57.40	10.66	1.47	2.82	26.42	3.16	9.32	73.74	10.66	0.00	2.82	99.70	1.00	0.11
5.50	50.09	18.66	0.94	2.82	26.07	2.02	0.71	74.44	18.66	0.00	2.82	98.65	1.00	0.01
6.00	36.59	34.55	5.11	2.15	20.16	10.99	0.00	49.31	20.40	15.52	2.15	98.36	0.57	0.00
6.50	23.82	47.37	14.35	1.36	12.24	30.85	0.00	17.77	31.47	17.69	1.36	99.14	0.64	0.00
7.00	27.74	45.90	10.55	1.42	14.23	22.68	0.00	28.70	35.81	11.22	1.42	99.84	0.76	0.00
7.50	30.07	40.15	10.37	1.56	16.03	22.30	0.00	32.50	25.25	16.57	1.56	98.18	0.60	0.00
8.00	26.50	43.24	13.06	1.52	33.88	28.08	0.00	23.55	27.08	17.97	1.52	98.20	0.60	0.00
8.50	40.35	32.57	1.04	1.80	23.24	2.24	0.00	60.35	14.33	20.29	1.80	99.00	0.41	0.00
9.00	45.89	23.00	0.61	1.63	26.99	1.31	0.00	69.38	1.95	27.76	1.63	98.12	0.08	0.00
9.50	40.35	32.81	0.96	1.61	23.73	2.06	0.00	60.45	10.32	25.02	1.61	99.46	0.29	0.00
10.00	43.34	23.44	7.13	2.02	23.70	15.33	0.00	57.00	7.07	18.20	2.02	99.63	0.28	0.00

Rapport RHG = hematite/(hematite + goethite); Rapport RBG = boehmite/(boehmite + gibbsite)

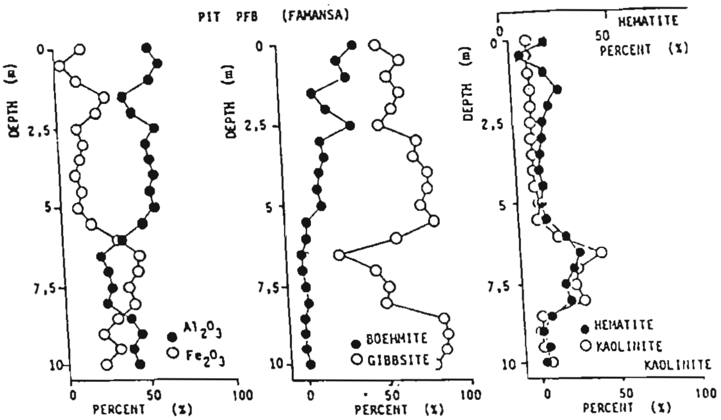

Figure B.6 - Mineralogical evolution in a white metabauxitic profile in Famansa, South-Mali, Africa, (from Tardy, 1993).

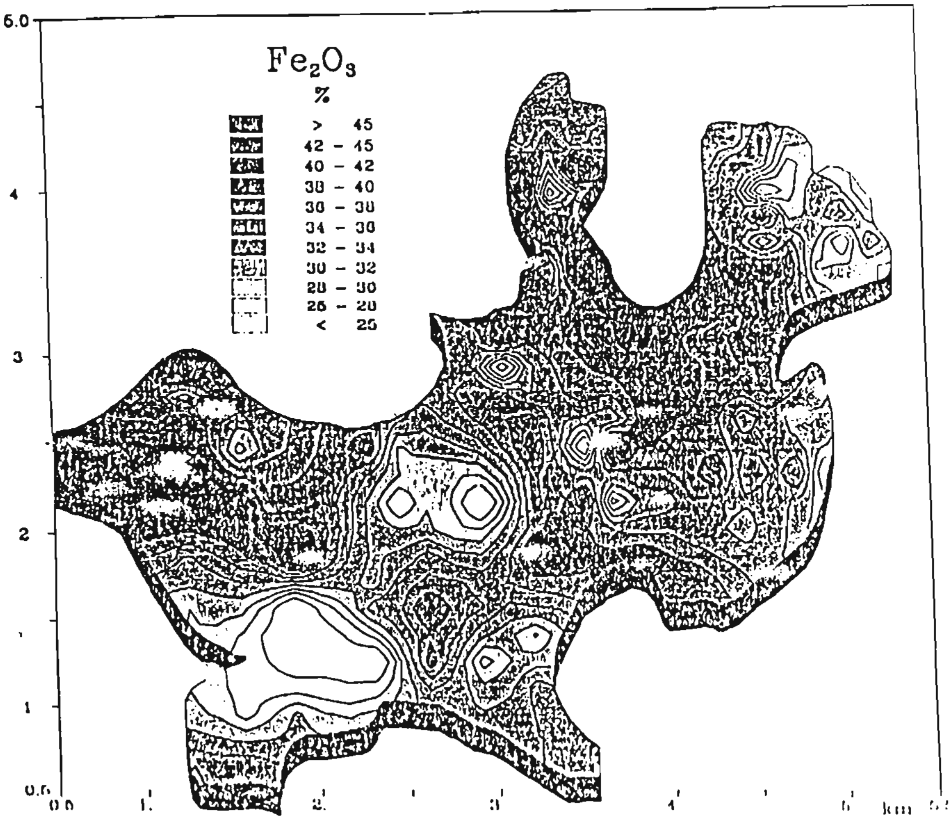

Figure B.7 - Distribution of aluminium and iron contents in superficial horizons of orthobauxitic (rich in iron) and metabauxitic (poor in iron, rich in aluminium) profiles of the plateau of Famansa, South-Mali, Africa, (from Tardy, 1993).

Seven regions were distinguished by Bourdeau (1991), who studied 3750 analyses of samples collected by Pechiney-Sarepa in bauxites of Guinea and Mali: (I) Fouta Djalon in Guinea, (II) Balea, North of Guinea, (III) Bamako-West in South Mali, (IV) Falea, (V) Kenieba in South-West Mali, (VI) Koulikoro, West Mali and (VII) Bafoulabe North-West Mali. In each region, there were distinguished the upper or superficial (S) from the lower horizon (I) of the profile (Table B.7).

It is clear that from the South (humid) to the North (dry and hot), i.e. from the humid Guinea to the Sahara (Fig. B.8 to B.13):

- water content diminishes;
- in the superficial horizon, iron content decreases;
- in deep horizon, iron content increases and aluminium decreases;
- gibbsite and goethite contents diminish; while hematite and

Table B.7 - Chemical and mineralogical characteristics of 3750 samples of bauxites collected in 7 different regions from South-Guinea to North-Mali, i.e. from humid to arid countries (after Bourdeau, 1991).

Regions		I	II	III	IV	V	VI	VII	Average
Al_2O_3	S.	40.69	41.54	39.35	42.10	39.34	41.19	38.48	40.39
Al_2O_3	I.	39.90	41.54	40.23	33.66	39.55	26.99		36.98
SiO_2	S.	2.10	1.42	3.39	5.84	7.67	13.73	15.25	7.06
SiO_2	I.	2.45	0.90	3.20	10.58	7.10	14.08		6.39
Fe_2O_3	S.	32.05	32.97	34.24	29.61	32.05	27.09	27.49	30.79
Fe_2O_3	I.	32.27	32.72	31.96	36.10	30.57	43.25		34.48
LOI	S.	22.00	20.27	19.63	19.79	18.21	15.32	15.28	18.64
LOI	I.	22.11	21.18	21.37	17.16	19.62	34.45		19.15
TiO_2	S.	2.83	3.49	3.09	2.35	2.42	2.36	3.20	2.82
TiO_2	I.	3.02	3.36	2.98	2.20	2.86	1.93		2.73
RAF	S.	1.27	1.26	1.15	1.42	1.23	1.52	1.40	1.32
RAF	I.	1.24	1.27	1.26	0.93	1.29	3.62	0.57	1.03
RAFSI		1.03	0.99	0.91	1.52	0.95	2.44	2.46	1.47
RAS	S.	19.04	29.31	11.61	7.21	5.13	3.00	2.52	11.12
RAS	I.	16.28	46.00	12.57	3.18	5.57	1.92		14.25
Boehmite	S.	0.82	4.87	4.24	7.31	7.64	13.01	15.47	7.62
Boehmite	I.	0.36	2.46	1.52	3.25	6.16	3.63		2.90
Gibbsite	S.	64.57	60.42	59.05	60.45	56.70	55.74	49.97	58.13
Gibbsite	I.	64.18	63.18	62.47	54.91	60.61	44.41		58.29
Hematite	S.	26.69	34.06	34.27	30.13	34.89	31.19	34.33	32.22
Hematite	I.	23.43	32.85	29.12	38.05	32.93	47.33		33.95
Goethite	S.	7.92	0.65	2.44	2.11	0.77	0.07	0.23	2.03
Goethite	I.	12.02	1.51	68.9	3.81	0.30	4.63		4.86
Kaolinite	S.	2.30	1.52	36.4	6.28	8.25	14.61	12.47	7.01
Kaolinite	I.	5.27	1.94	68.8	22.96	15.27	30.28	35.42	16.86
RBG	S.	0.01	0.07	00.7	0.11	0.12	0.19	0.24	0.12
RBG	I.	0.01	0.04	00.2	0.06	0.09	0.08		0.05
RHG	S.	0.77	0.98	09.3	0.93	0.98	1.00	0.99	0.94
RHG	I.	0.66	0.96	08.1	0.91	0.99	0.91		0.87
Nb analyses		538	349	1494	626	420	208	111	3746

S: surficial horizons (depth < 5m); I: lower horizons (depth > 5m)
LOI: loss on ignition
RAS: ratio Al_2O_3/SiO_2 (index of desilication)
RAF: ratio Al_2O_3/FeO_3
RAFSI: ratio Al_2O_3/FeO_3 (S) / Al_2O_3/Fe_2O_3 (I) (index of iron transfer from the top (S) to the bottom (I) of the profiles)
RBG: ratio boehmite/(boehmite + gibbsite)
RHG: ratio hematite/(hematite + goethite) (index of dehydration)

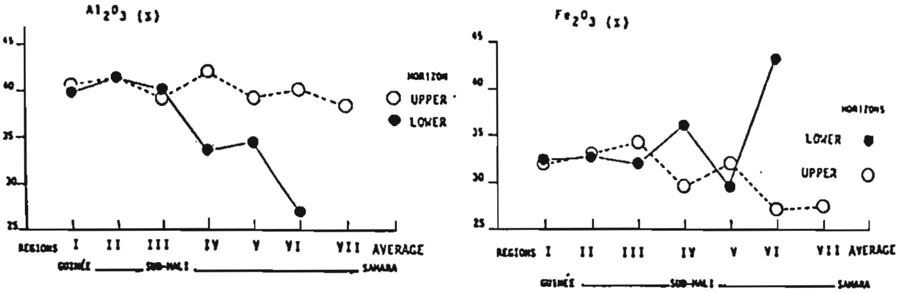

Figure B.8 - Evolution of aluminium and iron contents in bauxites of Guinea and Mali (from Tardy, 1993).

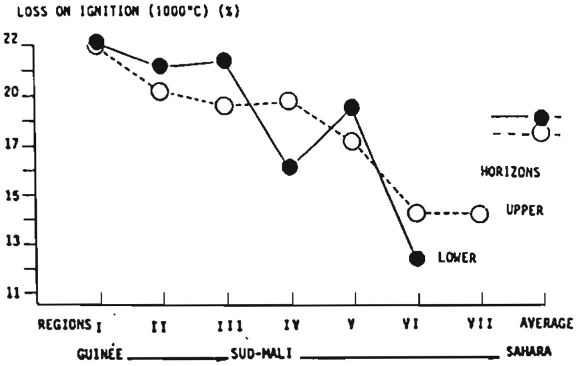

Figure B.9 - Evolution of water content in bauxites of Guinea and Mali (from Tardy, 1993).

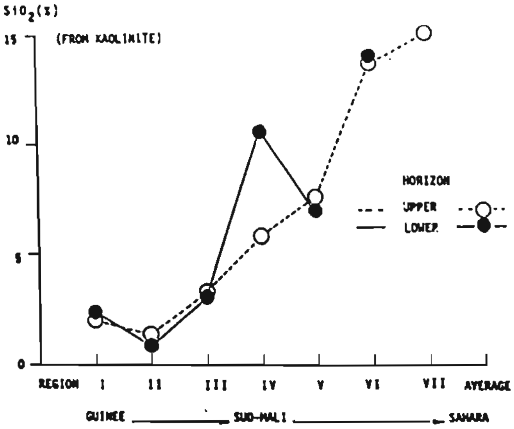

Figure B.10 - Evolution of kaolinite content of bauxites of Guinea and Mali (from Tardy, 1993).

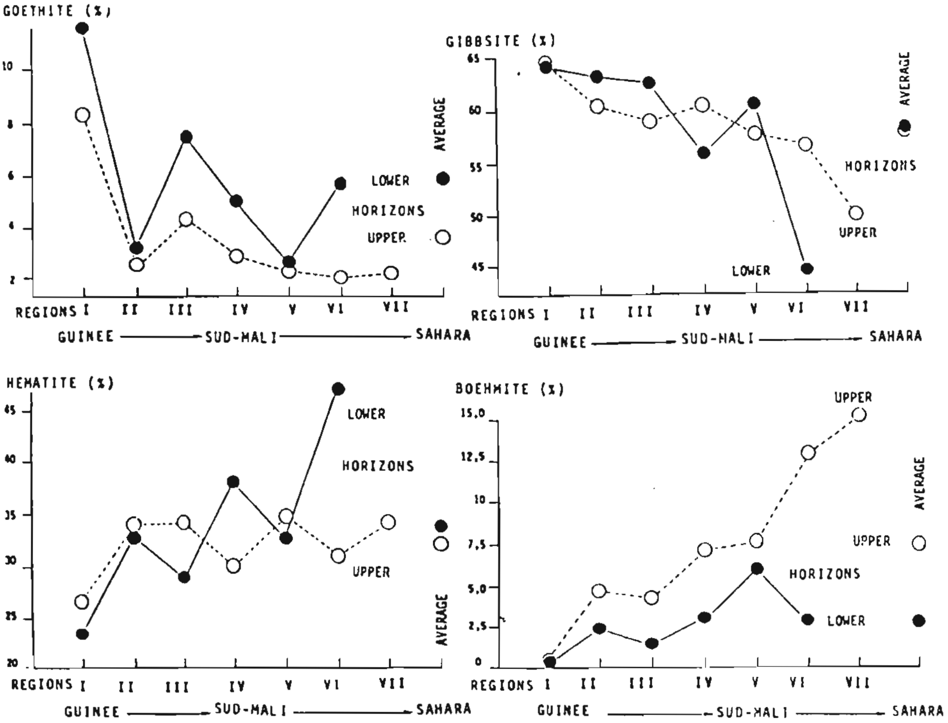

Figure B.11 - Evolution of the mineralogical composition of bauxites from Guinea to Mali (from Tardy, 1993).

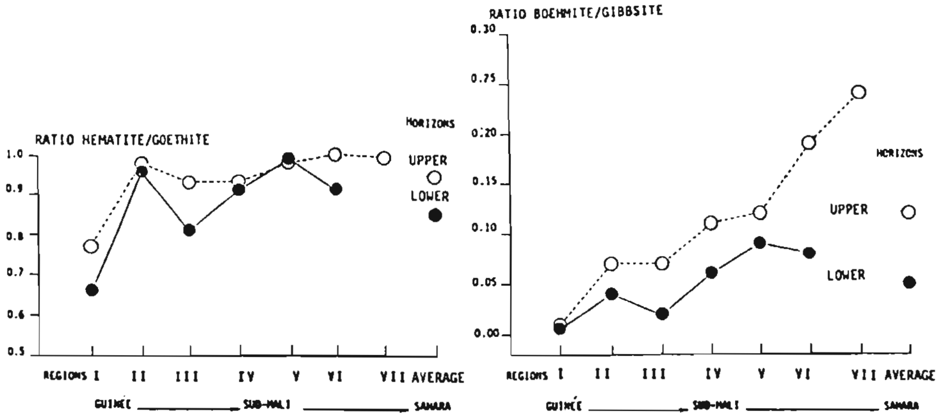

Figure B.12 - Evolution of the index of dehydration measured by ratios RBG (boehmite/(boehmite + gibbsite)) and RHG (hematite/(hematite + goethite)) in bauxites from Guinea to Mali (from Tardy, 1993).

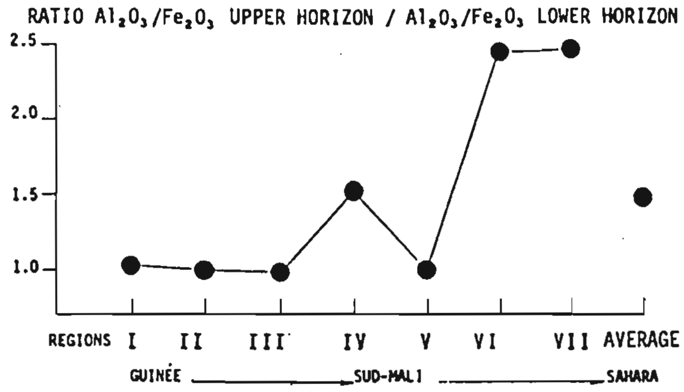

Figure B.13 - Evolution of the index of transfer of iron measured by the ratio Fe_2O_3/Al_2O_3 (S)/Fe_2O_3/AlO_3 (I) (from Tardy, 1993).

boehmite increase;

- kaolinite content increases;
- the contrast between ratios: Al_2O_3/Fe_2O_3 in the upper horizon versus Al_2O_3/Fe_2O_3 in the lower horizon increases significantly.

Bauxites dehydrate from the South to the North and so more in the upper than in the lower horizon. Accompanying the dehydration process, a migration of iron proceeds from the top (conakryte) to the bottom of the profile (ferricrete) (Fig. B.14).

Conclusion

Four predominant thermodynamic parameters are related to climatic factors: temperature, redox potential, activity of silica in the percolating solutions and activity of water in which equilibrium takes place (Table B.8, B.9 and B.10).

The thermodynamic temperature is the same as the climatic temperature. The activity of silica is related to the rate of percolation and to the rainfall. The redox potential is related to the nature of vegetation and water level depth, both controlled by climatic conditions. Activity of water is related to the climatic humidity.

Aluminous conakrytes and orthobauxites are associated in humid conditions. Ferricretes and metabauxites are associated in semi-arid or arid conditions. Metabauxites are ancient orthobauxites formed under humid climates while ferricretes are formed under seasonally

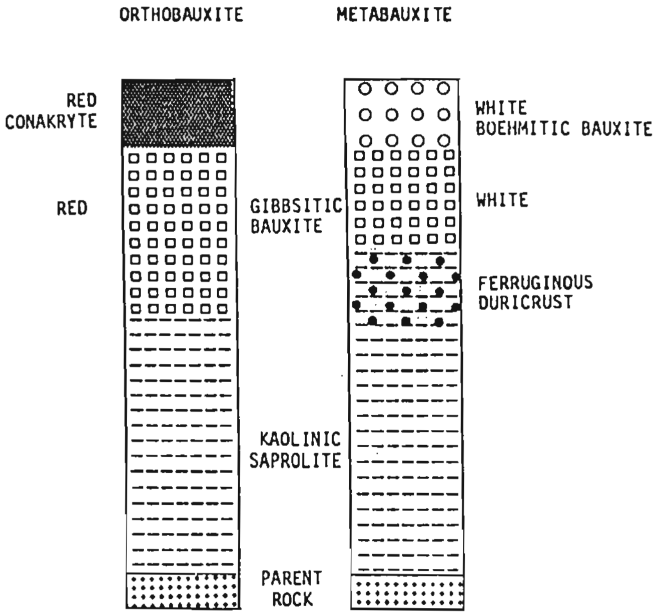

Figure B.14 - Schematic distribution of boehmite, gibbsite, kaolinite and hematite in conakrytes associated with orthobauxites in one hand and in ferricretes associated with metabauxites in the other hand (from Tardy and Roquin, 1992 and Tardy, 1993).

contrasted climates.

Hematite is less hydrated than goethite:

$$Fe_2O_3 + H_2O \rightarrow 2FeO(OH)$$

Boehmite is less hydrated than gibbsite:

$$Al(OH) + H_2O \rightarrow Al(OH)_3$$

and finally, kaolinite is more silicated, but less hydrated than gibbsite:

$$Al_2Si_2O_5(OH)_4 + 5\ H_2O \rightarrow 2Al(OH)_3 + 2H_4SiO_4$$

Reactions of hydration-dehydration and silication-desilication are the processes of laterite climatic formation and paleoclimatic evolution. Dehydration acts in favor of concretion and formation of nodules while hydration works in favor of excretion and development of crystalliplasmic structures. In ferricretes hydration of hematite into goethite it plays in favor of the dismantling of previously formed nodules. In bauxites hydration it plays, on the contrary, in favor of the induration of crystalliplasmas of gibbsite. Dehydration works in the direction of aggradation and induration. Hydration works in the direction of degradation and dismantling (Tardy, 1993).

Table B.8 - Elements of classification of iron and aluminium laterites.

Name	Structure	Al (content)	Fe (content)	Hematite (size)	Goethite (content)	Gibbsite (content)	Boehmite (content)	Kaolinite (content)
Conakryte	cristalliplasmic	poor	abundant	large	present	present	absent	absent
Ferricrete	nodular	moderate	abundant	very small	present	possible	absent	abundant
Orthobauxite	massive	abundant	moderate	large	present	abundant	absent	absent
Metabauxite	pisolitic	very rich	poor	very small	absent	present	abundant	present
Latosols	microglebular	medium	medium	small	moderate	frequent	absent	abundant

(Notice that hematite is always present but in different sizes and gibbsite is always present but in different proportions).

Table B.9 - Geochemical and mineralogical classification of laterites.

Name	Geochemical process	Mineral constituants	Geochimical composition
Conakryte(1)	hydro-ferrallite	goethite, hematite, gibbsite	$Fe_2O_3.H_2O.Al_2O_3$
Conakryte(2)	ferrite	hematite, goethite	$Fe_2O_3.H_2O$
Ferricrete	xero-fersiallite	hematite, kaolinite	$Fe_2O_3.SiO_2.Al_2O_3.H_2O$
Orthobauxite	hydro-alferrite	gibbsite, goethite, hematite	$H_2O.Al_2O_3.Fe_2O_3$
Metabauxite	xero-allite	boehmite, hematite	$Al_2O_3.Fe_2O_3$
Red latosol	xero-sialferrite	kaolinite, hematite, goethite	$SiO_2.Al_2O_3.H_2O.Fe_2O_3$
Yellow latosol	hydro-sialferrite	goethite, kaolinite, gibbsite	$H_2O.Al_2O_3.SiO_2.Fe_2O_3$
Podzol	sillite	quartz	SiO_2

(1) conakrytes on aluminous rocks, (2) conakrytes on ultramafic rocks

Table B.10 - Climatic conditions (H: humidity; T: temperature) and paleoclimatic evolution (H_1H_2; T_1T_2) for controlling the laterite evolution.

	Tropical climate	Parameters H	T	Paleoclimatic evolution	Parameters H1 H2	T1 T2
Conakryte(1)	humid	medium	high	constantly humid tropical	→	→
Conakryte(2)	undifferent	—	—	undifferent	—	—
Ferricrete	tropical contrasted	high	medium	constantly contrasted	—	—
Latosol	cool humid	high	medium	from contrasted to humid	↗	↘
Orthobauxite	humid	high	medium	constantly humid	→	→
Metabauxite	arid	low	very high	from humid to arid	↘	↗
Cryptobauxite	humid	high	medium	from arid to humid	↗	↘

(1) from ferrialuminous rocks; (2) from ultramafic rocks.

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AMAZONIAN BAUXITE

CHAPTER I - THE BAUXITE OF PORTO TROMBETAS

CHAPTER II - THE BAUXITE OF PARAGOMINAS

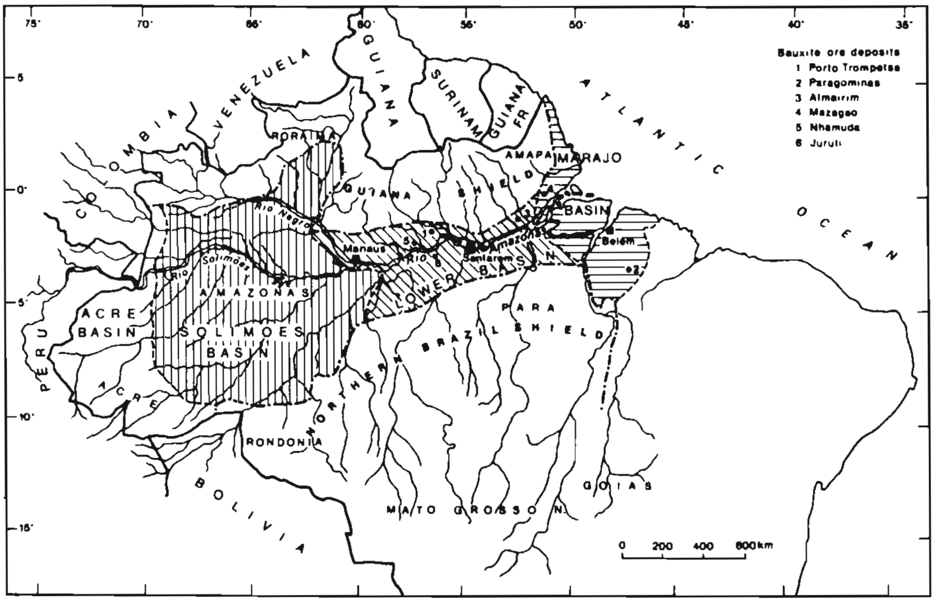
CHAPTER III - THE BAUXITE OF JURUTI

CHAPTER IV - THE BAUXITE OF CARAJÁS PROVINCE

AMAZONIAN BAUXITE

The Amazonian bauxites represent 97% of the estimated 3,200 million tons of the Brazilian reserves of bauxite. The main deposits are developed on clastic sedimentary deposits and they are located in the low and middle Amazon Basin (Porto Trombetas, Nhamundá, Juruti, Almeirim, Paragominas, Mazagão). All these deposits present a common profile structure. An atypical, poorly-extended deposit is developed on basalts associated with itaberites in the Carajás Province.

Amongst the Amazonian bauxites, Juruti, Trombetas and Paragominas deposits were selected as representative of bauxites developed on sediments, and Carajás, as the only deposit developed on non sedimentary rocks. Thus, an overview of their morphological and petrographic characteristics and a discussion of various genetic interpretations is given.



Situation of the main Amazonian bauxite deposits.

Chapter I

THE BAUXITE OF PORTO TROMBETAS

B. Boulangé & A. Carvalho

Introduction

The Porto Trombetas deposits were discovered in 1950, and the open cut began in 1979. As all the Amazonian deposits, the profile shows five layers that are, from the top to the bottom: a kaolinitic layer, a nodular bauxite layer, a ferruginous nodular layer, a bauxitic layer overlying an another kaolinitic layer. These layers previously described in Porto Trombetas (Aleva, 1981; Grubb, 1979) were the object of a very recent detailed study with emphasis on the petrological characteristics and its geochemical and pedogenetic consequences (Lucas, 1989) (see chapter III).

The deposit of Porto Trombetas was also studied with more detail (Boulangé & Carvalho, 1989) but the objective was mainly concentrated on the geochemical aspect and particularly on the distribution of the Rare Earth Elements (REE).

I. Regional aspects

The bauxite deposit of Porto Trombetas is located on the edge of the Rio Trombetas, and about 900 km east of Belém (Pará State). The lateritic bauxite deposits occur on various plateaux covering an area of more than 2,200 Km^2. These high plateaux are deeply cut, with altitudes varying from 160 to 190 m (Fig. I.1). With a gentle dip (1 to 5°) toward the Amazon river, they present convex slopes that can attain 30º. They overlook a large morphological unit, with altitudes varying from 100 m at the foot of the plateaux to 70 m near the Amazon river that has its water level at 40 m.

The studied area was situated on the large plateau of Saracá. Despite being flat, its summit presents ondulations with altitudes varying from 175 m to 185 m. Locally small depressions, attaining more than 10 m of diameter and from 2 to 5 m deep, were also observed.

The region of Trombetas is situated in Low Amazon Basin, which is characterized by a clastic sedimentation of continental origin, laying in discordance over Paleozoic sediments. It is the Alter do Chão Formation, dated Upper Cretaceous or more precisely, Aptian-Turonian (Daemon, 1975). Its thickness exceeds 600 m and is constituted by clayey

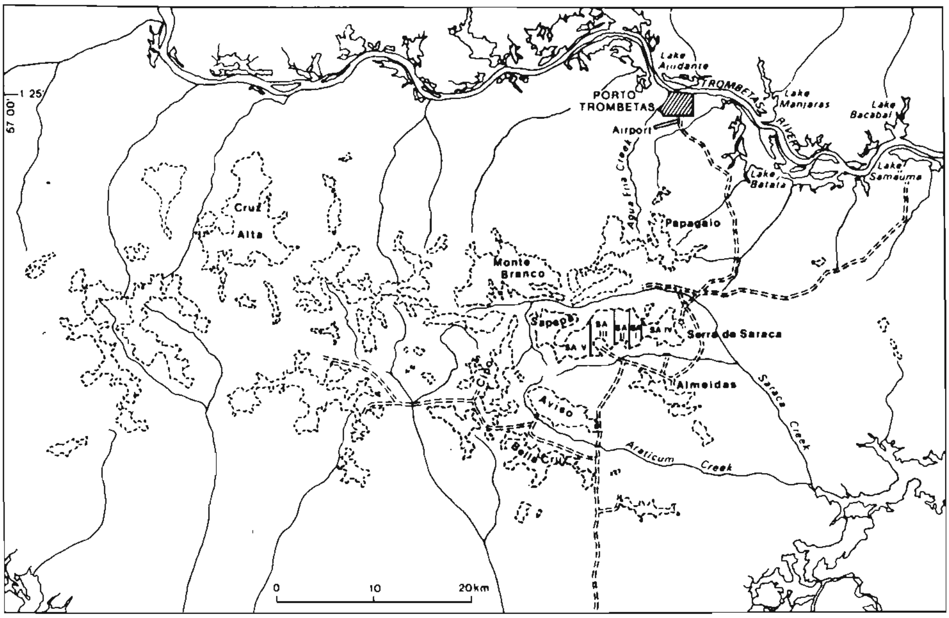


Figure I.1 - The bauxitic plateau of Porto Trombetas

sandstone, sometimes arcosian, intercalated with conglomerates, clay and siltstone.

The climate of this area can be considered as warm. The average temperature ranges from 24 to 26°C and the annual mean temperature normally exceeds 25°C. The temperature is high the whole year, particularly from September to November, when varies from 26 to 28°C. During June and July the temperature is milder but never below 22°C. On the other hand, it is a very humid climate, with 1,600 to 2,50 mm/year of rainfall. The precipitation is not evenly distributed throughout the year and the difference between the more humid and the dryer months is the largest of Brazil.

As concerning the vegetation the region of the so called firm land is covered by an hygrophile rain forest (Hiléia Amazônica). It is characterized by high trees with various strata. The other type is the evergreen forest that occurs in the valley bottoms. It presents smaller trees and lower number of species.

II. Profile characteristic

The deposit of Porto Trombetas presents nearly the same general characteristics of most of the other deposits of the Amazon Basin. The main difference refers to the thickness of the bauxitic layer, showing an average of 6 m and reaching 10 m in some regions.

The profile is rather homogeneous in the whole plateau (Fig. I.2) and presents practically the same sequence of horizons. They are the following, from the top to the bottom: upper kaolinitic layer; nodular bauxite layer; ferruginous nodular layer; bauxitic layer, lower kaolinitic layer and basal sediment.

1. Upper Kaolinitic layer

It is very homogeneous, yellow to reddish yellow downwards, without any apparent stratification. The thickness varies from 8 to 10 m on the plateaux and 0 to 5 m on the edges of the plateaux. It is constituted mainly of kaolinite (80%), gibbsite (10%) and quartz (10%). The kaolinite/gibbsite proportions have tendency to reverse toward the lower part, with a gradual transition to the nodular bauxite layer. The iron is present in a little amount as goethite in the upper part, and in a more important quantity as hematite in the nodular layer. In this kaolinitic ma-

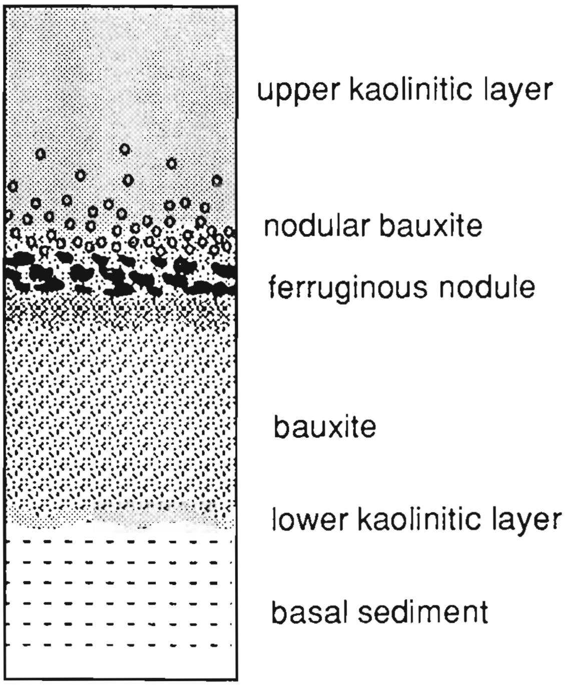


Figure I.2 - The bauxitic profile of Porto Trombetas trix one can observe small quartz grains and small aluminous or ferruginous nodules in the following form:

- small quartz grains (less than 0.8 mm diameter) which show an angular and irregular shape. They present fissures and dissolution cavities penetrated by the clay matrix or sometimes filled up with a hematitic red product. This red product is totally enclosed within the limit of the quartz grains showing that it was formed before the matrix. Sometimes, mainly in the lower part of the layer, the quartz grains are coated with well-crystallized gibbsite;
- small round-shaped aluminous nodules (less than 0.5 mm diameter), constituted by gibbsite crystals that can reach the size of the nodule. They keep some local traces of the hematitic red product. The limits of the crystals are not clear and the gibbsite fades out in the matrix;
- small round-shaped ferruginous nodules (less than 0.5 mm diameter), red, argilomorphous, hematitic or goethitic.

The characteristics described above of both the quartz and the nodules seem to indicate that they were not transported. On the contrary, they would be originated by in situ transformation of a previous bauxite layer. The process would include deferruginisation with changing of hematite into goethite, and dissolution of the gibbsite. Part of the alumina undergoes resilication to form kaolinite, and the rest is transferred to the subjacent bauxite.

2. Nodular bauxite layer (1 to 3 m)

These nodules are small (<5 cm) and with irregular shape. They are frequently coalescent forming sometimes true blocks, embedded in an yellowish red clay matrix. The nodules are heterogeneous, with a whitish violet nucleus. They are formed by porcellaneous gibbsite (very small crystals) showing at least three successive juxtaposed types, getting more and more clear towards the periphery. Each type is cut by a net of fractures fill up with well crystallized (sacharoïd) gibbsite, that indicate their independence and thus, their succession through the time. In the lower part of these layer occur some ferruginous nodules that become gradually coarser. They form, by anastomosis larger fragments of irregular shape, vertically elongated, enveloping the ferruginous round spots that increase in diameter downwards. Finally, this layer changes into the underlying one through a transitional zone (10 cm);

3. Ferruginous nodular layer (1 m)

It presents, in the upper part (30 cm), nodules of about 10 cm, cemented by a hard pinkish gibbsitic matrix. In the middle part (60 cm) they are embedded in a brownish yellow argilomorphous matrix. In the lower part, the ferruginous nodules are again cemented by a pinkish gibbsitic matrix forming a true crust. The nodules are reddish violet, hard and with irregular outline, without any coating. Under the microscope they present as very porous material formed by a red hematitic matrix. The pores are empty or sometimes filled in with well crystallized gibbsite. Some pores can present in its interior a small quartz relict. It seems that these nodules result from a ferruginisation of a very quartzous material. The quartz would be submitted to a strong dissolution followed by a gibbsite accumulation in the dissolution voids.

4. Bauxitic layer (1 to 6 m)

The upper part (1 m) is alumino-ferruginous, compact, massive. It is locally capped by a very ferruginous crust with alumina rich pale zones, and iron rich dark zones. The lower part (5 m) of this bauxitic layer, the main mined level, is formed by a porous and friable bauxite. This bauxitic layer is cut by large vertical pockets containing residual blocks and fragments of bauxite and a yellowish red clay material. The bauxite presents different degrees of ferruginisation with pale to dark red colors. Under the microscope these bauxites appears as formed only by well crystalized gibbsite (saccharoïd). Locally and upwards the bauxite form hematitic walls, delimiting large voids (up to 200 µm). Downwards the gibbsite crystals form aggregates, with only a slight porosity.

The transition to the underlaying layer is quite gradual.

5. Low kaolinitic layer

It is a yellow to brown colored horizon. It presents alumino-ferruginous relict nodules with gibbsite and hematite, embedded in the clay matrix. The hematitic red nodules fade out in the goethitic yellow spots. The bauxite relict nodules are constituted by large gibbsite crystals, sometimes in association with quartz. The quartz grains are fractured and show irregular outline, marked by dissolution features. The fractures are coated by well crystallized gibbsite, that is restrict to the grain limit. These quartz grains with gibbsite seems to be also residual in the clay matrix. The contact between the gibbsite and the kaolinite would indicate a dissolution and a resilication of the gibbsite rather than a desilication of the kaolinite.

6. Basal sediment

The deepest layer of these profiles were observed in an open ditch in the northeastern border of the Saracá plateau. It presents as a stratified quartzo-argillous sediment. The quartz, disposed in millimetric layers, presents dissolution features penetrated by the clay material.

III. Chemical composition

The samples were grouped according to their facies, and the results of the chemical analysis, for the major and trace, elements are shown in Table I.1 and Figures I.3, I.4 and I.5 . Some REE analysis were carried out and the results are presented in Table I.1. The curves normalized to NASC (Gromet et al., 1984) are shown in Figure I.6.

There are some points to be considered, before going in the discussion of the chemical composition. The first one refers to the possibility of existing lithological discontinuities in the basal sediment. This would be the source of the variations found in the different facies. The other point, concerns to the presence, in the basal sediment, of quartz layers which contains a rather high concentration of heavy minerals bearing Ti and Zr. The quartz layers were not included in the analysis of the basal samples and the result could be affected. Thus, in order to make possible the discussion that follows, some premisses were established. It was assumed that the sediment is rather homogeneous, which is quite possible but not certain. It was also assumed, that the influence of the quartz layer in the composition of the basal sediment, would be negligible, considering its relatively low abundance.

The upper kaolinite is very homogeneous as concerning its chemical composition. The SiO_2 et Al_2O_3 contents reflects its argillo-quartzous nature. The Fe_2O_3 content is low (about 8%) and the contents of TiO_2 (2.8%) and Zr (up to 1640 ppm) are rather high. The contents of TiO_2, Zr and HREE are three times greater as compared to the bauxite layer. This agrees with the microscopic observation which evidentiated a resilication process. Indeed this transformation would go with a volume reduction and a correlative increasing of the residual minerals, as anatase and zircon.

The nodular bauxite is rich in alumina (61%) and present a low content of Fe_2O_3 (2%). The content of trace elements and REE are just slightly higher than the bauxite. The matrix here has a kaolinitic composition and is rich in TiO_2 and Zr, which agrees with their residual behavior during the resilication process evidentiated in the upper kaolinitic layer.

Table I.1 - Chemical composition (major and trace elements of samples of different horizons of bauxitic profile from Porto Trombetas. REE analysis of some samples are also included.

	BTS1	BTS 2	BTS 3	BTS 4	BTS 5	BTS 7	BTS 8a	BTS 8b	BTS 8c	BTS 9a	BTS 9b	BTS 10a	BTS 10b	BTS 11	BTS 12	BTS 13a	BTS 13b	BTS 14	BTS 15	BTS 16	BTS 03b	BTS 03a	BTS 02b	BTS 02a	BTS 01	BTS 00
	KAOLINITIC LAYER					NODULAR BAUXITE			Fe. LAYER			BAUXITE						CLAY LAYER				BASAL SEDIMENT				
						matrix		Al nod	Fe nod	matrix	nodules	upper zone		lower zone												
												pale	dark													
SiO_2	38,90	37,10	36,50	36,10	34,50	26.50	25,90	4.30	18,80	22,80	6,90	2,10	0,63	0,95	2,80	3.30	8,50	29,40	31,20	25,30	38,27	15,78	48,54	40,73	47,08	47,24
Al_2O_3	34,80	36,30	36,95	37,10	37,90	43.40	43,30	61,20	19,10	29,00	26,30	60,20	47,40	55,30	61,00	61,60	53,70	40,80	35.60	44,70	35,17	56,62	33,98	28.77	33.49	30,39
Fe_2O_3	8,40	8,60	8.15	8,20	7.90	7,40	9,20	2,20	50,30	31,10	45,60	5,00	25,50	13,70	3,30	2,80	6,60	8,05	15,40	7,25	9.49	3,96	2,64	18.68	5,88	8,42
TiO_2	2,70	2,80	2,75	2,80	2,80	2.40	2,10	1,10	0,77	2,20	1,00	0,71	0,88	0,96	1,10	0,68	2,70	4,05	2,00	1,65	2,08	0,86	0,98	0,52	0,65	0,51
H_2O	14,97	14,83	15,16	15,24	16.46	19,95	19.01	30,57	10.54	14,45	19,77	31,32	25,51	28,51	31,30	31,03	27,90	17,29	15,57	20,48	14,05	23,52	12,77	11,40	12,60	12,27
V	148	152	153	178	148	148	186	97	545	625	640	137	270	173	98	89	152	169	270	163	133	61	40	208	64	97
Cr	140	156	154	174	142	188	186	114	320	220	220	76	152	100	48	50	116	173	122	84	87	51	43	110	36	32
Ga	58	68	63	76	68	66	70	58	60	76	74	52	64	54	48	58	76	73	60	51	84	29	22	29	21	32
K	180	160	135	110	96	83	50	50	58	64	50	50	50	50	50	50	50	50	50	50						
Zr	1320	1480	1550	1640	1600	1440	1360	640	640	1240	780	440	420	520	440	310	940	1580	800	720	535	228	340	180	207	122
Nb		70			70			34			23			32	42		58		40		54	23	31	21	22	5
Y		28			26			12			13			9	11		15		10		10	3	5	3	5	5
La		12,6			10			3,7			7,45			2,14	2,4		2,46		3,53		55	16	42	38	53	82
Ce		20,3			17,4			5,91			10,1			3,93	4,12		4,56		4,96		47	17	44	40	50	165
Nd		6,97			5,5			1,9			3,01			0,95	1,02		1,18		1,19		8,2	2,3	6	4,44	5,3	6,6
Sm		1,37			1,05			0,35			0,56			0,22	0,28		0,37		0,38		1,3	0,6	1	1	0,1	1
Eu		0,37			0,31			0,15			0,18			0,11	0,14		0,16		0,13		0,2	0,1	0,1	0,2	0,1	0,1
Gd		2,08			1,76			0,81			0,81			0,53	0,76		0,89		0,69		0,9	0,4	0,5	0,5	0,4	0,4
Dy		3,14			2,96			1,26			1,22			0,92	1,15		1,6		1,02		1,3	0,5	0,8	0,5	0,4	0,5
Yb		3,7			3,66			1,39			1,39			1	1,4		2		1,14		1,7	0,9	1,2	1	1	1,4
Lu		0,61			0,59			0,24			0,24			0,18	0,24		0,33		0,2							
ΣREE		51,14			43,23			15,71			24,96			9,98	11,51		13,55		13,24		115,6	37,8	95,6	85,64	110,3	257
ΣLREE		41,61			34,26			12,01			21,3			7,35	7,96		8,73		10,19		111,7	36	93,1	83,64	108,5	254,7
ΣHREE		9,53			8,97			3,7			3,66			2,63	3,55		4,82		3,05		3,9	1,8	2,5	2	1,8	2,3
La/Yb		3,40541			2,7322			2,6619			5,3597			2,14	1,7143		1,23		3,0965		32,353	17,778	35	38	53	58,571

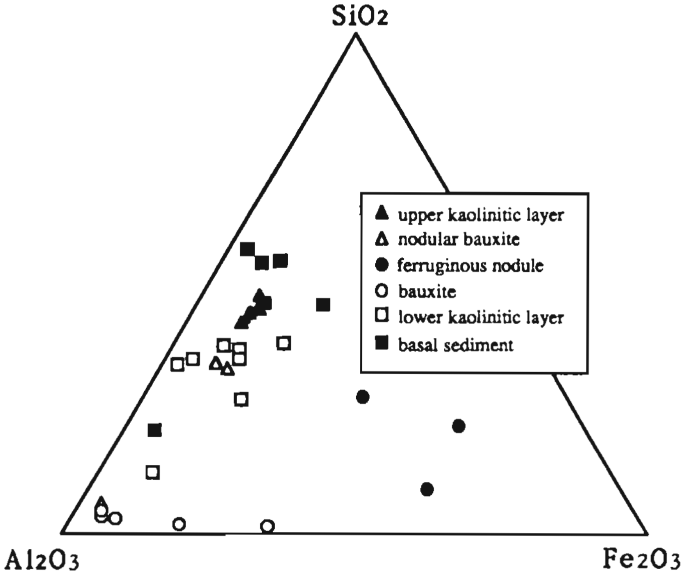


Figure I.3 - Samples of different horizons of bauxitic profiles of Porto Trombetas plotted in SiO_2 - Al_2O_3 - Fe_2O_3 diagram.

The iron crust and the ferruginous nodules overlaying the bauxites are very rich in Fe_2O_3 (45%) and show an excess of alumina, expressed as gibbsite in the dissolution voids. The matrix SiO_2/Al_2O_3 ratio is similar to that of the kaolinite. The TiO_2 content remains equivalent to the bauxite one (1%) but increases in the matrix (2%) (Fig. I.5). Zr and TiO_2 present always a good positive correlation. V and Cr, as well as iron, show strong concentration. The HREE concentration is nearly the same as compared to the subjacent bauxite, but the La/Yb ratio presents a clear increase (5.3 times). The formation of this horizon occurs through an intense ferruginisation of the bauxite layer upper part. Thus, the absolute iron enrichment is followed by V, Cr and HREE concentration. The present evolution tendency is a deferruginisation that isolates relicts ferruginous nodules and gives origin to a kaolinitic matrix with strong concentration of residuals elements (Ti, Zr and HREE)

The bauxite has a very low grade in silica (<3%) and high content of Al_2O_3 (50 to 60%). The Fe_2O_3 content is low (<3%) but increases upwards, reaching 25% in the dark red zones. The TiO_2 content is low, being only slightly higher than 1% (Fig. I.4). The V and Cr contents increase regularly with the iron content (Fig. I.5). In the bauxite layer, as compared to the basal sediment the Zr content is three times greater (Fig. I.4). On the other hand, the LREE content is lower while the HREE

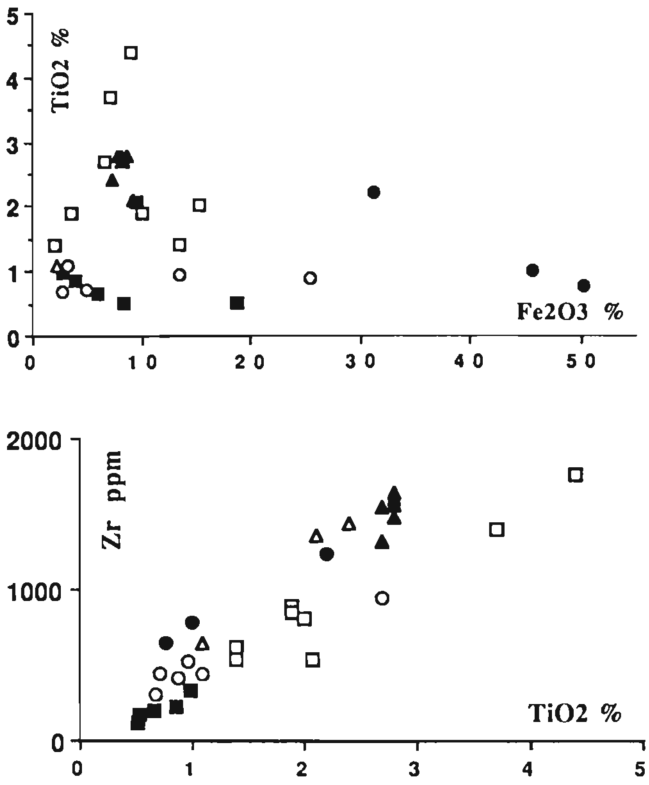


Figure I.4 - TiO_2 versus Fe_2O_3 and Zr versus TiO_2 of samples of different horizons of bauxitic profile from Porto Trombetas (For samples legend see Fig. I.3).

content rest uniform, as indicates the decrease of the La/Yb ratio (1 to 2 in the bauxite and up to 60 in the sediment). Thus, the bauxite seems to present a composition that agrees with the basal sediment. The transformation (ferruginisation and desilication) would be performed with a volume reduction of 3 to 4 times, leading to a concentration of elements included in the residual minerals (anatase and zircons).

The lower kaolinitic layer present a lower silica/alumina ratio as considering the kaolinite composition. The excess of alumina corresponds to the presence of gibbsite. In addition, the content of TiO_2 (2 to 4%) increases regularly upwards and it is higher as lower the iron content (Fig. I.4). The limit with the subjacent bauxite is not clear and some samples (BTS 13b) mark the transition. The average Zr content increases towards the upper part of the horizon, where it is multiplied by a factor of 9 (1,580 ppm) as compared to the basal sediment (170 ppm). The REE contents decrease, but the HREE increase (La/Yb=3) with reference to

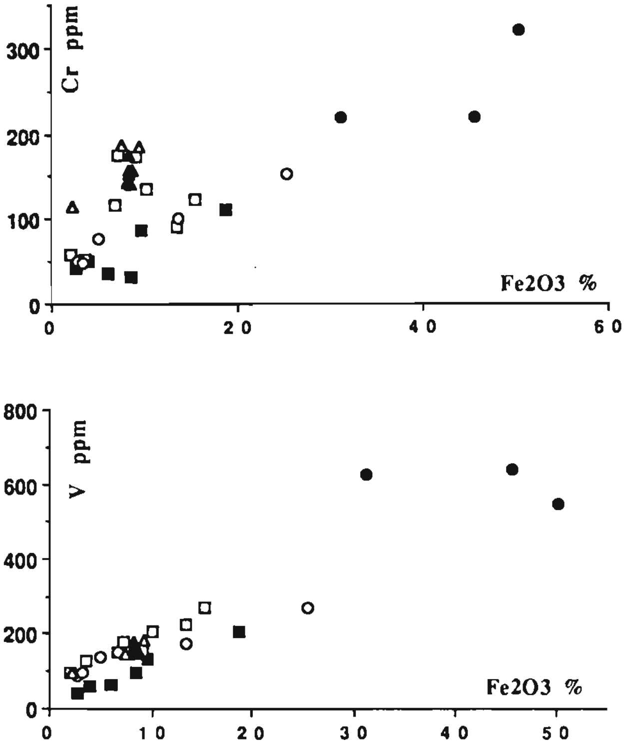


Figure I.5 - Cr versus Fe_2O_3 and V versus Fe_2O_3 of samples of different horizons of bauxitic profile from Porto Trombetas (For samples legend see Fig. I.3).

the basal sediment.

In the basal sediment only the kaolinitic material, not bearing quartz layers, was selected. The high SiO2/Al2O3 ratio shows that this sediment is constituted essentially by quartz and kaolinite. These very white kaolinites are quite poor in Fe_2O_3 (<3%), with red spots that contain up to 18% Fe_2O_3. The TiO_2 contents are very low (<1%) and increase towards the overlying layer. They are very homogeneous and in the diagram SiO_2-Al_2O_3-Fe_2O_3 (Fig. I.3), the samples are grouped together. Nevertheless, some samples (BTS 3a and 3b) presenting an intermediate composition, mark the transition between the basal clay sediment and the overlaying kaolinites. The average trace elements contents are lower in the deeper horizon and increase toward the transition zone. The La/Yb ratio decreases strongly from the base to the transition zone (from 58 to 17), indicating a preferential leaching of the LREE.

The analysis of the ternary diagram SiO_2-Al_2O_3-TiO_2 (Fig. I.4) show that each facies has a definite chemical composition and the transitional terms are not well developed. The TiO_2/Fe_2O_3 ratio (Fig. I.4) as a whole does not show a good correlation between these elements. Nevertheless, it seems that the TiO_2, in the form of anatase, behaves as a residual product. Thus, the lower kaolinitic layer and upper kaolinitic layer present the higher TiO_2 content and the lower amount of Fe_2O_3.

Among the analyzed trace elements, the zirconium shows significant variations according to the facies (Table I.1). Thus, the medium values for the basal sediments (170 ppm) are multiplied by a factor of 2.3 in the bauxite (400 ppm), of 3.7 in the nodular bauxite (640 ppm) and up to 9 in the upper and lower clay. This important concentration of zirconium is associated with the presence of residual zircons, which are very resistant to the alteration. The Zr/TiO_2 correlation (Fig. I.4) is rather good, which agrees with residual characteristic of these elements, preserved in the profile as anatase. It can be observed (Table I.1) that, Nb and Y show similar variation, marking as well the residual characteristics of these elements that could be included in the zircons (Gromet & Silver, 1983).

The vanadium and in less proportion, the chrome presents a good correlation with iron (Fig. I.5). It seems that they follow this element during the different phases of mobilization and transference. Thus, the ferruginous crust, resulting from an important absolute iron accumulation, presents the higher content of V (640 ppm) and Cr (up to 320 ppm).

The similarity of the REE spectra (Fig. I.6) seems to confirm that all the horizons, from the lower kaolinite up to the upper kaolinite layer, had similar origin. The presence of lower kaolinite layer, formed from the overlaying bauxite, reinforces the discontinuity between these bauxites and the basal sediment. Nevertheless the sample 3a seems to be an evidence of the affiliation between them. In addition, the variation of the HREE contents indicate a residual behavior, similar to the titanium and zirconium. On the contrary, the LREE are leached during the basal sediment bauxitisation and undergoes an absolute accumulation during the ferruginisation and resilication phases.

IV. Genetic relationship of the horizons

Despite the several studies carried out in the bauxites of the Amazon region, some aspects concerning their formation, are still a matter of discussion.

The objective of this paper, is to put out some aspects that could contribute to establish a model to these bauxites evolution. Nevertheless, it has be pointed out that, there is no idea of using the results obtained for Porto Trombeta deposit, to explain the origin of the Amazonian bauxite, as a general.

The kaolinitic upper layer, with no evident sedimentary structure, named Belterra Clay (Kotschoubey & Truckenbrodt, 1981), covers completely the bauxite layer. Its origin has been interpreted differently by various authors: as lacustrine deposits coming from the Andes region (Sombroeck 1966); as continental deposits following the bauxitization period, but related to the bauxites originated from the vicinity (Grubb, 1979; Kotschoubey & Truckenbrodt, 1981); as the upper part, extremely leached, of the continental deposits, named Barreiras Formation (Aleva, 1981; Dennen & Norton, 1977; Kistel, 1971); as an horizon resulting from pedogenetic evolution of a bauxite profile (Wolf & Silva, 1973; Lucas, in this book).

The petrological characteristics described previously, seem to indicate that they could not be transported. They would be originated by "in situ" transformation of a previous bauxitic and kaolinitic layer. The process would include deferruginisation with changing of hematite into goethite and dissolution of the gibbsite. Part of the alumina would suffer a resilication, forming kaolinite and the rest would be transferred to the subjacent bauxite. The process would involve a strong volume reduction, as suggested by the fact that the contents of TiO_2 and Zr in this layer is twice or three times higher than in the subjacent bauxite. This could be used as well, to give an idea of the thickness of bauxite necessary to form the upper clay horizon. The enrichment in REE and the similarity of the spectra configuration, between the bauxite and the upper kaolinite, would confirm the residual character of this layer.

The main problem refers to the source of silica necessary for the upper kaolinite formation process, particularly considering that the present bauxite contains very few quartz. One possible explanation would be an external source for the silica. Nevertheless, the absence of sedimentary evidences and the geochemical continuity within the profile seems to contradict this hypothesis. Thus, it would be more reasonable to imagine an "in situ" origin.

In this case, the silica could be considered as originated only from the original sediment submitted to a strong volume reduction during its surficial evolution. The high concentration of Zircon could be an evidence of this volume reduction. As a matter of fact, the Zr constant calculation would evidenciate that 90 m of original sediment would be necessary to produce 1 m of upper kaolinite. Under this context, the SiO_2 global losses would be very important, and a very low amount of silica would go into the formation of the upper kaolinite.

The nodular bauxite is an horizon of alumina accumulation in the form of gibbsite. The gibbsite itself is now submitted to a degradation

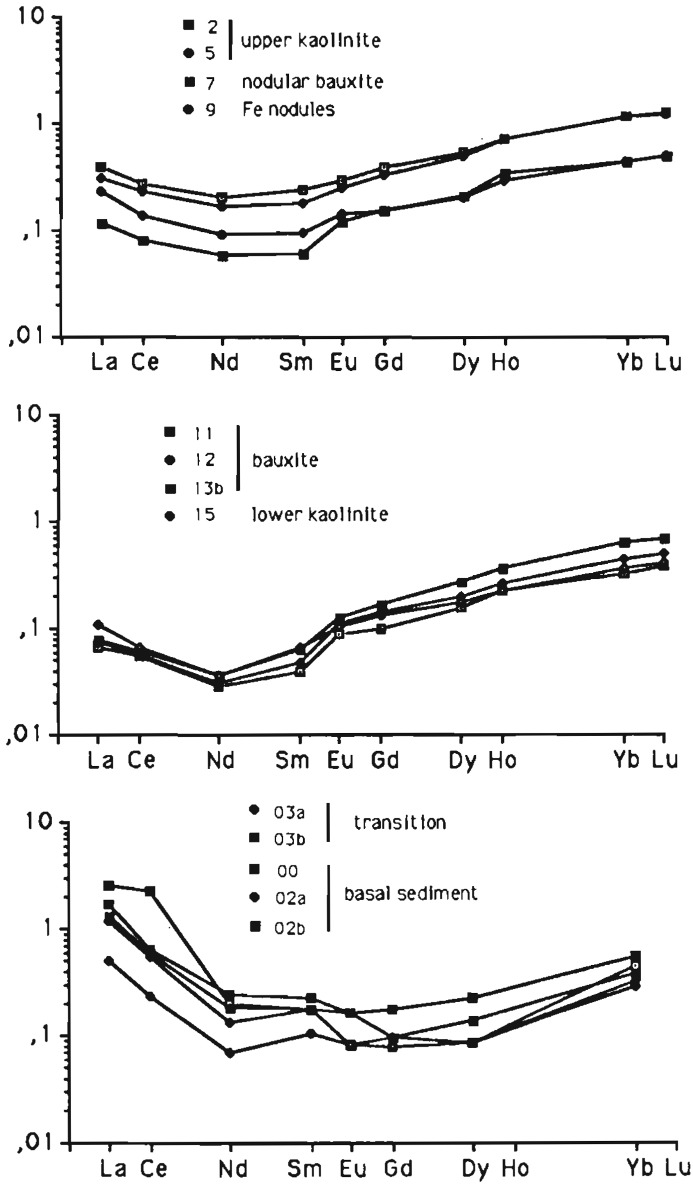


Figure I.6 - NASC normalized REE pattern for samples of different horizons of bauxitic profile from Porto Trombetas.

process. This is particularly evident in its upper part, where several generations of gibbsite nodules can be observed in the kaolinitic matrix. The low contents of TiO_2 (1.1%), Zr (640 ppm) and REE in the aluminous nodules, would confirm the absolute accumulation of alumina. This alumina could issued from the upper part existing bauxite degradation. The contents of TiO_2 and Zr in the matrix are similar to those of the upper kaolinite, that underlines the present degradation process of these bauxite nodules.

The ferruginous nodules seems to be an iron accumulation horizon in a quartz layer. The same as the aluminium, the iron comes from an old subjacent profile. The vertical migration of both elements was separated in the time. The matrix characteristics show that these nodules, like the upper gibbsitic ones, are presently undergoing a degradation process (deferruginisation).

The bauxite results by the sediments transformation (Lucas cf. ch. III). The TiO_2 and Zr contents are only slightly higher as compared to those of the basal sediment. This seems to confirm the idea that the bauxite formation from this sediment occurs with a rather low volume decrease and thus, preserving the original structure. Nevertheless, the sedimentary structures are no more evident and the volume preservation is only observed at a microscopic scale: ferruginous walls, delimiting cells invaded by the gibbsite. The REE content seems to indicate that, during this transformation the LREE are strongly leached. Meanwhile, the HREE, associated with the residual minerals (zircon), present a rather constant values. As it was mentioned before, it is also possible that this anomaly is due to the sampling bias.

The lower kaolinite layer seems to be a result of a bauxite recent transformation, submitted to a deferruginisation and resilication process. The TiO_2, Zr and HREE contents increase, show that these transformations occur together with a volume reduction, at the same proportion that in the upper kaolinitic layer.

It seems quite evident that the present tendency, in the profile as a whole, is not the bauxite formation but the deferruginisation and resilication.

V. Profile evolution

The recent evolution shows that the horizons assembly is not a result of a sedimentary process, but of a long geochemical history. The thick sedimentary cover, under equatorial or humid tropical climatic conditions, was submitted to several transformation fronts, that has progressed downwards.

1. A weathering front, where the sediments were transformed according to the described process (Lucas et al., 1989). The process includes kaolinization followed by desilication and formation of gibbsite, giving origin to the bauxite;

2. A pedoturbation front, occurring on the upper part of the forming bauxite, where the skeleton and matrix are dissociated. The presence of this front is accompanied by a temporary hydromorphy that mobilizes the iron from the bauxite, with the alumina undergoing a residual accumulation as cryptocristaline gibbsite.

3. A ferruginisation from where the iron previously mobilized is fixed;

4. A resilication front of the cryptocristaline gibbsite, with the residual silica, always present in small amounts, in the bauxite as residual quartz or traces of kaolinite. This silica would be mobilized and brought back to the profile by the influence of the vegetation cover (Lucas et al., 1993);

The proposed schema for the profile evolution, based on the petrografic and chemical analysis and field observation is shown in Figure I.7.

A. A weathering front (1) is installed on the sedimentary cover and through silica leaching and iron and alumina accumulation originates the bauxite. The iron content is low, since the sediment was poor in this element. The upper part of the bauxite, under the influence of the vegetation, is then submitted to a pedoturbation front (2), leading to the gibbsite partial deferruginisation and resilication. The resulting continuity between the bauxite and the upper kaolinitic layer is a consequence of the initial low iron content.

B. The weathering front (1) progress into the original sediment, thickening the bauxite layer. At the same time, but at a smaller rate, the pedoturbation front (2) goes downwards in the bauxite. The upper residual bauxite horizon is affected by the resilication front (4) keeping its thickness rather constant. The mobilized iron is accumulated within the bauxite, subjacent to the ferruginisation front (3). This zone corresponds to the water table oscilation level. Thus, the iron content increases gradually in the bauxite.

C. All the four fronts deep down simultaneouly. Bauxite and upper kaolinite layer get thicker. The amount of iron in the bauxite is more and more important.

D. The iron mobilized in the pedoturbation front, is fixed preferentially in a certain profile level, forming a real crust. This level is prob-

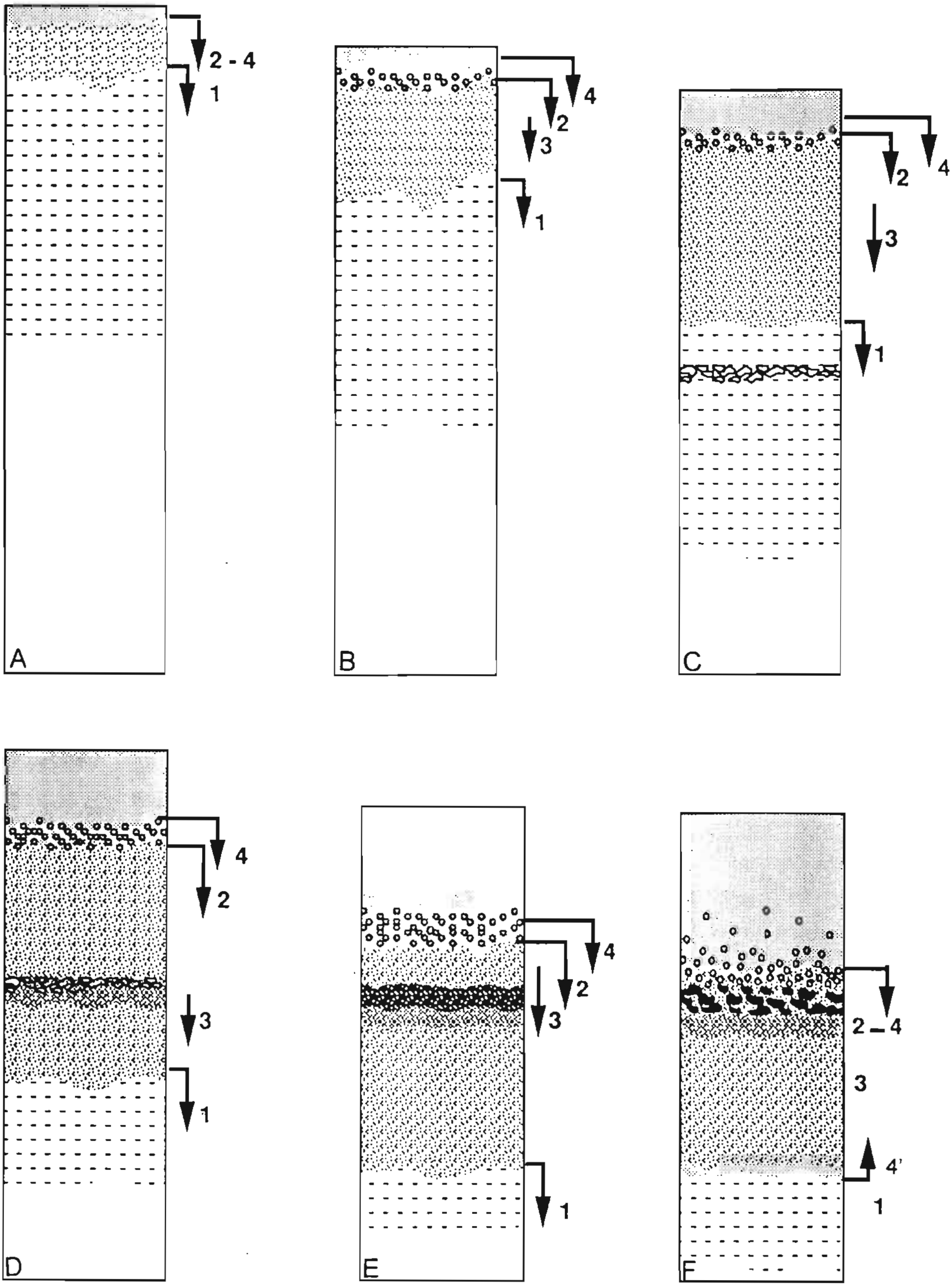


Figura I.7 - Stages of evolution bauxitc profile from Porto Trombetas.

ably associated to the original sediment structure (quartz layer). This iron imobilization, forming hematitic walls between the quartz grains, is susceptible to acentuate the quartz dissolution (Morris & Fletcher, 1987). This way, numerous voids are developed. Some of them are filled up with gibbsite coming from part of the alumina liberated in the pedoturbation front.

E. This iron crust development stops the pedoturbation front progression. The whole upper bauxite will be deferruginized, re-structured. The resilication front keep progressing, at the expenses of this bauxite.

F. This model originates the present profile, where the pedoturbation front is blocked by the iron crust. The resilication will keep on going, at the expenses firstly of the upper cryptocristalline bauxite and later on, of the iron crust itself. This result in the present nodular facies. In the lower part of the profile, probably due to morphoclimatic conditions changes, the alteration front progression is also stopped. It is then developed, at the expenses of the bauxite, a lower resilication front (4').

It is rather difficult to know the morphological and climatic conditions that have existed on these plateaux, during the transformation of 90 m of sediment. In any case, it is hard to admit that the plateaux surface has been always flat. On the contrary, it is more acceptable that they were undulated. The plateau general morphology could be identified as a doline system, which would give origin to the topography undulations, which have varied through the time. Residual Al, Fe and Si have been continuously mobilized, due to the local hydromorphic conditions variations. The Fe would be trapped in a permeable quartzous sedimentary layer, forming a deep crust which has an effect on the present horizontal structure.

Conclusion

The bauxite deposit of Porto Trombetas results from an in situ evolution of a thick layer of sediment. This evolution, that depends on biological and morphological factors, would occurred within a long period. Actually, up to now there is no defined hypothesis on the variation of the paleoclimatic and paleotopographic conditions during the bauxitization period. Nevertheless, known data on paleoclimatolgy (Parrish et al., 1982), show that during the late Cretaceous and the Terciary, the Amazon Basin was submitted permanently to a very humid climate.

In a model of continuous evolution, the present profile would result from combining processes, including the formation of a ferruginous bauxite and deferruginisation and resilication of this bauxite. The removed iron is accumulated in a layer of quartzous sediment forming a ferruginous crust that stops the system deepening. The present bauxite layer would be formed below this crust.

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Chapter II

BAUXITE DEPOSITS OF PARAGOMINAS

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Introduction

The Paragominas bauxites constitute the eastern and potentially richest part of the Amazonian bauxite province (Fig. II.1). Most of the economically valuable deposits - sectors of Jabutí, Futuro, Miltônia, Gurupi and Camoaí - are localized between Capim and Gurupi rivers, in the northeastern part of the state of Pará, while the Tiracambú bauxite sector is situated in the state of Maranhão, between Gurupi and Pindaré rivers (Fig. II.2). With a north-south extension exceeding 200 km and a width of about 100 km, the bauxite region has easy access by the Belém-Brasília highway, which crosses the area in a north-south direction. From Ligação do Pará southwards, the bauxites grade to a ferruginous duricrust, which is well exposed in the neighborhood of Açailândia and Vila Rondon.

The Paragominas bauxites, as most other deposits of the Amazonian bauxite province, are derived from Cretaceous/Lower Tertiary (?) sediments and are, as a rule, covered by a thick kaolinic clay (Belterra Clay). The bauxites are typically blanket-like and cap large plateaus (Fig. II.3).

The bauxites of the northeastern part of the state of Pará were discovered in the late sixties and explored in the different sectors during the seventies by Kaiser Aluminium Company, Companhia Brasileira de Alumínio (CBA), Rio Tinto Zinco (RTZ) and Companhia Vale do Rio Doce (CVRD). The total ore reserves of these deposits are estimated in about 2500 million tons (Santos, 1981), including more than 20 million tons of high quality refractory bauxite which occur in the Camoaí deposit (Santos et al., 1985). In 1982, the Tiracambú bauxite sector was discovered by CVRD. Its ore reserves are approximately 90 million tons (Alves et al., 1985).

I. Previous studies

The first studies concerning the Paragominas bauxites were restricted to field descriptions and tentative classifications (Wolf, 1972; Wolf & Silva, 1973; Assad, 1973, 1978). After Dennen & Norton (1977), who first suggested a rather complex evolution for the Almeirim bauxites

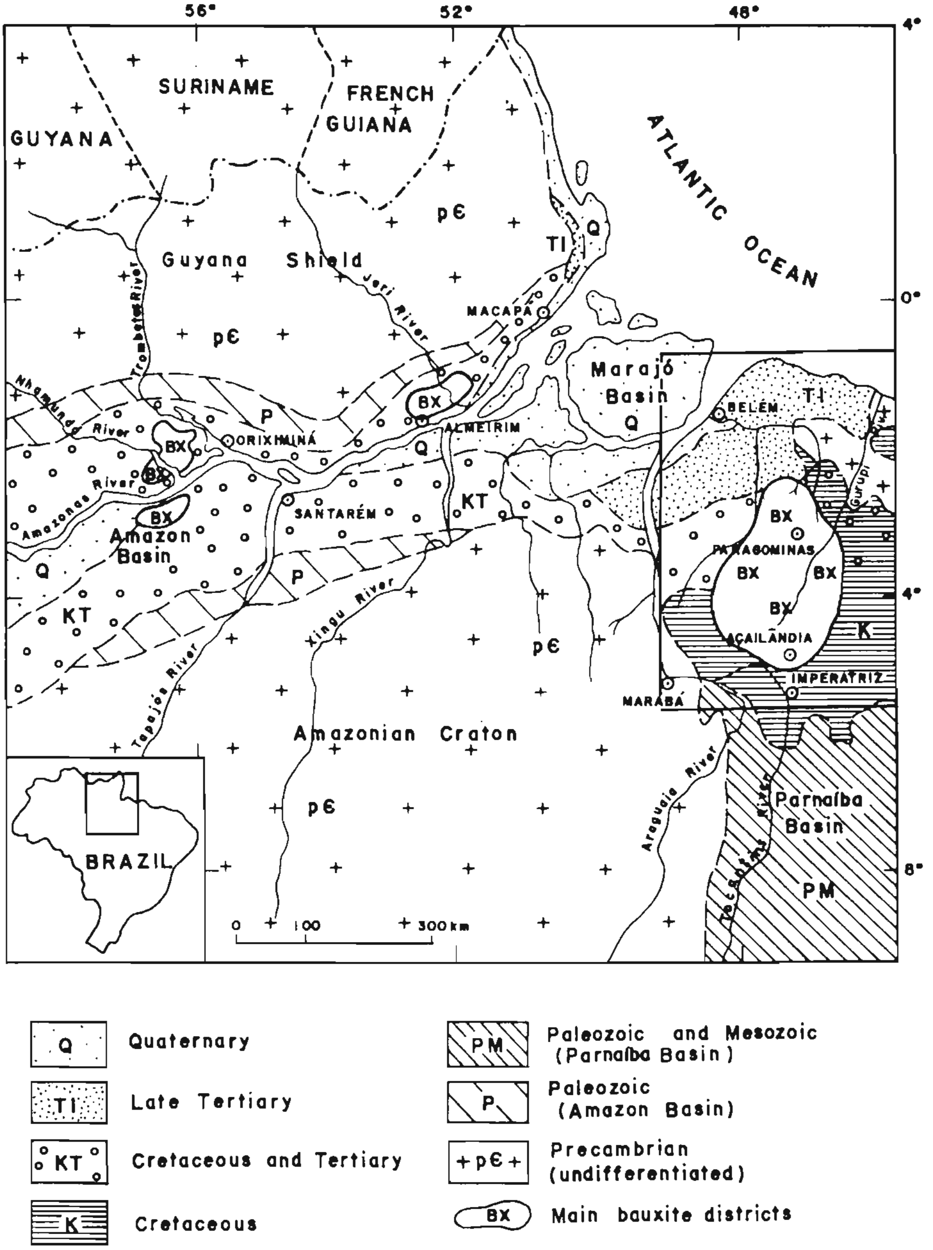

Figure II.1 - Geology of eastern Amazonia and location of the Paragominas bauxite region.

(Lower Amazon Basin), Grubb (1979) proposed for Amazonian bauxites an origin from sediments, including the Paragominas ones, through a

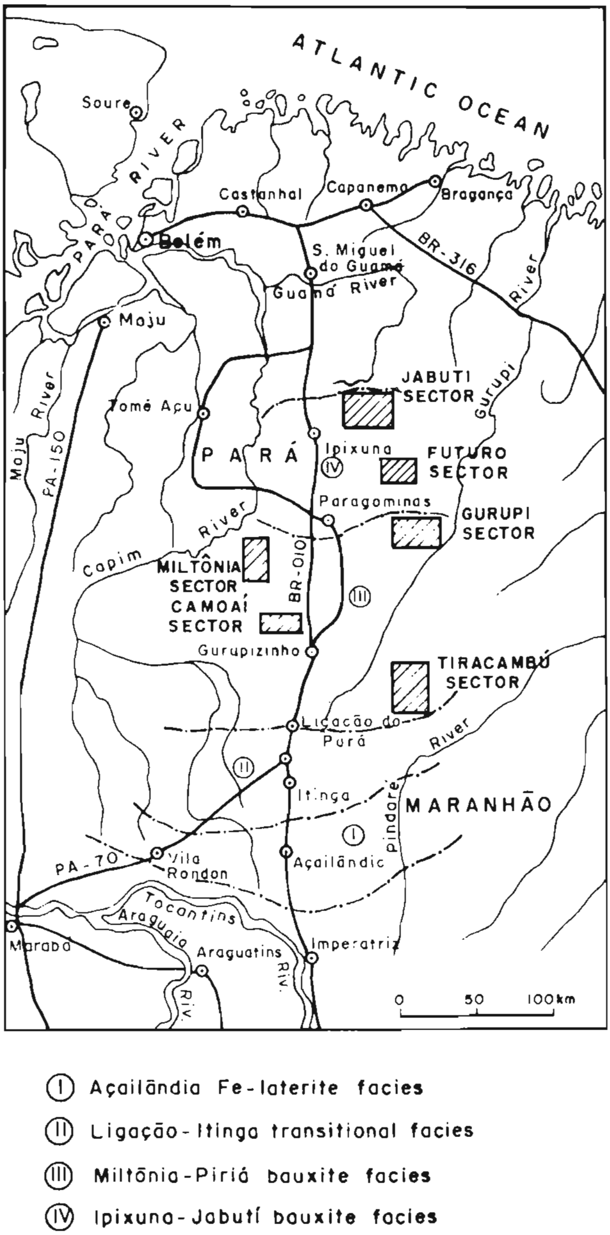

Figure II.2 - Paragominas bauxite region. Location of the main bauxite sectors and sketch of the facies distribution.

polyphasic evolution. According to this author, the process started with an intense bauxitisation followed by the deposition of a sandy layer which underwent ferrification in podzolic conditions. A secondary bauxitisation

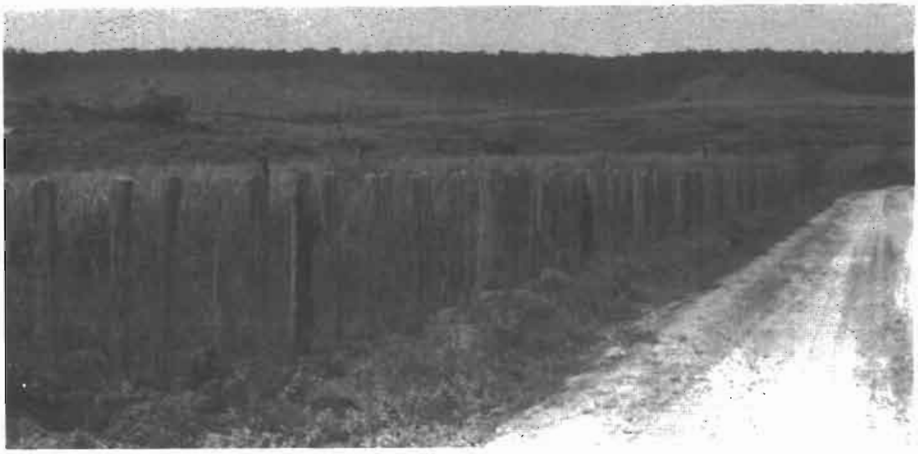

Figure II.3 - Bauxite plateau between Miltônia sector and Belém-Brasília highway (BR 010).

would have marked the end of the bauxitic evolution. A systematical survey and detailed studies of bauxite exposures along the Belém-Brasília highway and in Miltônia sector were undertaken by Kotschoubey & Truckenbrodt (1981, 1982) and Truckenbrodt & Kotschoubey (1982). These authors confirmed the polygenetic evolution of the Paragominas bauxites, proposed by Grubb (1979), and suggested the existence of five stages, including initial lateritisation, formation of Fe-rich horizon, first gibbsitisation, deposition of lateritic gravels and second gibbsitisation. In turn, Kronberg et al. (1982) described the Paragominas bauxites as a gibbsite enriched crust resulting from intense lateral percolations beneath a less altered zone. Studying the northern Jabutí sector, Kotschoubey et al. (1984) evidenced striking differences between these bauxites and the deposits situated to the south of Paragominas. The bauxite facies of Jabutí is apparently connected with a third bauxitisation phase, which succeeded partial dismantling of the formerly generated regional profile (Kotschoubey et al., 1984) and possible deposition of clayey material upon the crust. More recently, Kotschoubey et al. (1989) extended this model of three bauxitisation phases to all the bauxite occurrences localized to the north of Paragominas.

A general review of the Paragominas bauxites based on earlier studies pointed out a well defined regional facies zonation (Kotschoubey et al., 1987). In the southern part of the Paragominas district, this crust is ferruginous and only occasionally gibbsitic, while in the sectors situated closer to Paragominas and in the Ipixuna-Jabutí area, it exhibits, in contrast, a highly bauxitic composition.

An evolution model, including initial bauxitisation followed by the break-up and superficial reworking of the ferruginous upper zone of the bauxitic profile and deposition of the Belterra Clay, was recently proposed by Aleva (1989). According to this author, after the clayey overburden was deposited, gibbsite and ferruginous nodules developed within the lower part of the latter. However, a different hypothesis was presented by Bardossy & Aleva (1989). According to this model, after a preliminary bauxitisation stage and formation of a duricrust on the top of the initial profile, downward migration of Fe and Al-rich solutions yielded the regional profile and the "in situ" individualization of the Belterra Clay.

The origin of this clay cover poses a special problem of the bauxite profile and, until now, no definitive answer was found in spite of numerous proposals. Sombroek (1966), who gave the name Belterra Clay to the clayey overburden of the Amazonian bauxites, was the first to characterize it as an up to 20 m thick, uniform, yellowish, predominantly kaolinitic horizon without any visible stratification. He interpreted this clay as a lacustrine sediment with provenience from the Andean chain. Klammer (1971), for his part, considered this horizon as the upper part of the Barreiras sediments (Pliocene, after this author). Moreover, this author defined, as Belterra Clay concept, the superficial clay level, the laterite and the subjacent saprolitic horizon. Wolf & Silva (1973), Dennen & Norton (1977), Aleva (1981a), Boulangé & Carvalho (1989), Lucas et al. (1989) and Bardossy & Aleva (1989) held comparable opinions. All these authors stressed an "in situ" evolution of the Belterra Clay, either contemporaneously with or after the laterite/bauxite formation.

In contrast to the hypothesis of the autochthonous origin of the Belterra Clay, the allochthonous origin of the clayey overburden found few advocates. Besides Sombroek (1966), Grubb (1979) was the first to point out the presence of minor colluvial bauxitic horizons toward the bottom of the Belterra Clay. Truckenbrodt & Kotschoubey (1981) also defended a sedimentary origin of the Belterra Clay. These authors suggested the redistribution of clay material from the saprolitic horizon by mud-flow or sheet flood in a semi-arid climate. Recently, De Dekker & Stoops (1988) remarked that the Belterra Clay is most probably of sedimentary origin. Aleva (1989) recognized, just below the Belterra Clay, an horizon "that seems to represent a level of horizontal material transport or mass flow" (p. 27). A comprehensive paper about composition and origin of the clay cover on North Brazilian laterites has been given by Truckenbrodt et al. (1991).

II. Geological and geomorphological setting

The Paragominas bauxites are located in the north-western part of the Parnaiba Basin, between the Amazonian Craton and the Araguaia Orogenic Belt in the SW and the Gurupi Precambrian region and the São Luiz Craton in the NE (Fig. II.1). The outcropping rocks mainly belong to the Cretaceous Itapecuru Formation and the Cretaceous/? Lower Tertiary Ipixuna Formation.

The Itapecuru Formation occurs in the southern part of the Paragominas region and consists of cross-bedded sandstones, mudstones and, subordinately, conglomerates, which were deposited in a fluvial to deltaic system under conditions of a semi-arid climate (Petri, 1977; Góes, 1981). Very similar to the Itapecuru sediments is the Ipixuna Formation which extends farther to the north (Fig. II.4) and was interpreted by Góes (1981) as a fluvial-lacustrine facies of the Itapecuru Formation. However, a Lower Tertiary age for the Ipixuna sediments cannot be ruled out (Francisco et al., 1971). Younger formations, mainly referred to the Quaternary, include fluvial terraces and valley fillings as well as thick colluvial deposits and stone-layers. Typical sediments of the Barreiras Group (Miocene/ Pliocene, ? Pleistocene) (Arai et al., 1988; Beurlen, 1970, Bigarella, 1975) were not observed in the Paragominas district.

The bauxite and the Belterra Clay are bound to the upper part of

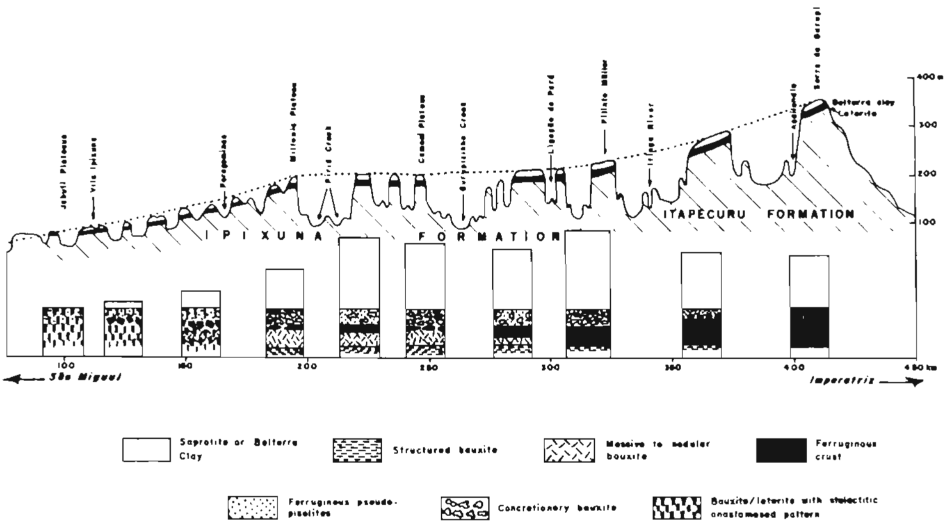

Figure II.4 - Synthetic north-south profile of the Paragominas bauxite region. Topographic profile after Sombroek (1966).

the dissected tableland and overlie Ipixuna and Itapecuru sediments. A north-south oriented topographic survey, effectuated by Sombroek (1966), showed that the planation surface does not rise constantly, but is characterized by the presence of two slight slopes, in the northern and southern parts of the bauxite region, and a nearly horizontal surface between them (Fig. II.4). The altitude of the plateaus in the neighborhood of Paragominas does not exceed 200 m, while, in the southern margin of the district, it increases to about 400 m. In the Jabutí area the plateaus are small and well individualized, differing from the dissected, large and more unique plateau in the south of Paragominas. The downcutting of the tableland and the present altitude of the laterites are related to Late Tertiary and possibly Quaternary uplifting.

III. Lateritic facies

Four principal facies were defined in the Paragominas region: Miltônia-Piriá, Ligação-Itinga, Açailândia and Ipixuna-Jabutí facies.

1. Miltônia-Piriá facies (Fig. II.5)

This bauxite facies, disregarding the thickness variations, characterizes the sectors of Miltônia, Gurupi, Camoaí and Tiracambú (Fig. II.2). It also can be observed in excellent road cuts along the Belém-Brasília highway between Paragominas and Ligação do Pará. In the

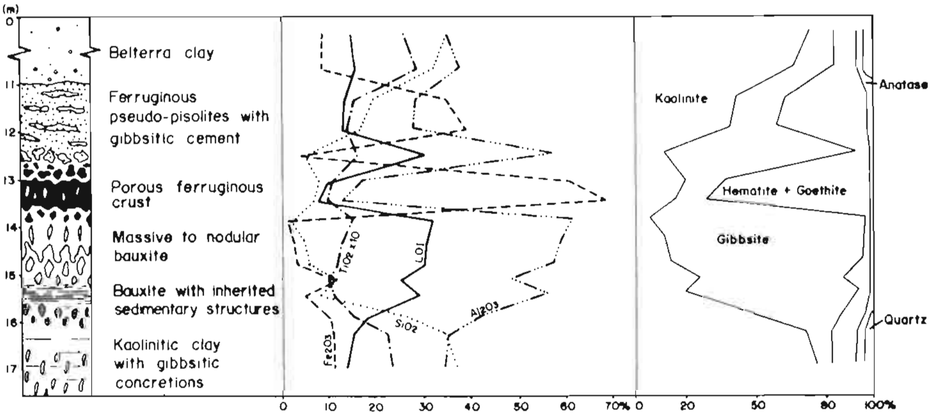

Figure II.5 - Chemical and mineralogical composition of the Piriá profile; km 1,603 of the Belém-Brasília highway.

north of Paragominas, however, this facies rarely occurs. There, the best examples were found in Jabutí sector (trench 07, Kotschoubey et al., 1989) and at km 16 of the Paragominas-Tomé Açu road. In the latter location, although the different horizons are still perfectly individualized, a stalactitic anastomosed framework can also be observed. Therefore, the profile in question may already be considered as a transitional one to the Ipixuna-Jabutí facies.

The profile representative of the Miltônia-Piriá facies is constituted, from bottom to top, by a thick saprolite, a lower nodular to massive bauxite horizon with inherited sedimentary structures at the base, a ferruginous crust and an upper pseudopisolitic ferruginous to nodular bauxitic horizon; the uppermost level of the profile is represented by an up to 15 m thick kaolinic clay (Belterra Clay).

Saprolite. Grading from weathered and bleached mudstones and clayey sandstones of the Ipixuna Formation, the thick saprolite (up to 10 m) consists of compact, whitish, columnar clayey relics with sedimentary lamination and a pinkish to light brown, earthy, homogeneous sandy clay between the columns, filling vertical anastomosed pockets and tubules interpreted as originated by root activity. Towards the top of the horizon, the whitish relics progressively disappear at the cost of the earthy sandy clay and disseminated microcrystalline gibbsite increases. The upper part of the saprolite is also characterized by vertically oriented tubular concretions, of some centimeters in diameter, which may represent pseudomorphs of roots. These concretions consist of microcrystalline gibbsite and little iron (hydro)oxide, and normally exhibit an irregular, roughly concentric structure. In some localities, clayey or gibbsitic sub-spherical nodules with central voids are associated with the concretions.

Nodular to massive bauxite. This horizon consists of nodular bauxite which normally grades upwards to a more massive, roughly columnar one. In the sectors of Miltônia, Gurupi, Camoaí and Tiracambú, this highly aluminous horizon is very thick and constitutes the main mineralized layer of the deposits. The bauxite is essentially composed of well crystallized, microcrystalline gibbsite, intimately associated with some iron hydroxide and shows variable amounts of shrinkage and dissolution pores, which are filled or coated by macrocrystalline gibbsite, forming veinlets and geodelike microfeatures. Highly porous and cavernous bauxite can also present a box-work structure. The uppermost part of the massive bauxite often contains angular to rounded fragments of the overlying ferruginous horizon (Fig. II.6). The base of this bauxite horizon is generally marked by an up to 1.5 m thick nodular, rarely massive level,

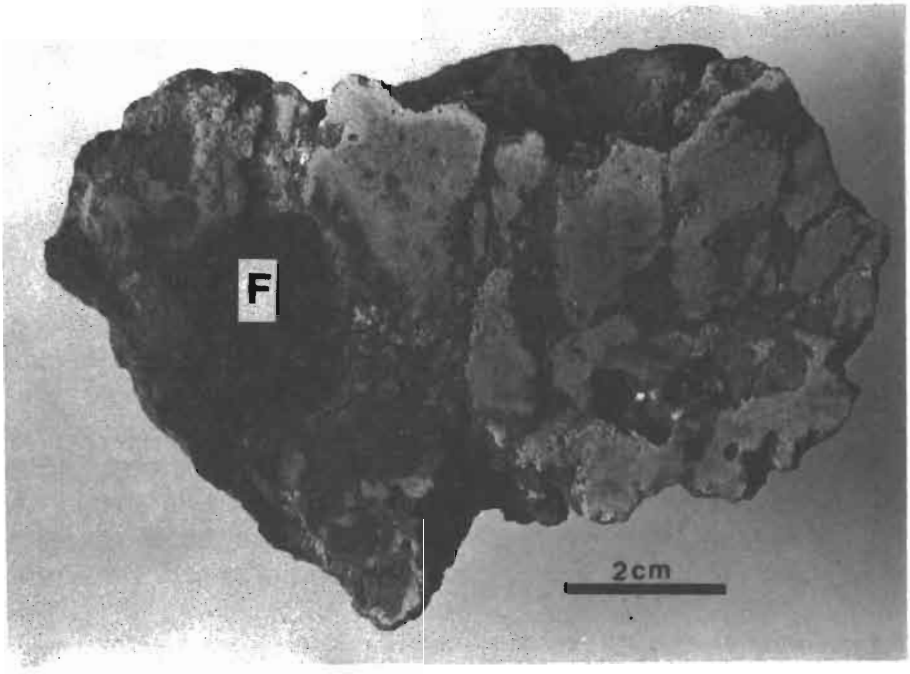

Figure II.6 - Fragment of ferruginous crust (F) engulfed by bauxite (main bauxite horizon); Piriá profile, km 1,603 of the Belém-Brasília highway.

which preserves well the original textures and structures of the Ipixuna sediments. Complexly twinned macrocrystalline gibbsite is the main constituent of this lowermost level; relics of highly corroded quartz grains are sometimes observed as well as dispersed aggregates of microcrystalline gibbsite.

Ferruginous crust. The ferruginous horizon is in sharp contact with the underlying bauxite and exhibits variable thickness and facies. In most cases, it appears as an up to some decimeters thick, highly porous duricrust with a roughly columnar structure and ferruginous nodules at the top. Sometimes more or less well defined levels of fine-grained, angular to rounded fragments can be seen embedded in a porous matrix.

On the whole, this horizon is predominantly composed of hematite and goethite in variable proportions with low amounts of kaolinite, gibbsite and quartz grains. The most porous parts of this ferruginous level are often rich in goethitic cutans and concretions. The pores are generally coated by thin botroidal hematitic films; locally, well crystallized goethite or macrocrystalline gibbsite fill the voids. The porous texture (molds) and corroded and fractured quartz grains, enclosed in the crust, testify to the former abundance of this mineral.

Locally, the ferruginous horizon appears to be discontinuous and occurs as an accumulation of irregularly shaped and densely packed fragments (Miltônia) or as an up to some centimeters thick lenses (Paragominas-Capim river road). It may even not exist at all as in the Camoaí sector, where the lower massive bauxite is in immediate contact with the upper nodular bauxite.

Pseudopisolitic horizon. This level, which shows a sharp contact with the underlying ferruginous crust, generally consists of tightly packed, millimetric to centimetric, well rounded, frequently ovoid structureless ferruginous gravels, here referred to as pseudopisolites (Fig. II.7). This upper layer is commonly up to 1 m thick, but it may reach 3 m. Most of the pseudopisolites are composed of a reddish, fine grained mixture of variable amounts of goethite, hematite, kaolinite and gibbsite. Smaller amounts of highly porous, essentially ferruginous pseudopisolites can be observed, while gravels exclusively composed of gibbsite or hematite and kaolinite seldom occur. The pseudopisolites occasionally show normal grading (Fig. II.7) and may be arranged in layers or lenses constituted, each one, by a specific type of pseudopisolites in shape and composition (Fig. II.8). In some localities and particularly in the Piriá profile, a well shining surface, similar to desert varnish, is exhibited by pseudopisolites near the contact with the Belterra Clay. A light colored, porcelaneous gibbsitic cement with very low amounts of kaolinite may fill the pore space between the pseudopisolites.

The quantity of this cement is extremely variable and often it is reduced to irregular, sub-horizontal lenses, erratically distributed in the pseudopisolitic horizon. Where it occurs in higher amounts, the cement generally shows a clear tendency for replacement of the pseudopisolites. In several places, however, the gibbsite is enriched in the upper part of the horizon, forming a variably thick fringe (Fig. II.9). It is not rare to find a level of bauxite concretions enriched in macrocrystalline gibbsite at the base of the pseudopisolitic horizon. The result of cementation and substitution of the ferruginous constituents is a light colored, concretionary, scoriaceous bauxite.

Belterra Clay. The contact of the duricrust with the up to 15 m thick Belterra Clay is always extremely sharp (Figs. II.7, II.9). This reddish to yellowish overburden consists, mainly, of kaolinite and subordinately of goethite, hematite, variable amounts of gibbsite and a few percent of corroded quartz grains.

Generally, rounded ferruginous and irregular bauxitic gravels, both

Figure II.7 - Tightly packed ferruginous pseudopisolites showing fining-upward trend and sharp contact with Belterra Clay; Miltônia sector.

of variable size, which, however, rarely exceed 1 cm in diameter are dispersed in the clayey matrix (Fig. II.10). Most of the bauxitic gravels are whitish and composed of microcrystalline gibbsite. However, brownish to pinkish bauxite fragments, rich in macrocrystalline gibbsite, may also occur. The ferruginous gravels show different textures which include porous and dense ones. Although the gravels represent, normally, only a few weight percent in the clay cover, higher contents of these constituents (up to 10%) are found in the lowermost part of the overburden.

Figure II.8 - Bedding structure in the pseudopisolitic horizon marked by different grain sizes; km 1,590 of the Belém-Brasília highway.

The earthy texture, high porosity and absence of any visible sedimentary structure allow to characterize the Belterra Clay as a latosol.

2. Ligação-Itinga facies (Fig. II.11)

To the south and southwest of Ligação do Pará, structural and compositional modifications of the duricrust can be observed. A gradual transition from bauxite to an essentially ferruginous crust takes place,

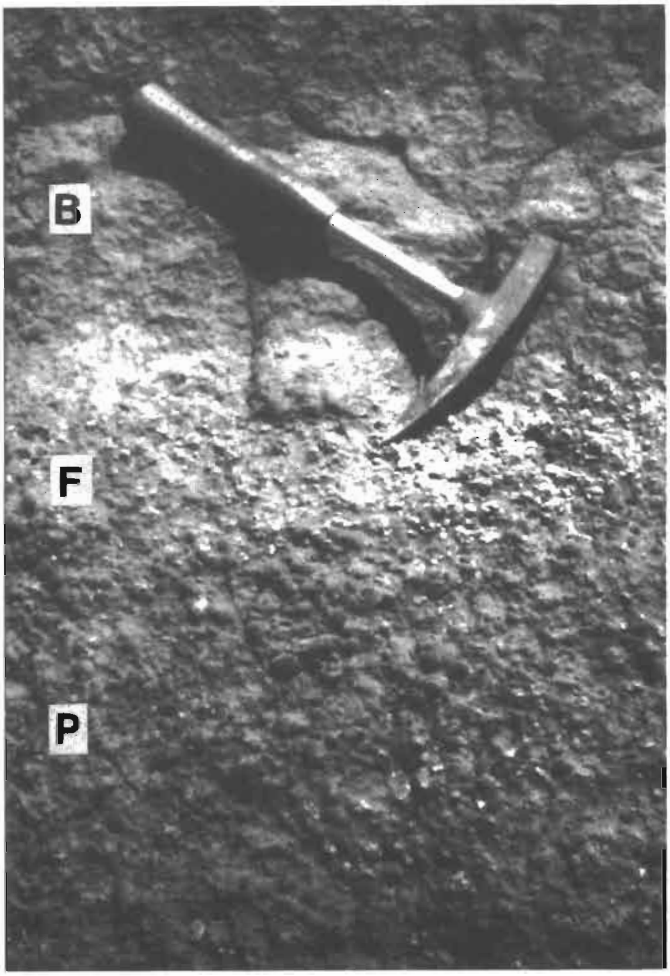

Figure II.9 - Bauxitic fringe (F) resulting from cementation and substitution of ferruginous pseudopisolites (P) by gibbsite in sharp contact with Belterra Clay (B); km 1,603 of the Belém-Brasília highway.

giving rise to a regional zonation, described by Kotschoubey et al., (1987).

The main bauxite horizon gradually decreases in thickness southward, resulting in a thin nodular horizon, enriched in macrocrystalline gibbsite, underlain by a centimetric to decimetric thick, laminated, coarsely crystalline bauxite which, sometimes, contains identically structured ferruginous remnants. Between Itinga and Açailândia, the lower bauxite disappears definitively.

The overlying ferruginous level normally preserves its roughly

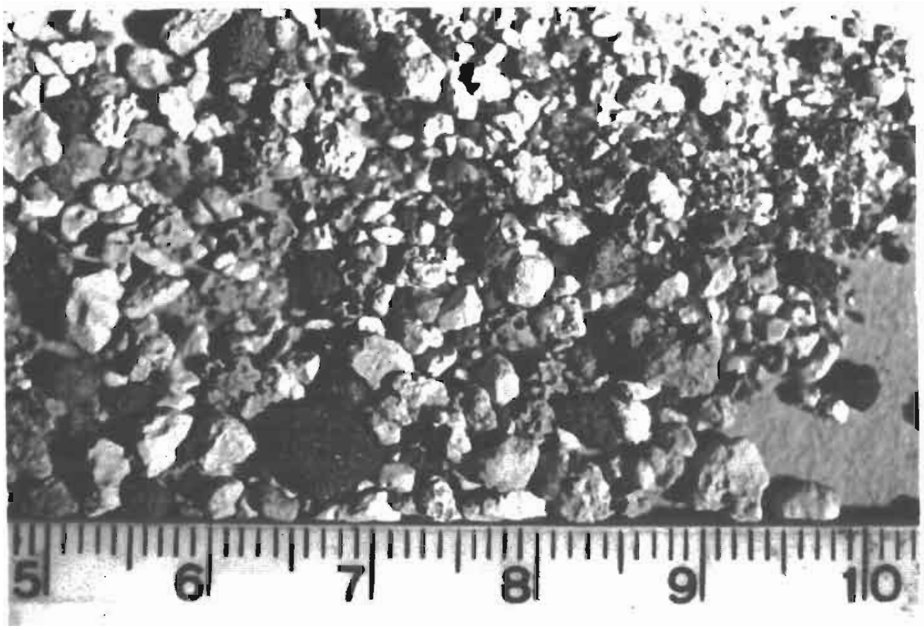

Figure II.10 - Ferruginous and bauxitic gravels separated from Belterra Clay; Gurupizinho area.

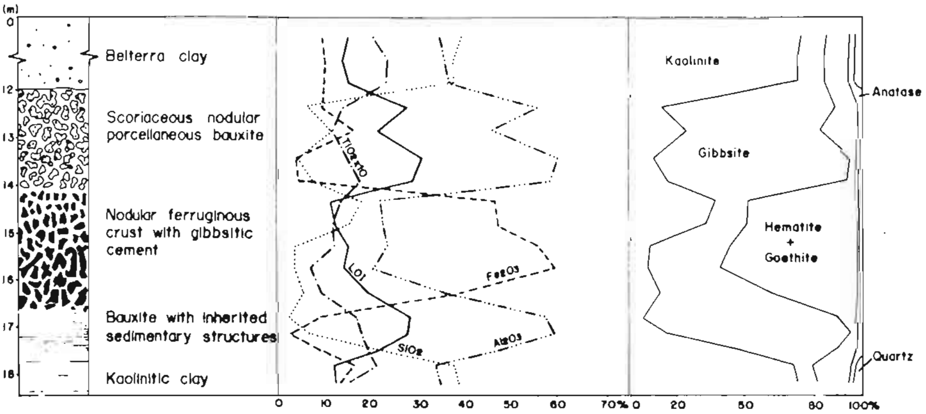

Figure II.11 - Chemical and mineralogical composition of the Ligação do Pará profile; km 1,508 of the Belém-Brasília highway.

columnar structure becoming more nodular at the top. However, in some places, as, for example, at km 1,508 of the Belém-Brasília highway, the ferruginous horizon shows more accentuated degradation features.

There, it appears as a predominantly nodular, up to 2.5 m thick horizon, where part of the nodules are still interconnected.

Abundant ramified and roughly tubular cavities are partially cemented by pinkish bauxite, rich in macrocrystalline gibbsite. Clayey matrix fills the remaining pore space. A yellowish goethitic cortex lines the nodules and, thus, clearly marks the contact with the bauxite cement (Fig. II.12). It must also be pointed out that the size of the nodules decreases gradually from bottom to top of this horizon.

The upper pseudopisolitic level is quite similar to that of the typical bauxite profile of the Paragominas district. However, the abundance of gibbsitic cement decreases drastically southwards. South of Dom Eliseu

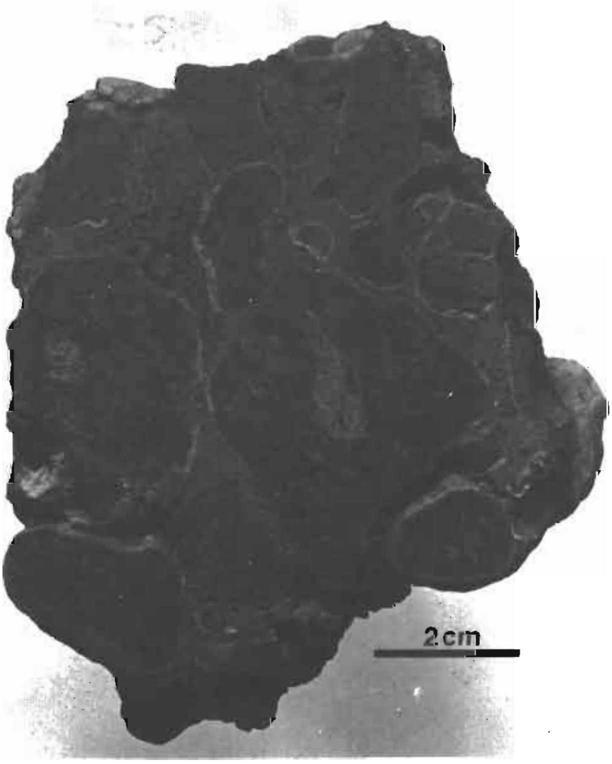

Figure II.12 - Nodular ferruginous crust cemented by macrocrystalline gibbsite; nodules lined by goethitic cortex; km 1,508 of the Belém-Brasília highway.

and along the PA 70 road (Dom Eliseu - Vila Rondon-Marabá), no more gibbsite cement occurs in the upper part of the pseudopisolitic horizon; instead, a nodular bauxite can be observed in its lower part. These aluminous nodules often contain remnants of altered, partially deferrified pseudopisolites and abundant macrocrystalline gibbsite. They decrease in size, while the bauxite level becomes thinner and, finally, disappears.

3. Açailândia facies (Fig. II.13)

At the southern margin of the Paragominas district, an exclusively ferruginous crust, with a thickness of up to 6 m, occurs. It is well represented in the neighborhood of Açailândia, where it caps large plateaus. Here, a structureless reddish clayey sandy saprolite, which encloses fine-grained, angular, hematite-rich fragments and small, porous, mainly goethitic nodules, grades into a several meters thick, columnar crust, predominantly composed of hematite and goethite with a subordinated amount of kaolinite. Highly corroded quartz grains can sometimes be found in this crust, while the greater part of this constituent was dissolved, giving rise to a moldic porosity. Only in rare cases, macrocrystalline gibbsite was observed to have partly filled the dissolution pores. Abundant goethitic cortex and cutans testify later iron remobilization. Upwards, the cuirass becomes nodular and is represented, at the top, by an up to 50 cm thick pseudopisolitic layer. At the contact to the Belterra Clay, the well rounded pseudopisolites exhibit a

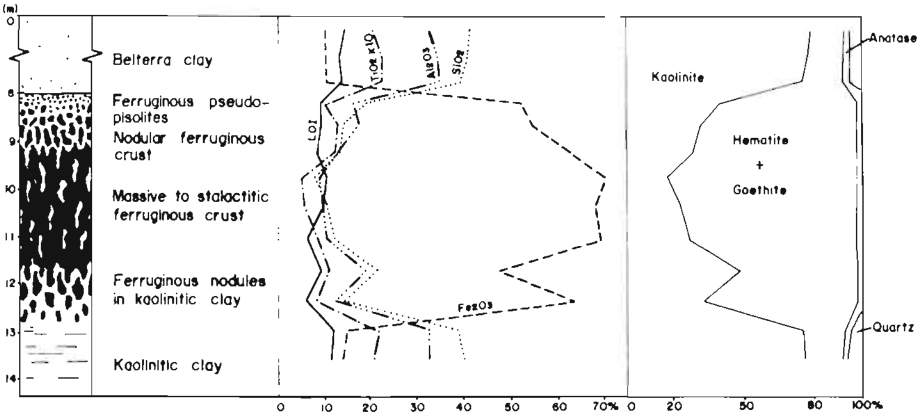

Figure II.13 - Chemical and mineralogical composition of the Açailândia profile; km 1,409 of the Belém-Brasília highway.

shiny surface similar to desert varnish (Fig. II.14) (Truckenbrodt & Kotschoubey, 1981). No gibbsite was found in this level, but recent analyses detected aluminum in the lattice of goethite (Hieronymus et al., 1990). Finally, an up to 10 m thick Belterra Clay, which only contains traces of gibbsite, overlies the duricrust.

4. Ipixuna-Jabutí facies (Fig. II.15, II.16, II.17)

The northern part of the bauxite region, which has a north-south extension of approximately 80 km, is characterized by pronounced faciological modifications within the aluminous duricrust, when compared with the profiles described above. Its southern margin is situated some kilometers to the south of Paragominas and corresponds to an inflection of the regional planation surface, which makes the altitude progressively drop from 180-200 m to less than 100 m to the north of Vila Ipixuna (Fig. II.4). The northern border of the bauxite area is localized about 20 km to the north of Vila Ipixuna (Fig. II.2). Beyond this limit, no more bauxite

Figure II.14 - Ferruginous pseudopisolites with shining surface suggesting subaerial exposure.

was observed and only more recent sedimentary and lateritic formations occur.

Total absence or only partial preservation of the layered structure described above and an ubiquitous columnar/stalactitic pattern are the most significant characteristics of the crust in the Ipixuna-Jabutí sector. In detail, three specific lateritic/bauxitic subfacies were distinguished:

1. obliterated Miltônia-Piriá subfacies; 2. detrital subfacies; 3. simple ferro-aluminous subfacies.

Obliterated Miltônia-Piriá subfacies (Figs. II.15, II.16). This facies is common and can be observed in several road cuts along the Belém-Brasília highway (km 1,666 to 1,703) and in the Jabutí sector. It is normally characterized, from bottom to top, by a clayey pinkish saprolite which grades into a stalactitic, more or less anastomosed laterite predominantly composed of kaolinite, cryptocrystalline gibbsite and hematite. This horizon, in turn, grades into a roughly columnar, sometimes massive, mottled aluminous laterite. As the underlying concretions, it contains cryptocrystalline gibbsite and variable amounts of iron oxide but with much less kaolinite. Fine-grained, light-colored bauxitic fragments can sometimes be observed enclosed in the ferro-aluminous matrix. When this horizon is less developed, it presents the same stalactitic, roughly reticular pattern as the lowermost part of the duricrust. This aluminous horizon is overlain by an iron-rich level consisting of remnants of the original ferruginous crust. The ferruginous fragments of this level frequently are porous and rich in goethitic cutans. Normally, they are cemented by gibbsite and sometimes can be reduced to blocks or even smaller fragments enclosed in a pinkish to purplish gibbsitic matrix.

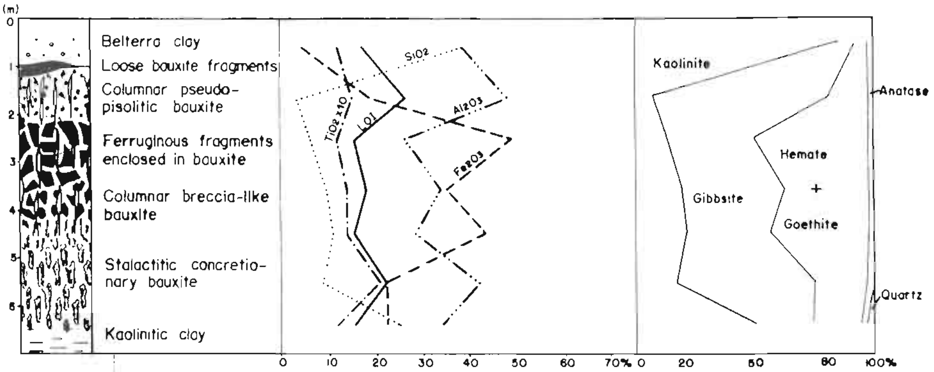

Figure II.15 - Chemical and mineralogical composition of the Ipixuna profile 1; km 1,703 of the Belém-Brasília highway.

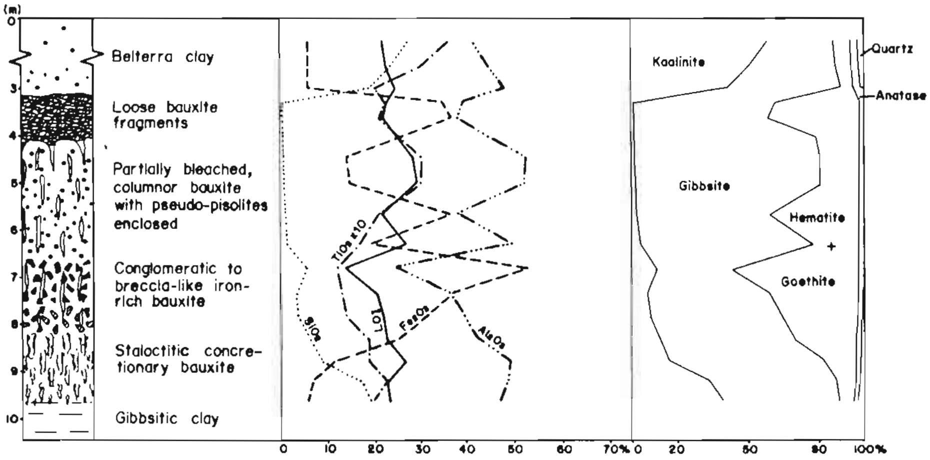

Figure II.16 - Chemical and mineralogical composition of the Jabutí profile; trench 16 of Jabutí plateau.

It follows a columnar, bauxitic horizon which, in places, is highly deferrified. Its cryptocrystalline gibbsitic matrix encloses small porcelaneous bauxite concretions and pseudopisolites, which are composed of microcrystalline gibbsite and often present a concentric zonation, due to partial deferrification. The bauxitic columns are separated by subvertical pockets which are coated by a goethitic film and pustule-like gibbsitic concretions, and filled with a yellowish clay similar to the Belterra Clay.

In the profiles of km 1,703 (Fig. II.15) and trench JS16 (Fig. II.16) in the Jabutí sector, elongated and flat bauxitic fragments cover the aluminous crust forming some centimeters to 1 m thick, lenticular accumulations which seem to fill slightly depressed zones (Fig. II.18). The fragments are weakly or not cemented at all and essentially consist of cryptocrystalline gibbsite and high amounts of hematite. Their contact with the clayey overburden is very sharp. In this type of bauxitic duricrust the Miltônia-Piriá facies still can be recognized, although the original layered structure is strongly obliterated by a columnar-stalactitic structure.

Detrital subfacies. An essentially detrital facies, closely associated to the duricrust type described above, is well exposed at km 1,666 and km 1,668 of the Belém-Brasília highway. It consists of an up to 2 m thick accumulation of densely packed, irregular pebbles (up to 30 mm in diameter) enclosed in a friable, whitish, gibbsitic kaolin matrix with a superimposed roughly reticular pattern (Fig. II.19). The pebbles are composed of porcelaneous (microcrystalline) gibbsite, smaller amounts of iron (hydro)oxide and traces of kaolinite. They generally present an outer completely deferrified zone, while the core is still ferruginous. The superimposed framework, which mainly consists of cryptocrystalline gibbsite and variable amounts of hematite, encloses small rounded remnants of porcelaneous bauxite. The uppermost part of the profile is marked by a 10 to 20 cm thick, intensely deferrified fringe composed of small, essentially gibbsitic pseudopisolites. As in other places, the contact with the Belterra Clay is very sharp (Fig. II.19).

Simple ferro-aluminous subfacies (Fig. II.17). This type of duricrust can commonly be observed along the Belém-Brasília highway, in road cuts between km 1,668 and km 1,725, the Paragominas-Tomé-Açu road and in the Jabutí Plateaus. From bottom to top, it consists of a thick saprolite horizon, an intermediate concretionary horizon and an upper, massive, roughly columnar laterite/bauxite.

The lowermost part of the saprolite is represented by bleached Ipixuna sediments, with preserved structures and small vertical tubules filled by pinkish clay, which probably resulted from root activity.

Upwards, the tubular structures become more frequent until only diminute fragmented columnar relics of whitish sediments persist in a fairly homogeneous clayey matrix composed of kaolinite with little quartz and traces of gibbsite. The up to 4 m thick intermediate lateritic level typically exhibits a loose nodular structure which rapidly grades to a more or less anastomosed stalactitic, sometimes roughly reticular pattern. The framework consists of variable amounts of kaolinite, gibbsite and hematite, while the more friable matrix is intensely deferrified, and predominantly composed of kaolinite with minor amounts of gibbsite. This horizon is overlain by an up to 2 m thick, fairly massive, mottled bauxite or kaolinite-rich ferruginous laterite. Frequently, tubular cavi-

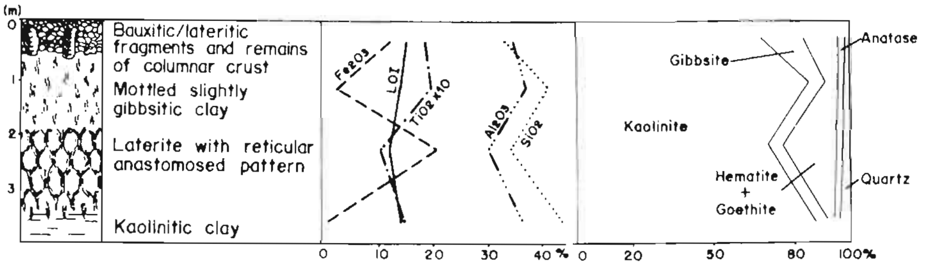

Figure II.17 - Chemical and mineralogical composition of the Ipixuna profile 2; km 1,709 of the Belém-Brasília highway.

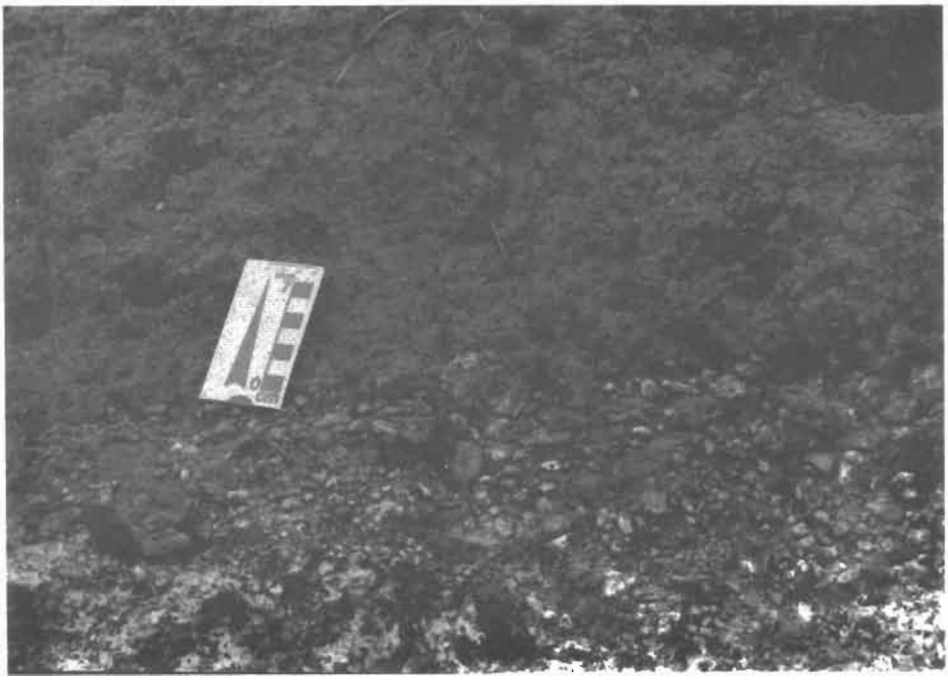

Figure II.18 - Poorly sorted bauxitic fragments at the top of the Ipixuna profile 1 (see fig. 15) overlain by Belterra Clay. This accumulation of sedimentary origin points to the allochthonous nature of Belterra Clay.

ties are lined by a thin goethitic film and are normally filled by a yellowish kaolinitic, gibbsite clay, which is similar to the overlying Belterra Clay.

As in the cases described above, the contact between this duricrust and the overlying Belterra Clay is sharp. Locally (km 1,670), decimetric thick lenticular accumulations of bauxitic/lateritic fragments were observed, marking this contact.

In the northern part of the Ipixuna-Jabutí area, particularly to the north of Vila Ipixuna, the above described profile underwent pronounced modifications that can be clearly observed along the Belém-Brasília highway, between km 1,705 and km 1,709. The Belterra Clay disappears and the upper horizon of the duricrust is, partially to totally, replaced by a stone-layer of variable thickness composed of centimetric to decimetric large fragments. In some places, the intermediate stalactitic horizon also exhibits pronounced modifications. Then, its upper part appears to be deferrified, giving rise to mottled features, while the reticular anastomosed structure is strongly obliterated.

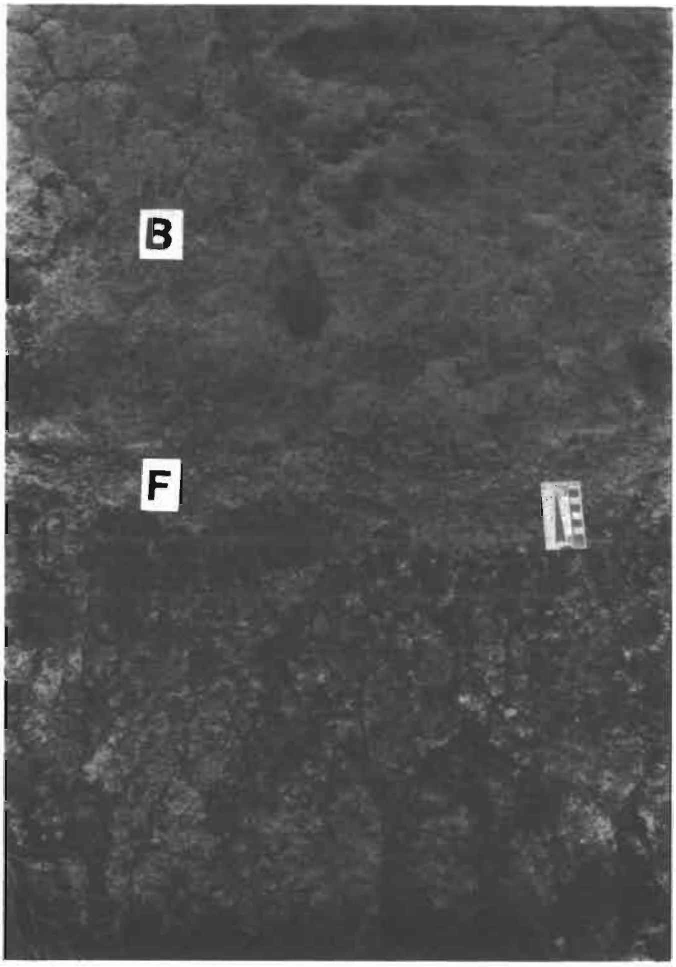

Figure II.19 - Detrital bauxite showing reticulate pattern enhanced by iron oxide and a fringe (F) composed of gibbsite pseudopisolites. The contact with the overlying Belterra Clay (B) is sharp.

The latter, however, remains well preserved at lower levels in the profile.

The Belterra Clay in the Ipixuna-Jabutí area is very similar in composition and texture to the overburden of the other sectors. However, a lower iron content and/or a more significant gibbsite content can locally be observed (kms 1,666 and 1,703, JS 16).

IV. Discussion

Regarding the genesis of the bauxites/laterites, any hypothesis on their formation must consider the following characteristics:

Thickness variations of the different horizons

Pronounced thickness variations can be observed in all the horizons. While the lower bauxite horizon is several meters thick in Jabutí, Miltônia, Gurupi, Camoaí and Tiracambú sectors, it only reaches some decimeters south of Gurupizinho and near Ligação do Pará. The pseudopisolitic horizon may change in thickness from 3 m to less than 1 m in neighboring profiles. Locally, the ferruginous level becomes lenticular or even is absent. These differences in thickness are probably caused by variable intensity of the chemical and mechanical processes involved in the duricrust formation, and total dismantling of the ferruginous horizon is suggested where the latter does not occur.

Nature of the contacts between different horizons

The contacts between the horizons, particularly that between the pseudopisolites and the clayey overburden, are always fairly sharp (Figs. II.7, II.9, II.19). Simple autochthonous bauxitic profiles, however, generally show continuous transitions between the horizons. It seems that the sharp boundaries point to chemical and mechanical processes developed in distinct phases.

Gibbsite facies in the lower bauxitic horizon

The main part of this horizon consists of microcrystalline gibbsite, probably formed by desilication of kaolinite (Truckenbrodt & Kotschoubey, 1982). However, fissures and pores filled by coarser gibbsite also suggest precipitation from alumina-rich solutions. The macrocrystalline gibbsite is particularly abundant in the lowermost, still structured part of this horizon (Truckenbrodt et al., 1995). Its rare, highly corroded quartz grains and locally still preserved sandstone texture indicate that the replacement of former minerals by gibbsite was the predominant process in this level. Vertical and lateral migrations of alumina-rich solutions would have been responsible for such metasomatism.

Relics of the ferruginous crust occurring in the underlying bauxite.

The presence of remnants of the ferruginous crust in the upper part of the underlying aluminous horizon (Fig. II.6) clearly indicates that the ferruginous level already existed when the lower bauxite was formed.

Texture and structure of the ferruginous level

The ferruginous horizon does not show concretionary features typical of lateritic process. On the contrary, the presence of moldic pores and hematite cement indicates that it is the result of ferrification of Ipixuna-

Itapecuru sediments and later dissolution of their framework grains. Part of the iron was remobilized and precipitated as goethitic cutans.

Distribution, structure and composition of the pseudopisolitic horizon

The widespread distribution of the pseudopisolites and their eventual bedding-like disposition and fining-upward trend (Miltônia, Piriá, Figs. II.7, II.8) suggest the degradation of a former duricrust followed by reworking of the debris and its accumulation over an extensive landsurface.

However, the textural and compositional differences between the pseudopisolites and the immediately underlying ferruginous crust point to a partially allochthonous origin of these components. Thus, it is likely that the break-up of an older, no more visible ferro-aluminous crust also contributed to the formation of these thick gravely deposits. Wash processes, probably associated to mass movements would explain the dense packing of the pseudopisolites.

All transitional stages can be observed between pseudopisolitic accumulation without gibbsite cement (Açailândia and Vila Rondon areas) and porcelaneous bauxite, composed of tightly interlocking crystals of microcrystalline gibbsite cementing and replacing the ferruginous pseudopisolites. Irregularly distributed, subhorizontal lenticular accumulations of gibbsite in this horizon characterize the transitional stages.

These observations suggest that lateral migration of Al-rich solutions was significant because lenticular distribution of gibbsite cannot be easily explained by downward migration of alumina from the Belterra Clay.

Occurrence of columnar to reticulate framework in the Ipixuna-Jabutí area.

The Ipixuna-Jabuti facies is characterized by the development of a columnar to reticulate bauxitic framework, which partially obliterated the features of the Miltônia-Piriá bauxite profile.

According to the observations above, it appears that ferrification of Ipixuna-Itapecuru sediments (ferruginous horizon) preceded the bauxite formation. The iron accumulation is interpreted as the result of a podzolic process. However, the very high iron content in this relatively thick layer is far greater than can be accounted for by the loss from the surface horizon (Mohr et al., 1972). Consequently, this implies lateral accumulation in ground water podzolic conditions. Hypothetically, it is assumed that the iron was supplied by a now eroded laterite as it is described by Maignien (1966) and Millot (1970). The same laterite could also have furnished gravels by progressive, breakaway retreat of the crust. Their heterogeneity and, in part, different composition compared with that of the underlying ferruginous crust support this assumption.

Bauxitisation probably occurred with gradual lowering of the base level. The pseudopisolitic horizon firstly underwent cementation or cementation and replacement by microcrystalline gibbsite resulting in the formation of irregular lenses of concretionary bauxite. With deepening of the weathering mantle, the lower bauxite was generated in significant part by absolute alumina enrichment.

In the northern sectors of the Paragominas district, the bauxitic duricrust underwent supplementary modifications(Kotschoubey & Truckenbrodt, 1994). There, the Miltônia-Piriá facies was partially to totally dismantled and a later lateritisation/bauxitisation imposed a pervasive columnar stalactite structure upon the former, predominantly layered profile. Very fine-grained purplish bauxite was formed enclosing relics from bauxite and ferruginous horizons.

Concerning the Belterra Clay, the following characteristics must be taken into consideration:

a) its expressive thickness, particularly well represented in the Açailândia, Tiracambú, Piriá, Gurupi and Miltônia sectors;

b) its predominantly kaolinitic composition;

c) lack of significant compositional variations along the vertical profiles;

d) presence of pseudopisolites with shining surface at the contact with the Belterra-Clay in some profiles (Açailândia, Piriá, Fig. II.14). According to Alexandre (1976), this type of grain surface points to a subaerial exposure of these gravely deposits;

e) occurrence of variably thick discontinuous accumulations of laterite/bauxite fragments marking the contact between the Belterra Clay and laterite in profiles of the Ipixuna-Jabutí area (kms 1,670 and 1,703 of the Belém-Brasília highway; JS 16 trench on the Jabutí Plateau, Fig. II.18).

f) increasing occurrence, from top to bottom, of laterite granules (similar to the constituents of the pseudopisolitic horizon) interpreted by Grubb (1979) as being of colluvial origin;

g) in the case of the eroded Belterra Clay, degradation and dismantling of the lateritic duricrust resulting in a stone layer but not in a Belterra Clay-like product;

h) differences among the Belterra Clay from various localities;

i) distinct relations in chemical composition between the Belterra Clay and the underlying material (Truckenbrodt et al., 1991).

The origin of the Belterra Clay still constitutes a problem and no definite conclusions could be drawn as yet. There are arguments for both allochthonous as well as autochthonous formation. While structural and textural features (contact Belterra Clay/laterite, pseudopisolite layer with bedding-like structure and fining-upward trend) supply strong arguments for deposition of the Belterra Clay, the compositional relationship between Belterra Clay and the underlying laterite favor an "in-situ" formation of the clay cover (Truckenbrodt et al., 1991).

In any case, an origin of the Belterra Clay by resilication of a former bauxite layer (Kobilsek & Lucas, 1988) can be rejected, since the kaolinic clay also covers highly ferruginous laterite which is nearly free of gibbsite (Açailândia, Vila Rondon). Also, bauxite formation by lateral throughflow of ground water beneath a less altered clayey surface layer (Kronberg et al., 1982) is rather improbable. Even if such a process may form locally bauxite under appropriate geomorphic and geochemical conditions, widely extended bauxite horizons form close to the surface as a result of predominantly vertical percolation of water.

Under specific conditions, a kaolinite-rich laterite may alter into a latosol (Nahon et al., 1989). However, the formation of an up to 15 m thick kaolinic clay from a bauxite or a highly ferruginous crust is very questionable, although Bardossy & Aleva (1989) assumed primary bauxite/laterite formation followed by downward leaching of Fe and Al, with simultaneous formation of Belterra Clay.

Although the problem of the formation of the Belterra Clay is still waiting for a definite solution, preference is given to the sedimentary origin based mainly on the occasional occurrence of irregular, angular lateritic fragments at the contact Belterra Clay-laterite (Fig. 18) and the presence of dispersed ferruginous and aluminous granules in the overburden. In this case, the Belterra Clay should have been derived from eroded saprolitic material coming from former elevations inside or outside the present laterite terrains (Truckenbrodt et al., 1991). The present facies of the overburden is the result of biological activity and also, probably, of chemical alteration.

Conclusions

The evolution of the bauxite/laterite profile appears to have been complex and polyphasic. Although it was predominantly controlled by chemical phenomena, events of mechanical reworking and deposition cannot be ruled out. Climatic variations seem to have been of utmost importance during the formation of the lateritic profile, while tectonic movements, i.e. weak uplift, probably only played a relevant role during the later stages of its evolution. Certainly, the biological factor (root activity, organic matter accumulation, termite activity) was significant throughout the development of the lateritic crust, but its real importance is now difficult to estimate.

The regional zonation, stressed in the present work, and emphasized in former reports (Kotschoubey & Truckenbrdot, 1981; Kotschoubey et al., 1987), was interpreted as the result of climatic zonation. Thus, it is thought that the southern part of the region, where only ferruginous duricrust occurs, never underwent conditions favorable to bauxitisation. The very differentiated climatic conditions observed at the present in the Paragominas region show that such zonation could have existed as well in former geological time.

Concerning the age of the Paragominas bauxites, it is suggested, in the absence of correlative sediments and paleontological criteria, that they were formed mainly during Eocene-Oligocene time like those in Guyana, Surinam and French Guyana (Krook, 1979; Aleva, 1981b; Truckenbrodt et al., 1982; Pollack, 1983).

The Barreiras sediments (Mioceno/Pliocene-?Pleistocene) which occur north of the Paragominas bauxite region did not alter to bauxite, but only bear immature laterites.

The formation of the bauxite duricrust is related to the evolving tropical landscape. In this respect, the following stages are proposed (Fig. II.20):

1) under drier tropical conditions, progressive break-up and retreat of an ancient lateritic duricrust and consequent extension of pediment slopes and large accumulation glacis characterized by pseudopisolitic deposits. Ferrification of Ipixuna/ Itapecuru sediments in ground water podzolic conditions giving rise to the formation of a layer of ferruginous sandstone with interbedded ferruginous mudstone;

2) with change to a more humid climate, bauxitisation of variable intensity of the pseudopisolitic deposits;

3) deepening of the profile and development of the lower bauxite horizon at the cost of part of the ferruginous level and of the upper saprolite; aluminisation (replacement of framework grains) of the underlying sediments by macrocrystalline gibbsite mainly caused by lateral ground water migration;

4) exclusively in the northern part of the bauxite region and possibly in drier conditions, intense degradation and fragmentation or complete erosion of the duricrust;

5) in the same area, bauxitisation forming a stalactite pattern upon the remnants of the former duricrust or saprolite;

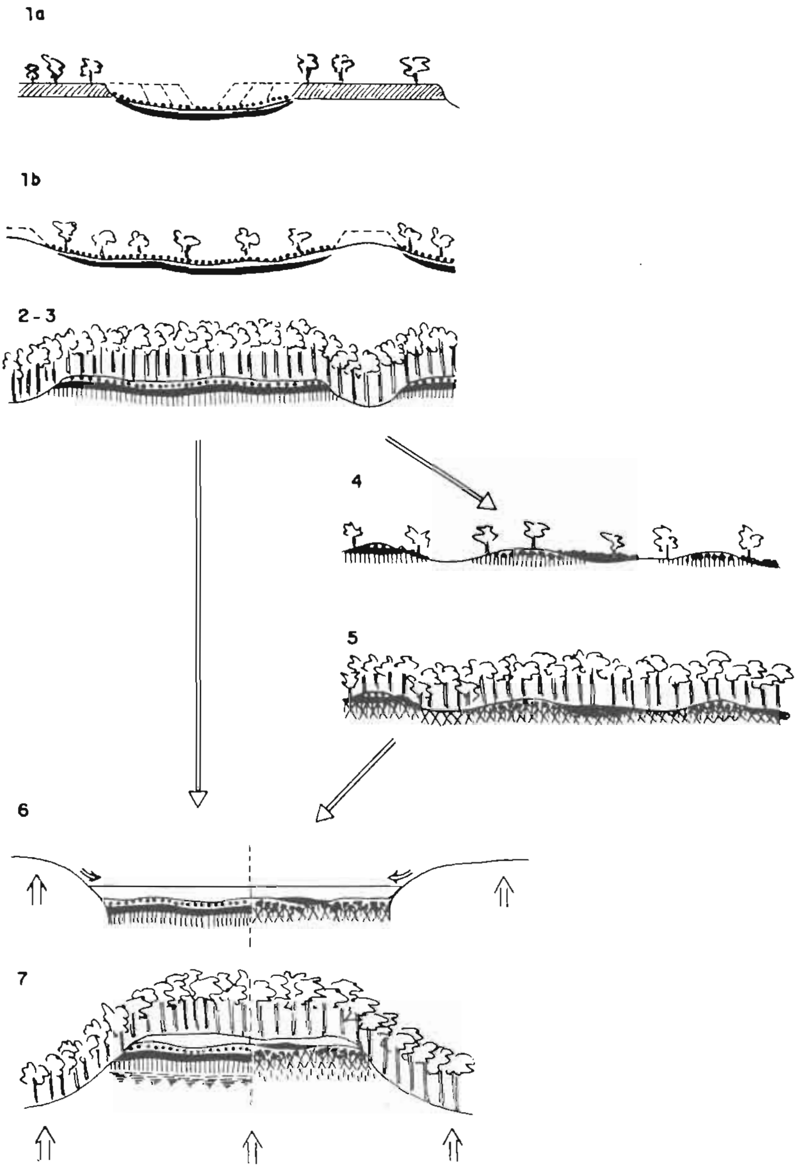

Figure II.20 - Model of the bauxite evolution in the Paragominas region. 1a and 1b: Accumulation of pseudopisolites derived from an older lateritic duricrust and formation of the ferruginous horizon; 2 and 3: Bauxitisation of the pseudopisolitic deposits and subsequent development of the lower bauxite; 4: Degradation and partial erosion of the bauxitic duricrust limited to the northern area; 5: Late bauxitisation limited to the northern area; 6: Deposition of Belterra Clay; 7: Uplifting and intense dissection of the regional surface.

6) deposition (?) of Belterra Clay from mud flows of saprolitic material containing ferruginous pseudopisolites and bauxite granules derived from reworked lateritic duricrust;

7) general uplifting and deepening of the weathering profile; formation of bauxite concretions in the saprolite and transformation of the clayey overburden into a latosol;

8) in the Ipixuna-Jabuti area, local erosion of the Belterra Clay and degradation of the duricrust into a lateritic stone-layer.

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THE BAUXITE OF JURUTI

Y. Lucas

Introduction

The extensive bauxitic terrains of the lower Amazon area exhibit common features, which have been described and discussed by a number of authors (Assad, 1973; Dennen & Norton, 1977; Grubb, 1979; Kronberg et al., 1979, 1982; Aleva, 1981; Kotschoubey & Truckenbrodt, 1981, 1984). Authors generally agree with the macroscopic description of the bauxitic profiles, which are characterized by six main horizons, from the top downwards:

- a kaolinitic loose yellow clay horizon, 1-14 m thick (also called "Belterra Clay"),
- a nodular horizon, 0,2-3 m thick, formed by gibbsitic and hematitic nodules embedded in a yellow clay material,
- indurated iron-rich horizons, 0.2-3 m thick,
- indurated bauxite, 1-9 m thick,
- kaolinitic mottled horizons, more than 2 m thick, white, and pale red in color,
- parent material, which is a quartzo-kaolinitic weathered clastic sediment.

However, authors differ significantly on the genetic interpretations of this profile. Some of them (Grubb, 1979; Aleva, 1981; Kotschoubey & Truckenbrodt, 1981, 1984) stress that the bauxitic horizons have been formed in the upper part of profiles which have suffered later erosion and re-deposition processes, considering, for example, the upper yellow clay horizon as a lake deposit named "Belterra Clay". Nevertheless, interpretations differ in the number of phases and the horizons which are considered as allochtonous. Others stress that the profile remained in situ since bauxitisation time, but differ in the processes involved. Dennen and Norton (1977) concluded that Al and Fe were leached from the upper part of the profile, transported downwards in solution and accumulated at depth. Kronberg et al. (1982) assume high flow rates of meteoric waters through highly permeable upper horizons, resulting in gibbsite formation by relative enrichment of Al beneath a less weathered zone. The possible occurrence of erosional-depositional processes during the profile formation is an important question in the history of the lower

Amazon basin.

The purpose of this paper is to describe the alteration minerals and textures of sedimentary rocks in Central Amazonia, to infer the genetic sequence that has led to the present bauxites, and to discuss the pedogenetic and geochemical consequences of these results. We find that the entire profile is characteristic of an in situ geochemical differentiation. If erosional or depositional events have occurred in the past, sedimentological features and depositional facies have been completely erased or transformed by a subsequent geochemical evolution. Present-day evolution of the profile shows that gibbsite is currently precipitated in the zone of aeration, below a thick stable kaolinitic zone, which is at variance with most models of supergene weathering.

I. The studied areas

The studied bauxitic formations are located in the lower part of the Amazon basin (Fig. III.1), between the Guyana and the Brazilian shields. The Juruti area, south of the Amazon river (2°30'S and 56°14'E), and the Trombetas area, north of the Amazon river (1°27'S and 56°24'E)

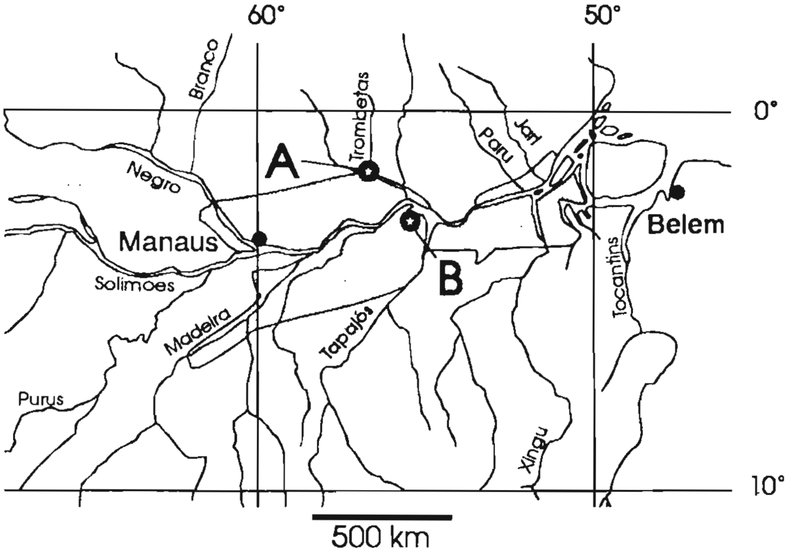

Figure III.1 - Location of the studied areas. A : Trombetas bauxitic area, B : Juruti bauxitic area. In gray, extent of the low plateaux landscape (data from Radam Brazil, 1978).

are amongst the major bauxite regions in the world (Bardossy, 1983).

The sediments beneath the bauxitic formation are composed of alternating clayey, silty and sandy layers of a weathered clastic sediment consisting of kaolinite, quartz and a small quantity of iron and titanium oxides. Although it lacks fossils, this sediment is related to the Cretaceous Alter-do-Chão Formation (Putzer, 1984).

The terrain forms gently undulating plateaus, 100 to 170 m above the level of the Amazon. This plateau landscape covers a great area north and south of the Amazon river (Fig. III.1), where most of the plateaus are not bauxitic, but covered by thick kaolinitic soils overlying the same Alter-do-Chão Formation (Chauvel et al., 1982; Lucas et al., 1986). No apparent geomorphologic features distinguish the bauxitic plateaus from the non-bauxitic ones. According to Radam Brasil (1978) or Klammer (1984), the plateaus are dissected remnants of a Plio-Pleistocene surface.

The present-day climate is equatorial, of Amazonian type, with a slight dry season and an average annual rainfall of 2100 mm. The average annual evapotranspiration is 1600 mm and the surface runoff on the plateaus is negligible (Franken & Leopoldo, 1988), so that only 500 mm percolates annually through the soil. The vegetation is a dense, humid, evergreen rain forest.

II. Analytical procedures

The macroscopic investigations were done in 5 to 25 m deep surveying shafts and road cuts (Juruti area) and on mine stope faces (Trombetas area). Color names are given from the Munsell Soil Color Chart (1954). Microscopic investigations were done by optical microscopy on thin section, and by Scanning Electron Microscopy (SEM) and Scanning Transmission Electron Microscopy (STEM) observations on suspensions and ultra-thin sections. Mineral constituents were identified and studied by X-rays diffractometry, thermogravimetric analysis and IR spectrometry on bulk samples or on microsamples collected by microdrilling of small volumes. Chemical analyses were done by atomic absorption spectrometry after strontium metaborat melting and by microprobe analyses on thin sections (Energy Dispersive Spectra). Porosimetry of the different facies was carried out by mercury pressure porosimetry (Fies, 1984). The pressure P, necessary to inject mercury in a given pore, is proportional to the inverse of the equivalent radius f(P) of the pore. Thus, volume of mercury injected in a sample between a P1 and P2 pressure indicates the volume of pores having and equivalent radius between f(P1) and f(P2). The porosimeter which was used is a Carlo Erba 2000, permitting measurement of pores volume between 3.75 nm and 100 µm.

III. Profile description and petrographical characteristics

A typical plateau profile consists of four main horizons which are described from the base to the top as follows (Fig. III.2). A facies is a characteristic association of authigenic texture and minerals; the different facies are identified in each horizon.

1. Mottled horizon

It consists of a white and pale red mottled kaolinitic clay, so called "mottled kaolinitic facies", organized into a polyhedral structure with platy structural voids. Transition from the underlying parent sediment is gradual: the sub-horizontal structure of the parent rock is cut by vertical fingers of the mottled kaolinitic facies, which upward anastomose with each other

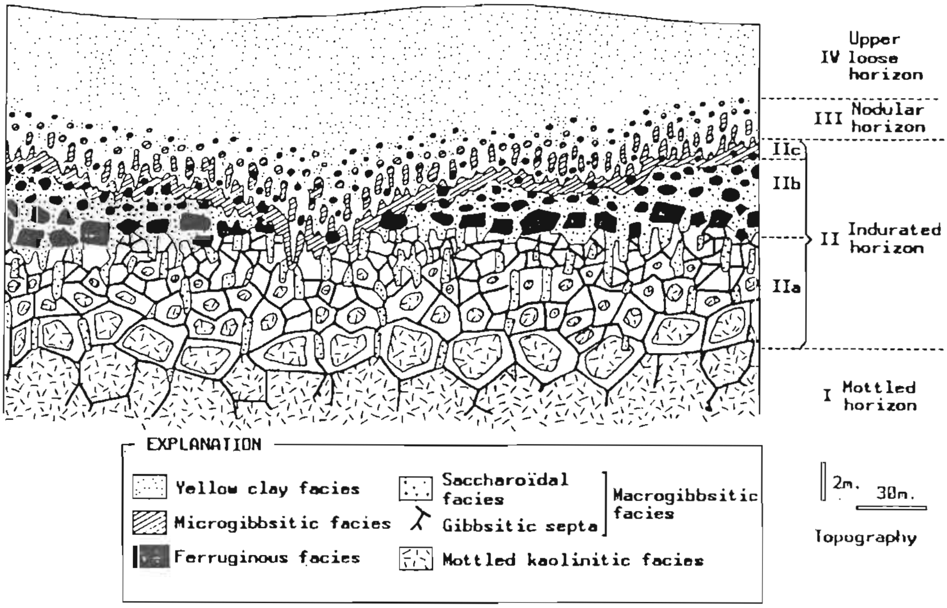

Figure III.2 - A typical plateau bauxitic profile of Juruti.

leading to a continuous kaolinitic horizon. The thickness of this horizon varies from 5 to more than 10 meters. In the upper 3 meters, 0.2 to 2 m thick septa interconnected in a broad network develop within the mottled clay. The septa are composed of palisadic coarse gibbsite crystals, which exhibit features of alteration and replacement by kaolinite at the contact with the mottled kaolinitic facies (Fig. III.3a).

2. Indurated horizon

This horizon can be divided in three sub-horizons characterized by their constitutive facies.

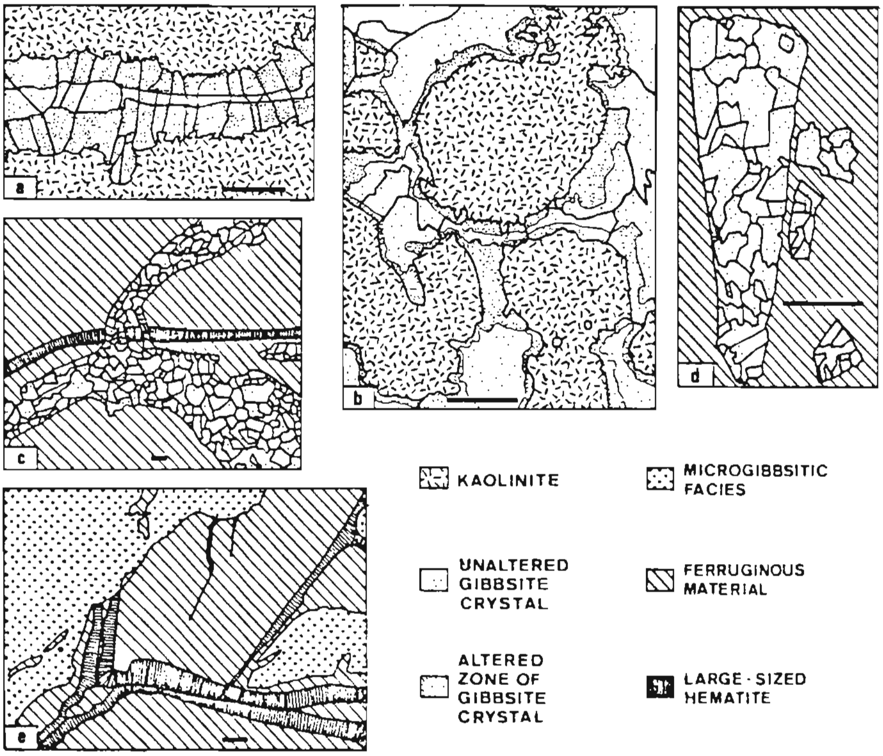

Figure III.3 - Microscopic features : (a) Gibbsitic septa; (b) Kaolinitic spherules in the saccharoidal facies, the spherules cut the fabric of coarse gibbsite crystals; (c) Saccharoidal facies cutting across the structure of the ferruginous facies; (d) In the ferruginous facies, cavity pseudomorphic of a quartz grain secondarily filled by gibbsite; (e) Microgibbsitic facies cutting across the structure of the ferruginous facies. Drawings after photographs of thin sections. Black bar in the lower part of each figure represent 0.1mm.

2a - With mottled kaolinitic and macro-gibbsitic facies. Ascending in the profile from horizon I, the gibbsitic septa become thicker and more abundant, giving a boxwork indurated structure. The mottled kaolinitic facies is reduced to rounded remnants in the core of the boxwork cells, the macroporosity (voids more than 0.1 mm) considerably increases. A "saccharoidal facies" appears and gradationally develops upwards. It is very indurated, white to pink colored, and forms centimetric to pluridecimetric vertical columns. It consists of a mosaic of coarse gibbsite crystals, whose fabric is dissected by tiny spherulae of kaolinite (Fig. III.3b). Both septa and saccharoidal facies consist, mainly, of coarse gibbsite crystals (1 to 20 μm), they are called "macrogibbsitic facies". Some large vertical tubular voids, where water, now, percolates actively, are coated by unaltered coarse crystals of gibbsite.

2b - With macrogibbsitic and ferruginous facies. In the middle part of the horizon II, the gibbsitic septa gradationally disappear as the saccharoidal facies becomes abundant and turns yellowish-red. A red-colored "ferruginous facies" is developed, forming numerous angular-shaped patches (average size 10-15 cm). In the upper part of the horizon II, the patches of ferruginous facies diminish in size to reach 1 to 3 cm of average diameter, and their shapes change, gradationally, from angular to rounded (Fig. III.4a). The ferruginous facies is, mainly, composed of hematite, kaolinite and gibbsite, with platy structural voids lined with coarse palisade hematite, and 0.1 to 3 mm cavities which exhibit an angular shape and internal hematitic septa. These cavities in the ferruginous facies are scarce in the lower part of the horizon and become numerous towards the top of the horizon. Their size, shape and septa are pseudomorphic after quartz grains and of their cracks, as those are observed in the sediment at depth. Many of these pseudomorphic cavities are secondarily filled by gibbsite macrocrystals (Fig. III.3d). The center of the larger pseudomorphic cavities is often occupied by a strongly corroded quartz grain. The association of both saccharoidal and ferruginous facies forms a very indurated breccia-like structure. On a microscopic scale, however, the saccharoidal facies clearly cuts across the structures of the ferruginous facies (Fig. III.3c).

2c - With microgibbsitic facies. The top of the horizon II is very irregular and interfingered with horizon III. It is sublimed by an indurated micro-horizon (1 to 30c m thick) which consists of a hard, compact, porcelaneous, yellow to pink facies. This facies is made up of a mosaic of small crystals of gibbsite (<1 μm), so it is called "micro-gibbsitic facies" (it is sometimes called "porcelaneous facies" in literature). The micro-gibbsitic facies obviously cuts across the structure of the macro-gibbsitic

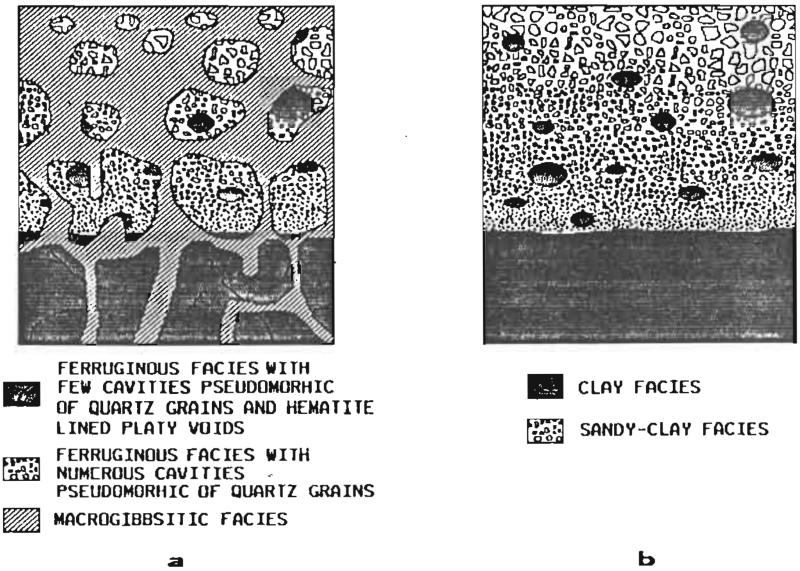

Figure III.4 - a: sketch of the vertical sequence of ferruginous facies in the upper part of the indurated horizon; b: reconstitution of the initial sediment structure.

facies as well to that of the ferruginous facies (Fig. III.3e).

3. Nodular horizon

The upper limit of the micro-gibbsitic facies horizon is irregularly penetrated by tongues of a yellow loose clay facies, so-called "yellow clay facies". This facies develops upward at the expense of the microgibbsitic facies; isolated vertically lengthened and contorted blocks and nodules of gibbsitic facies of gradationally smaller size are observed upwards through the horizon. Rounded small spots of ferruginous facies are observed in these nodules and blocks.

4. Upper loose kaolinitic horizon

This horizon, apparently greatly homogeneous, is composed mainly of the yellow clay facies, and by sparse micronodules (diameter<1 mm) of ferruginous or microgibbsitic facies. The structure is finely polyhedral, with rounded micro aggregates (ø < 0.1 mm) among the elementary polyhedrons. The yellow clay facies consists of kaolinite, closely associated with small gibbsite and goethite crystals (size<1 µm). On a microscopic scale, the transition with the microgibbsitic facies is deeply serrated, with microtongues of clay penetrating the hard facies, and it is characterized by relative variation of kaolinite, gibbsite and goethite content over 1 mm. The mode of the fine porosity of the yellow clay facies diminishes very gradationally upward, all along the horizon (Fig. III.5). As observed on STEM investigation, this fine porosity (10 to 50 nm) is directly linked to the average size of the kaolinite particles, this indicates a very progressive decrease of kaolinite particle size from the bottom to the top of the upper loose horizon. These results are in accordance with results from the upper loose horizon of north Manaus soils (Lucas et al., 1986), in which the very progressive decrease of the kaolinite particles size corresponds to a progressive decrease of their crystalline characteristics, as measured from infra-red spectrometry.

The above description refers to the more frequent vertical succession of facies. The horizons can however be divided in two groups, as sketched on Figure III.2.

* The first group shows the following vertical succession:

- the mottled kaolinitic facies at the base of the profile (horizon I);
- the macrogibbsitic facies, as septa at the lower part of the indurated horizon (sub-horizon IIa), and as continuous saccharoidal matrix at the upper part of the indurated horizon;
- the ferruginous facies, as patches which vary in size and shape from the base to the top (sub-horizon IIb);

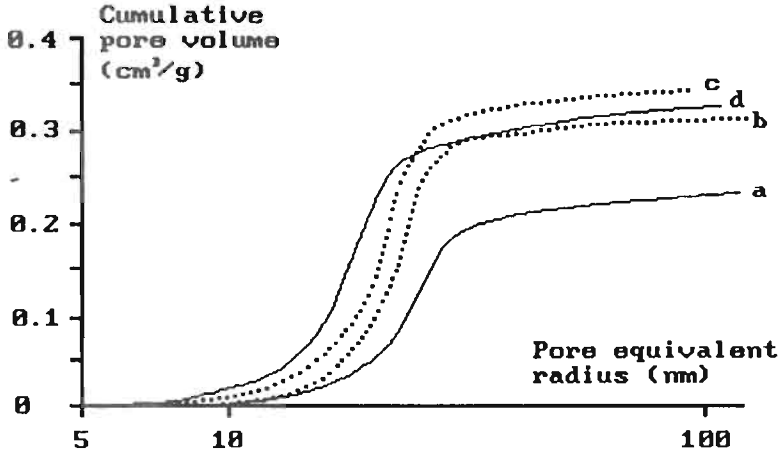

Figure III.5 - Fine porosity of the yellow clay facies along the upper kaolinitic loose horizon. Measurement by mercury pressure porosimetry. Depth of samples - (a) 9 m, (b) 7.5 m, (c) 5 m, (d) 2 m.

* The second group cuts across the former succession:

- the microgibbsitic facies, as a micro-horizon (sub-horizon IIc) at the top of the indurated horizon, and as blocks and nodules in the nodular horizon (horizon III);
- the yellow clay facies which constitutes the upper loose horizon (horizon IV)

IV. Water circulation in the profile

Plateau profiles are entirely situated high above the water-table level, in the zone of aeration. Field observation and measurement of moisture content in the upper loose horizon (Chauvel & Lucas, 1988) reveal that water percolates slowly and steadily in the upper loose horizon. The roots uptake in the top meter of the profile is sufficient to buffer the free water (water with pressure potential > atmospheric pressure) which appears in the topsoil after the rains, even in very rainy season. Deeper, water percolates mainly as capillary water (water with pressure potential < atmospheric pressure). Rosanski et al. (1991) give 2 m. within 139 days as the downward movement of the soil moisture in the same upper loose horizons from Manaus area. Extrapolation of this result gives more than 1,5 year for water percolating through an average 8 meters thick upper loose horizon. Free water reappears at the base of the upper loose horizon, even at the end of the dry season, then percolates downwards as laminar films in the coarse voids of the indurated horizon.

V. Chemical and mineralogical composition

Chemical and mineralogical compositions of the main facies are given in Table III.1. Absolute values of the composition may change from a profile to another, but relative abundance of the different elements and minerals varies in the same way along all the profiles. Compositions of the mottled kaolinitic facies and the microgibbsitic facies are slightly variable; compositions of the macrogibbsitic facies and the ferruginous facies are highly variable, according to their microscopic heterogeneity; the yellow clay facies exhibits a very progressive diminution of gibbsite content from 10-12% in depth to less than 5% near the topsoil. The sediment now observed at depth in Juruti area were studied from a drilling penetrating 20 m below the bauxitic profile. Analysis of 20 samples (a sample each meter) gives an average composition of the

Table III.1 - Chemical and calculated mineralogical composition of the different facies. Normative values in % weight. avg. = average, std = standard deviation.

Type of facies		Chemical composition				Mineralogical composition					Aluminium substitution in Fe oxydes (molar %)	
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Kaolinite	Gibbsite	Iron as Fe_2O_3	Quartz	Anatase		
Yellow clay (1 m. above indurated facies, 10 analyses)	avg	47,5	41,9	7,7	2,9	78,0	8,5	6,2	4,8	2,5	Goethite Hematite	30 9
	std	0,8	1,1	0,2	0,4							
Microgibbsitic (22 analyses)	avg	5,6	86,5	5,1	2,8	8,4	86,2	3,5	0	1,9		
	std	3,0	3,8	1,9	2,2							
Ferruginous (examples)		3,5	4,1	90,5	1,8	2,2	0,4	93,1	2,4	1,8	Hematite	3
		10,5	26,4	62,3	0,8	20,3	22,9	56,1	0	0,7		
		18,1	25,6	54,7	1,7	35,6	10,9	51,9	0	1,5	Hematite	5
		27,9	24,2	46,8	1,1	55,5	0,3	43,2	0	1,0		
Macrogibbsitic (examples)		3,1	89,6	5,9	1,5	4,5	90,5	4,0	0	1,0		
		15,6	65,0	16,4	3,0	25,5	59,9	12,4	0	2,2	Hematite	4
		26,6	70,1	1,9	1,3	43,1	54,9	1,1	0	1,0		
White kaolinite (13 analyses)	avg	51,4	44,5	1,7	2,3	95,5	1,9	0,6	0	2,0	Hematite	1
	std	0,6	0,9	0,4	1							
Pale red kaolinite (13 analyses)	avg	47,7	43,6	5,4	3,4	88,5	4,7	3,9	0	2,9		
	std	2,4	1,9	2,5	0,7							

sediment at 51% kaolinite, 43% quartz sand and 6% others, but the composition of the sediment is quite variable from one sample to the other, the kaolinite content ranging from 20 to 76%, and the heavy minerals content from 0.2 to 5%. The heavy minerals observed along the profile are mainly zircon and Fe-Ti oxides (ilmenite, rutile, anatase). A weathering sequence of the Fe-Ti oxides grains is observed from the base to the top of the profile, characterized by the progressive diminution of the grain size, the increase of the grain porosity, the diminution of their ilmenite content and the increase of their rutile and anatase content.

VI. Discussion

As described above, the bauxitic profile is formed by four main horizons, each one being characterized by the nature and fabric of various interpenetrated facies. Cross-cutting relations between the facies, geometry of the facies boundaries and vertical variation of facies textures give information about the facies genesis and the profile formation.

1. Genetic relationships between facies

Deeply contorted and interpenetrated boundaries between facies are inconsistent with allogenic hypotheses, and indicate an authigenic origin of the facies, which have geochemically replaced each other in situ. The direction of the replacement is given by the cross-cutting relationships on a microscopic scale. The following relationships are thus assessed from petrographical data:

* the macrogibbsitic facies has replaced in situ the ferruginous facies;

* the microgibbsitic facies has replaced in situ the macrogibbsitic facies and the ferruginous facies;

* the yellow clay facies has replaced in situ the microgibbsitic facies.

Regarding the ferruginous facies, the progressive vertical sequence of size, shape and texture of the ferruginous patches included in the gibbsitic indurated material is another evidence against a clastic origin of the patches (Fig. III.4a). Thus, we infer that they are the relic of a former continuous ferruginous horizon, which have been partially dissolved and replaced in situ by the macrogibbsitic and microgibbsitic facies. Reconstitution of the vertical sequence of quartz repartition in the parent material before ferruginisation and gibbsitisation is sketched on Figure III.4b. Such a repartition of quartz grains is frequently observed in the Alter-do-Chão sediment. This suggests that the vertical variation in the ferruginous facies texture is originated from an heterogeneous parent material, which was formed by a clay material buried by a sandier layer. The hematitic impregnation of the clay material has given a ferruginous facies with hematite-lined platy voids, which are relics of the structural clefts in the clay. The hematitic impregnation of the sandier layer has lined the quartz grains by hematite; the later dissolution of quartz grains has left pseudomorphic cavities, a few of which containing a corroded relictual quartz grain.

Regarding the macrogibbsitic facies, the network of septa and the palisade crystalline fabric of the septa suggests a genesis by progressive growth in the structural clefts of a clay material. All of the septa and saccharoidal facies at depth, however, exhibit microscopic features of dissolution and replacement by a kaolinitic material; thus, they are relics of a former process. Septa and vertical columns of saccharoidal facies have been formed at the expense of a clayey parent material, and afterwards have suffered dissolution processes. Only scarce gibbsite macrocrystals without features of corrosion are observed at depth, coating large voids where water now percolates. This means that genesis of gibbsite macrocrystals occurs nowadays at depth, but is limited to active water percolation zones.

These genetic relationships give the following temporal succession of the facies: (1) ferruginous facies; (2) macrogibbsitic facies; (3) micro-gibbsitic facies; (4) yellow clay facies. This temporal succession is in accordance with the cutting relationships observed at the plateau scale

(Fig. III.2). The consequences of these relationships on the profile genesis will now be examined.

2. Profile Genesis

The genesis of old, deeply weathered profiles may combine erosional processes, depositional processes by water or wind, and in situ geochemical processes.

Most models of in situ profile genesis are based on the premise of downward advance of transformation fronts, each horizon having been derived from material similar to that now underlying it (Nahon, 1976; Millot, 1983); the vertical succession of horizons or facies can, thus, be considered to represent a time sequence (Butt & Nickel, 1981).

In the present profile, three main transitions have a fingered, deeply serrated geometry, which is characteristic of geochemical transformation fronts and discards the hypothesis of a sedimentological unconformity.

- At depth, the transition between the sediment and the mottled horizon (I) corresponds to the dissolution of quartz grains in a kaolinitic matrix. This is in accordance with results from Irion (1984), Lucas et al. (1984) or Lucas (1989), who studied genesis of kaolinitic soils formed from the same sediment in the same geographical area.
- At the upper part of the indurated horizon, the transition between the microgibbsitic horizon (IIc) and the underlying indurated horizon indicates the replacement of a highly heterogeneous material by an homogeneous, gibbsitic material.
- Immediately above, the transitions between the microgibbsitic horizon (IIc), the nodular horizon (III) and the upper loose horizon (IV) indicates the replacement of the indurated microgibbsitic facies by the loose yellow clay facies. More, the vertically lengthening of the blocks and nodules is also inconsistent with a depositional origin: the nodular horizon does not correspond to a detrital stone-line, but to a chemically formed stone-line (Lucas et al., 1990). Block and nodules in the nodular horizon are relics progressively dissolved as the front proceeds down.

Regarding the indurated horizon (II), it is assessed above that its constitutive facies have formed in situ by authigenic geochemical processes; allochtonous processes during their differentiation must be discarded. There is, however, a discrepancy between the vertical succession of facies (or sub-horizons), and the temporal succession of facies assessed from microscopic data. More, the structure of the ferruginous facies in horizon IIb is inherited from the sediment structure, when this sediment structure has disappeared in the underlying horizon. Thus, IIb horizon cannot derive from the horizon now underlying it, and the ferruginous facies is a relic of a former paragenesis. In the same way, it is assessed above that the macrogibbsitic facies is now being replaced by a kaolinitic material, and is a relic of a former paragenesis. The conclusion is that the vertical succession of facies in the indurated horizon cannot be considered as a time sequence; the limits between I, IIa and IIb horizons are not presently active transformation fronts, but are relics of past processes.

Regarding the upper loose horizon, the idea of a clastic clay deposition on top of an old bauxitic profile, which gave rise to the "Belterra Clay" stratigraphic name, was supported in the literature by the following arguments: (1) the ferruginous patches and the nodules found on top of the cemented horizons indicate a detrital stone-line; (2) the upper loose horizon, greatly homogeneous, overlies bauxitic as well as non-bauxitic horizons on a large geographic extent, which indicates a widespread sedimentary process.

The first argument may be discarded in view of the present petrographic data discussed above. Regarding the second argument, the homogeneity of the upper loose horizon is only apparent. On the contrary, its chemical and mineralogical composition change vertically very gradationally. This has also been observed for the upper loose horizon of non-bauxitic plateau soils (Lucas et al., 1984, 1986). Furthermore, studies from Irion (1984) establish, in various sites, the lithodependence of the "Belterra Clay" with the underlying parent material. The conclusions are (1) that the possibility of an old depositional event is restricted to the upper loose horizon; (2) if erosional or depositional events have occurred in the past, sedimentological features and depositional facies have been completely erased or transformed by subsequent geochemical evolution.

These conclusions imply necessary events during the profile genesis, which are explained on Figure III.6. These events are necessary in view of the petrographic data, but other events may have occurred which cannot be deduced from the petrographic analysis.

(1) The first event identified is a ferruginous impregnation of the parent sediment, giving a ferricrete. The ferruginous facies is a relic of this ferricrete. The ferruginous textural sequence (Fig. III.4) is likely due to an initial heterogeneity of the sediment. According to the available data, it is not possible to conclude whether this ferruginisation have occurred in depth or near topsoil.

(2) The second event identified is the formation of macrogibbsitic

facies, which has partly replaced the ferruginous facies. This process has been more intense in the upper part of the indurated horizon, leading to massive bauxite. In the lower part of the indurated horizon, septa were likely formed in the structural clefts of a clayey material. Most of the quartz grains were dissolved, quartz/kaolinite ratio of the parent material is, however, undetermined. Under present-day climate, the strong dissolution of quartz grains in saprolite is broadly observed in the area (Lucas et al., 1984). The problem of the origin of the upper loose horizon remains. Whether the profile has formed entirely in situ, and bauxite formation has occurred at depth, leaving in the topsoil a stock of silica sufficient to form, afterwards, the upper loose horizon; or depositional processes have occurred since the bauxitisation, being, afterwards, morphologically erased, but contributing to the presence of a silicic horizon above bauxitic horizons.

(3) The third event is the current evolution of the profile. On the top of the indurated horizon, intense resilicification is due to the downward geochemical progression of the yellow clay, preceded by a transient microgibbsitic facies. Gibbsitic and hematitic nodules in the upper yellow clay are relicts left behind as the yellow clay formation front progresses downwards. In the middle part of the indurated horizon, dissolution of the macrogibbsites gives large voids which cut the facies structure. At the base of the indurated horizon, moderate resilicification is brought about by the replacement of the macro-crystalline gibbsite by a kaolinitic matrix. Locally, the precipitation of macrogibbsite continues as coatings on large active voids.

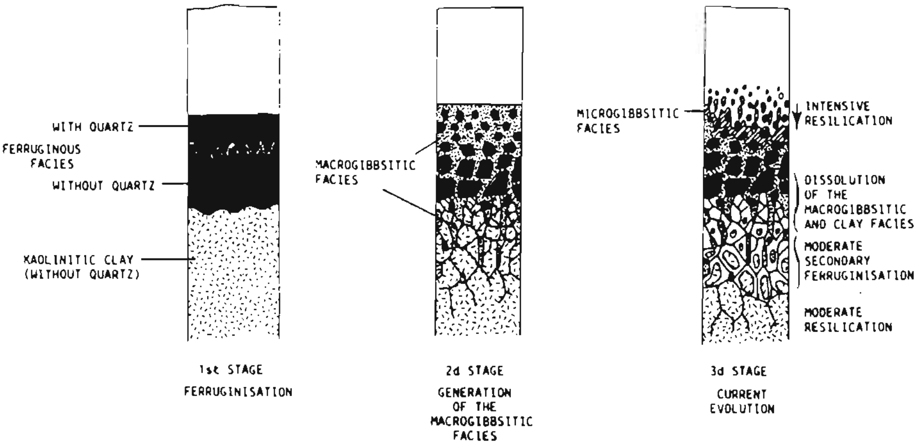

Figure III.6 - Successive stages of the bauxite profile genesis.

3. Geochemical outcomes of the profile current evolution

The current evolution of the profile is sketched on Figure III.7. Gibbsite is currently precipitated as microgibbsitic facies at the base of the upper loose horizon, and as macrocrystalline coatings at depth. The detailed observation of the base of the upper loose horizon shows two successive fronts which follow each other closely: a front of microgibbsitic facies generation, and a front of yellow kaolinitic facies generation. This means that gibbsite is currently precipitated some centimeters beneath an horizon, where kaolinite is currently precipitated: the new profile which develops at the expense of a bauxitic paleoprofile is characterized by the formation of a gibbsitic horizon beneath a thick, stable kaolinitic horizon. In other words, the profile structure characterized by a kaolinitic horizon overlying a gibbsitic horizon is in equilibrium in the climatic zone.

These facts have broad geochemical and pedogenetic consequences, because this general structure of profile is widely observed in the climatic zone, on very ancient soils as well as on younger soils (Leneuf, 1959; Delvigne, 1965; Siefferman, 1969; Boulet et al., 1978; Chauvel et al., 1982; Muller, 1988; Tardy & Novikoff, 1988; Bitom, 1988). Most soils not having undergone hydromorphic and podzolic processes are

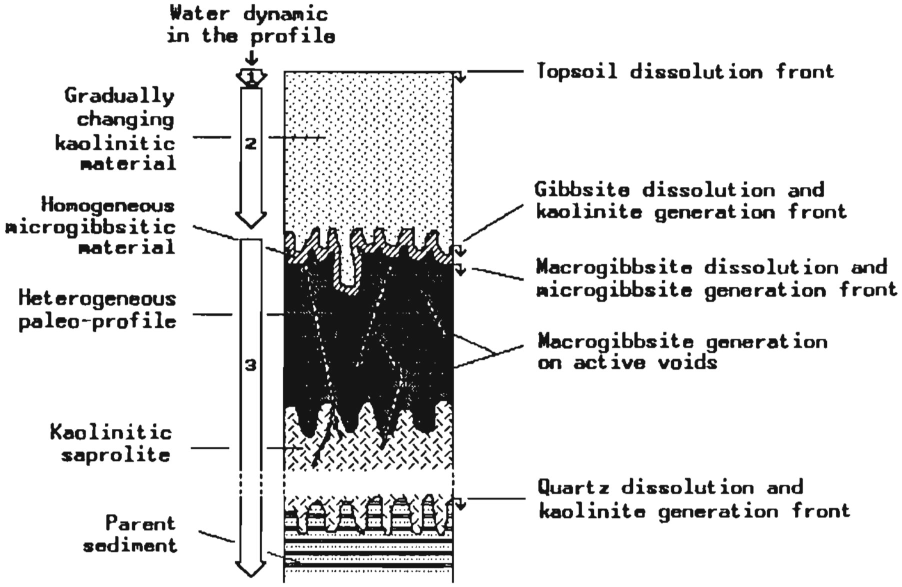

Figure III.7 - Sketch of the current evolution of the profile.

characterized by the accumulation of gibbsite beneath a stable upper kaolinitic horizon. Gibbsite accumulates in the saprolite, or in an intermediate horizon between the saprolite and the upper kaolinitic horizon. Because the gibbsite accumulation in the intermediate horizon often occurs as gibbsitic or gibbsito-hematitic nodules, these horizons have often been considered as detrital stone-lines buried by kaolinitic material itself also interpreted by others as allochtonous. This interpretation was widely accepted in the 50-60s. Since this time, numerous studies have pointed out that most of the upper loose horizon are strictly lithodependent and that most of the stone-lines were formed in-situ (Laporte, 1962; Collinet, 1969; Colin & Lecomte, 1986; Lecomte, 1988; Lucas et al., 1990), bringing up the problem of their genesis. The results from the present study establish that this type of profile is a steady state geochemically in equilibrium in the climatic zone, which questions most of geochemical models for weathering and soil formation: how can gibbsite precipitates beneath a thick, stable kaolinitic horizon, and why is the upper kaolinitic horizon stable?

In models based on relative rates of water flow and reaction (Brown & Garrels, 1980), as proposed by Kronberg et al. (1982), water flows through the upper kaolinitic horizon at a rate much faster than the rate of mineral-water reactions, then is focused in an aquiferous gibbsitic zone. This hypothesis cannot be applied to the present profile, because (1) gibbsite precipitation occurs far above the groundwater level; (2) kaolinite precipitation occurs above the gibbsite precipitation zone; (3) water percolates slowly and steadily in the upper loose horizon (Fig. III.7).

Most of the models of soil formation are based on equilibrium thermodynamics of mineral assemblages (Fritz & Tardy, 1973; Fritz, 1975; Lasaga, 1984; Ambrosi, 1990): the percolating water reaches an equilibrium with mineral species at each level of the profile. In the studied soil, the solution which has percolated the upper kaolinitic horizon are in equilibrium with kaolinite, which is assessed by kaolinite generation at the base of this horizon. To generate gibbsite immediately underneath, some parameters of the equilibrium have to change. Tardy et al. (1988) explain the presence of gibbsite beneath kaolinitic horizon by seasonal fluctuation of the water activity (aw) along the profile, due to water uptake by roots. In the studied profile, there is actually a change of the physical state of the water at the front between the upper loose horizon and the microgibbsitic horizon. Above the front, water percolates as a capillary water which is at a negative pressure potential (positive suction), which means aw<1 (Bourrie et al., 1983). Beneath the front, water percolates as free water, at a zero pressure potential, which means aw=1. Values of aw in the upper loose horizon are, however, always close to 1. Even considering that, during exceptionally dry periods, soil suction can reach 15 bars, which is the limit for roots water uptake, maximum change of aw at the transformation front would be from 0.989 to 1.

$$(1)\ 0.5Al_2Si_2O_5(OH)_4 + 0.5H_2O <=> SiO_{2(aq)} + Al(OH)_3$$
$$\log[SiO_{2(aq)}] - 0.5 \log(aw) = \log(K)$$

K: equilibrium constant of the reaction
aw = $[H_2O]$: water activity

Considering the equation (1), such change of aw corresponds to a change of +0.0024 for $\log[SiO_{2(aq)}]$, i.e. a +0.55% shift of $[SiO_{2(aq)}]$ at the equilibrium gibbsite-kaolinite. Though the direction of the resulting equilibrium shift agrees with the petrographic observations, this change seems actually very small.

Studying the soil solution in weathering ferrallitic systems from the same climatic zone (French Guyana), Grimaldi (1987, 1988) has established a differential behavior for Al and Si in the soil solution: Al concentration is the higher in the topsoil, and progressively decreases with increasing water time residence in the soil, that is as the water percolates in the soil; but Si concentration increases with time residence. This means that Al and Si are released in the topsoil, and that Al is controlled in depth by a mineral likely to be gibbsite, as Si is preferentially leached out of the system, and questions the presence of organic Al^{3+} chelates migrating through the upper kaolinitic horizon. In agreement with this results, Chauvel et al. (1989) show that significant quantities of Al, Si are released by dissolution of the soil material in the topsoil, due to microbiological activity under native Amazonian forest.

The conclusion is that the present geochemical dynamics of the weathering cover is in agreement with results from petrographical observations: the profiles characterized by a kaolinitic upper horizon above more gibbsitic horizons are in equilibrium with present climate of the equatorial zone. Geochemical modeling of these soils has to take into consideration biological activity in the topsoil and to identify the chemical state of the mobile Al.

4. The Problem of the Upper Loose Kaolinitic Horizon

From the results exposed above, the presence of the upper loose horizon can be explained only by geochemical processes, without the need of an allochtonous deposit of siliceous material on top of the profile. In this hypothesis, the source of silica for current resilicification is due to a stock of silica which has ever existed in the upper part of the profile.

Although the upper loose horizon has petrographical features indicating that it is mainly the result of a geochemical evolution, and although no trace of sediment deposits was identified by the methods used in this study, it is impossible to completely discard past allochtonous events. Such events would have contributed to the maintenance of the silica stock over the bauxitic horizons. Amongst the possible events, deposition of aeolian dust is one of the more acceptable because of the broad extent of the thick upper kaolinitic horizon in lower Amazonia and because the nature of the deposit allows its progressive incorporation in the upper horizon, by biological processes (bioturbation) as by geochemical processes (dissolution of quartz grains).

To the moment, no data from paleoclimate studies allows to identify such a dust source on the Amazonian or peri-amazonian area. Paleoclimates reconstitution from the tertiary and most of the quaternary are mainly speculative in the Amazonian zone (Irion, 1989). It is assessed that climatic variations in the past 60000 years have lead to local replacement of forest by savannah (Absy et al., 1991), but these data do not permit to conclude about the presence of a dust source, as it presently exists in Australia (Brimhall et al., 1987) or Africa (Orange et al., 1990). Saharan dust, having crossed the Atlantic, is a very likely source in view of recent studies about aerosols in the Amazon basin (Artaxo et al., 1990; Talbot et al., 1990; Swap et al., 1991). It is assessed that Saharan dust reach the Amazonian atmosphere, but estimation from these studies gives a low Si and Al input with regard to chemical erosion.

The stability of the kaolinite in the upper loose horizon is better explained by biological activity. Quantitative measurement of chemical elements in the litterfall of an Amazonian ecosystem indicates that the forest cycles a significant amount of elements, particularly silicon. As a result fluids that percolate through the upper part of the soil already contain dissolved silicon. This process keeps silica from being leached down, and may account for the stability of kaolinite in the upper loose layer (Lucas et al., 1993, 1996).

5. Simulation of the Profile Evolution

Most of the plateaus from the lower Amazon area, situated in the same geomorphological and climatic area and developed over the same sedimentary formation, are not bauxitic but covered by thick kaolinitic soils. The determinism of this difference in evolution may be suggested by simulating the profile evolution.

The Alter-do-Chão sediment has little mineral species variability, but the relative abundance of the different minerals may greatly change from a layer to the other: the kaolinite content ranges from 10 to 95%, and the heavy mineral content from 0.2 to more than 5%. The consecutive uncertainty on the parent material composition with regard to a chemically immobile element (as Zr or Ti) turns impossible the determination of strain and translocation of the constitutive elements in the profile by the well-known and widely used mass-balance calculations (Millot et Bonifas, 1955; Leneuf, 1959; Lelong, 1967; Hervieu, 1968; Trescases, 1975; Nahon & Lappartient 1977; Brimhall et al., 1985). It is however possible to calculate, in the hypothesis of an in-situ formation and for various composition of the parent material, minimum values for the thickness of parent material which has been weathered to form the profile. In the hypothesis of weathering conditions identical to current ones, it is possible to calculate the thickness of sediment weathered, the general strain and the time of genesis to form a profile having the same Al/Si ratio than the studied profile. Volume composition of the different horizons of the average present profiles were calculated from bulk densities and ponderal composition. The minimal thickness, which have been weathered to produce the average present profiles, was calculated comparing the Al, Si, Fe and Ti volume contents of the profiles with those of the parent material. The current rates of the geochemical evolution were calculated from the volume and the composition of the waters presently leached out of the system. From these rates, there were calculated the time of genesis, the thickness of parent material and the lowering of the soil surface required for forming, under same weathering conditions, profiles having the same Al/Si ratio than the present profiles. Such calculations do not present any difficulties, they are described with values of parameters in the Appendix.

Calculations were done considering various average compositions of the parent material, from 20 to 70% kaolinite, for an average bauxitic profile and an average kaolinitic profile from non-bauxitic plateaus situated at the north of Manaus. These soils consist of an upper loose kaolinitic yellow clay horizon, a middle horizon with gibbsite and hematite nodules embedded in a kaolinitic matrix, and a lower kaolinitic saprolite (Lucas et al., 1986).

Results are given in Table III.2. The given time of genesis do not

Table III.2 - Rates of evolution of average profiles: results in sublimed characters for an average bauxitic profile, in normal character for an average bauxitic profile.

Mineralogical composition of the protolith	Kaolinite % Quartz % Others % (Fe2O3-TiO2)	20 74 6	30 64 6	40 54 6	50 44 6	60 34 6	70 24 6
Whatever the conditions	Minimal thickness of sediment weathered (m)	58 139	40 95	31 73	25 60	22 52	19 46
Under current weathering conditions	Thickness of sediment weathered (m)	169 419	63 157	40 99	30 73	24 59	20 50
	Lowering of the soil surface (m)	154 393	48 131	25 73	15 47	9 33	5 24
	Time of genesis (million years)	96 243	30 79	15 42	8 26	5 17	2 11

pretend to determine the age of bauxitic or kaolinitic soils: weathering conditions may have been greatly different during profile formation, due to climate changes (Berner et al., 1983) or to change in water dynamics in the profile. This approach is a simulation with the aim to compare bauxitic and kaolinitic soils. The rates of the profiles evolution vary greatly, in a 1/3 or 1/4 ratio, as the initial composition of the parent material varies from 30 to 60% kaolinite. The time of genesis and the surface lowering required to form a kaolinitic profile, from a 30 to 40% kaolinite sediment, vary respectively from 15 to 30 m.y. and from 25 to 48 m. These values are close to the values required to form a bauxitic profile from a 50 to 60% kaolinite sediment, which are respectively 17 to 26 m.y. and 33 to 47 m. These results support the hypothesis by which kaolinitic as well as bauxitic plateaus have suffered the same weathering conditions, the difference in evolution being due to an initial difference in kaolinitic content of the parent material. The average kaolinite content, presently observed, is around 51% beneath the Juruti bauxite (analysis of 20 m of sediment), but such value has little meaning, because the present profiles have formed at the expense of a parent material which may have been different.

Conclusions

The entire profile of the studied Amazonian bauxitic formations is characteristic of an in situ geochemical differentiation. Erosional or depositional events may have occurred in the past, but sedimentological features and depositional facies have been completely erased or transformed by a subsequent geochemical evolution: the upper loose kaolinitic horizon ("Belterra Clay") is a pedogenic material.

The succession in time of the different parageneses observed on the profile indicates three main weathering episodes.

(1) The oldest is a ferruginisation of the sediment, giving a lithorelictual ferricrete. Relicts of such a lithorelictual ferricrete were broadly observed in soils from the Amazonian area (Melfi et al., 1988; Tardy et al., 1988; Nahon et al., 1989), suggesting that this episode probably belongs to an old, generalized, intense lateritic episode, which has transformed weakly weathered parent materials.

(2) The second episode is a bauxitisation by precipitation of a macrocrystalline gibbsite facies, which has partly replaced the ferricrete and has formed massive bauxite horizons. Simulation of the profile evolution under current weathering conditions suggests that the differential evolution between bauxitic and non-bauxitic plateaus from the same geomorphologic area is due to an initial difference in kaolinite content of the parent material: bauxitic soils has been formed where the kaolinite content of the sediment was over 40-50%; elsewhere kaolinitic soils has been formed.

(3) The last episode is the current evolution of the profile. A new profile develops at the expense of the old bauxitic profile. On the top of the indurated horizon, intense resilicification is due to the downward geochemical progression of a kaolinitic clay. Gibbsitic and hematitic nodules forming a nodular horizon are relicts left behind as the kaolinitic clay formation front progresses downwards. Beneath the upper kaolinitic clay horizon, a thin gibbsitic horizon is characterized by the precipitation of a microgibbsitic facies. In the middle part of the indurated horizon, dissolution of the bauxite gives large voids which cut the facies structure. At the base of the indurated horizon, moderate resilicification is brought about by the replacement of the macrocrystalline gibbsite by a kaolinitic matrix. Locally, the precipitation of macrogibbsite continues as coatings on large active voids.

The present-day evolution of the profile demonstrates that gibbsite is currently precipitating in the unsaturated zone, beneath horizons where kaolinite is currently precipitating and stable. Consequences lie far beyond bauxite genesis, because such a striking spatial relation was identified in many soil profiles developed in humid tropical areas, in which gibbsite accumulates in the saprolite or as nodules at the limit between the saprolite and a stable upper kaolinitic horizon. This prevalent structure of the profile is in dynamic equilibrium with the climate, a conclusion opposite to most models of soil genesis. Geochemical modeling of these soils has to take into consideration biological activity in the topsoil, Si and Al migration through the upper kaolinitic horizon, and to identify the chemical state of the mobile Al.

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Appendix

Simulation of the Profile Evolution

Parameters

Weathering profile:

Lp	Thickness
Pa	Al_2O_3 content/surface unit ^{o}
Ps	SiO_2 content/surface unit ^{o}
Pf	Fe_2O_3 content/surface unit ^{o}
Pt	TiO_2 content/surface unit ^{o}

Calculated from each horizon bulk density and chemical composition

Sediment:

Sa	Al_2O_3 content/volume unit
Ss	SiO_2 content/volume unit
Sf	Fe_2O_3 content/volume unit
St	TiO_2 content/volume unit

Water leached out off the system:

Vw	Volume of water/ surface unit/year
Ca	Al_2O_3 concentration
Cs	SiO_2 concentration

Equations

Local parameters:
Wa = Vw.Ca Weight of Al2O3 annually leached / surface unit
Ws = Vw.Cs Weight of SiO2 annually leached / surface unit

* Minimal thickness of sediment necessarily weathered to form the present profile, whatever the weathering conditions (Tmin):

$$\text{Tmin} = \max(\text{Pa/Sa, Ps/Ss, Pf/Sf, Pt/St})$$

* Under present weathering conditions, rates of evolution to form a profile with the same Al/Si ratio:

- Thickness of annually weathered sediment (Ts):

(Ts.Sa-Wa)/(Ts.Ss-Ws) = Pa/Ps; then:

Ts = (Wa.Ps-Pa.Ws)/(Sa.Ps-Pa.Ss)

- Thickness of profile annually formed (Tp):

Tp.Pa=Ts.Sa-Wa then Tp = (Ts.Sa-Wa)/Pa; and replacing Ts:

Tp = (Wa.Ss-Sa.Ws)/(Sa.Ps-Pa.Ss)

- Time for the profile genesis (Tim):

Tim = Lp/Tp

- Thickness of sediment weathered to form the profile (Tsed):

Tsed = Tim.Ts

- Lowering of the soil surface during the profile genesis (Lss):

Lss = Tim(Ts-Tp)

Parameters used for calculation:

* Average bauxitic profile (calculated from 16 profile):

	Thickness	Bulk	Chemical composition (%)			
	(m)	density	Al_2O_3	SiO_2	Fe_2O_3	SiO_2
Upper loose horizon	7,0	1,4	42,4	46,2	8,3	3,1
Indurated horizon	3,9	1,6	55,9	55,9	23,9	2,8
Lower kaolinitic horizon	15,0	1,4	49,6	49,6	3,6	2,9
Oxyde content (t/m^2) (Oxyde weight for a column of $1m^2$ section)			18,0	14,9	3,0	1,1

* Average nodular lateritic profile (from Lucas, 1989):
Oxide content: 7,6 t/m2 Al_2O_3; 11,1 t/m^2 SiO_2; thickness of the profile 15m.

* Composition of the sediment:
SiO_2 and Al_2O_3 vary with the kaolinitic content of the sediment.
Average Fe_2O_3 content: 4,3%
Average TiO_2 content: 1,8%

* Elements leached out of the system:

Hydrological data (from Franken and Leopoldo, 1984):
Annual precipitation: 2100mm
Annual transpiration: 1600mm

Chemical data (from C. Grimaldi, 1987 and K. Furch, 1984; discussed in Lucas, 1989):
Average composition of the rain water: Al 10 µg/l; Si negligible
Average composition of the leached water: Al 120 µg/l; Si 2,1mg/l.

From these data, estimation of the elements annually leached out of the system, in oxide weight:

SiO_2: 2,3 10-6 t/m^2/an; Al_2O_3: 0,15 10-6 t/m^2/an.

Chapter IV

THE BAUXITE OF CARAJÁS MINERAL PROVINCE

M.L. Costa, V.P. Lemos, R.N.N. Villas

Introduction

The Bauxite Discovery

The Serra dos Carajás Bauxite Ore Deposit, located in the N5 plateau, was discovered in 1974 by Amazônia Mineração S/A (AMZA), as a consequence of intense geological research in this region, after the discovery of its large iron ore reserves and implantation of the Carajás metallurgic-mining program. The reserves were evaluated and delimited by DOCEGEO, a subsidiary of Vale do Rio Doce Company (CVRD), from 1979 to 1983.

Initial interest was given to this bauxite because of its cover-free occurrence - the major problem of the great Amazon bauxites deposits - low contents in reactive silica and its nearness, at that time, to the future railroad Carajás (EFC), as part of "Grande Carajás Program". Therefore, following researches have shown that reserves were small, of metallurgic quality and with high content of organic carbon. Nearly twenty years have been passed since the bauxite discovery and the Carajás Program is already a reality, while the mining of N5 bauxite is still in the paper.

Researches

Preliminary investigations have shown that Carajás bauxite is quite different from other bauxites in Amazon region: the latter were derived from sedimentary rocks, while the first from basic rocks. After mineralogical and geochemical studies of several lateritic profiles from N5 and N4 plateaus, Lemos (1982) and Lemos & Villas (1983) concluded that N5 bauxites were formed from basic paleovolcanic rocks from Grão-Pará Group. The genetical relationship between N4 profiles (directly over mafic volcanics) and N5 profiles (without reaching fresh rock) was demonstrated by geochemical and mineralogical similarities between both profiles.

Subsequent researches from Kotschoubey & Lemos (1985) and Kotschoubey et al. (1989) agreed that the lateritic profile under the bauxite was formed over basic volcanic rocks. After these authors, the bauxite deposit derived from sedimentary covers that overlaid those profiles, as Belterra Clay cover of Amazon bauxites, studied by Kotschoubey & Truckenbrodt (1981) & Kotschoubey (1984). These conclusions contradict the mineralogical and geochemical data from Lemos (1982) and Lemos & Villas (1983), practically the unique existent, which will be presented and discussed in this paper in the light of actual geochemical knowledge about lateritic bauxite.

Presently, several bauxite occurrences are well-known in Carajás, with different textures and chemical-mineralogical compositions, outcropping from N1 to N5, and mentioned by Kotschoubey et al.(1989).

I. Regional aspects

1. Geographical situation

The Carajás Mineral Province is located in the southern part of Pará state, northern Brazil (Fig. IV.1). Its bauxite deposit is on N5 plateau, which correspond to the eastern part of the bigger Serra Norte plateau in Serra dos Carajás region (Fig. IV.2), 150 km southwest from Marabá city. Marabá is the main industrial and most important city of the region, which has been developed after Carajás mining installation.

2. Climate and Vegetation

The Serra dos Carajás has a tropical climate, the same of the whole Amazon region, with an annual mean temperature of 26ºC and 2,000 mm rainfall. The altitude reaches 600 to 800 m, where the temperature is mild.

Actual vegetation includes dense tropical forest covering great part of Serra Norte. On the iron crust, the vegetation is only constituted by gramineous and shrub (savannah type), giving rise to so called clareiras - small clean areas - from N1 to N5 plateaus. For example, the western part of N5 plateau is occupied by "clareiras", where the iron ore outcrops as iron crust, and its eastern part, by dense tropical forest over the earthy bauxite.

3. Geology

The Carajás Mineral Province is formed by Fe, Al, Mn, Ni, Cu and Au ore deposits and mines originated mainly by lateritisation processes. The Serra Norte represents a thick lateritic sequence developed over

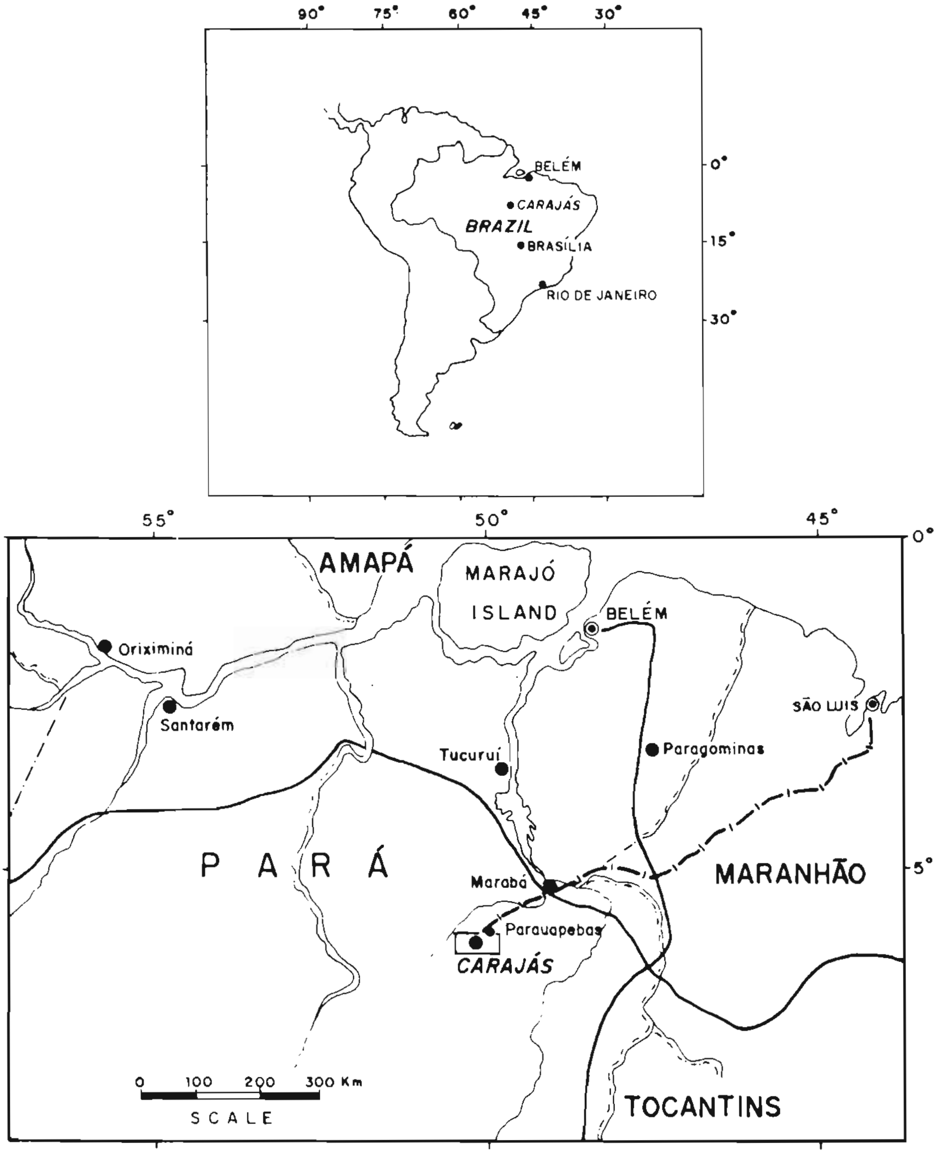


Figure IV.1 - Situation of the Carajás Province in South of Pará.

several Precambrian units that outcrop at the footslopes and in deep valleys around the plateaus. After Tolbert et al. (1971), Beisiegel et al. (1973), Tassinari et al. (1982), Cordani et al. (1984) and DOCEGEO (1988), these pre-lateritic units are represented by:

- Xingu Complex, the regional basement, constituted by granitic

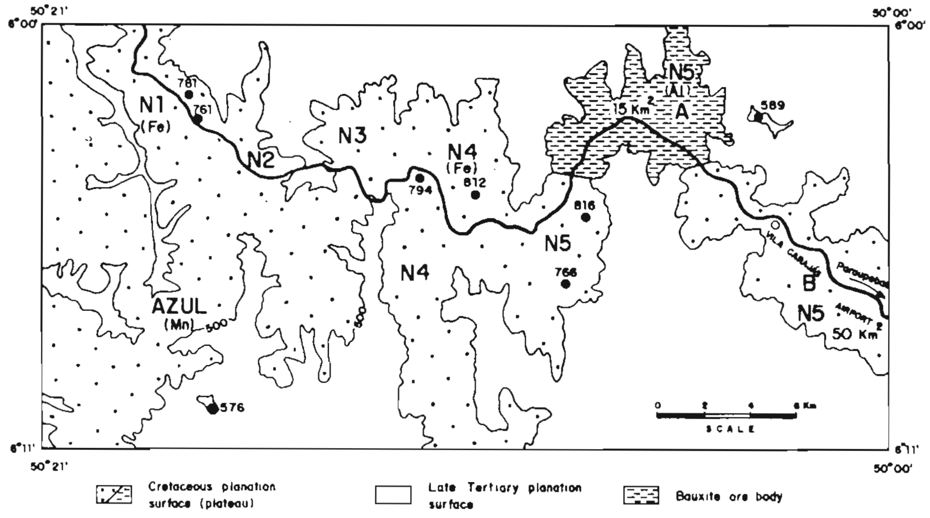


Figure IV.2 - The location of the N5 bauxite ore deposit in the Serra Norte Plateau (Carajás).

migmatites, intrusive granites and thick deformed and sheared volcanic-sedimentary sequences like greenstone belts. These sequences are divided in: 1) Grão Pará Group, with thick basaltic sequences intercalated by banded iron formations (oxide facies), besides restrict felsic volcanics. All exhibit low grade metamorphism; 2) Igarapé Pojuca Group, formed by chemical metasediments in green schists to amphibolite metamorphic facies; mafic and intermediate volcanics and metapelites intercalated with chemical sediments are also present; 3) Rio Fresco Group, of Lower Proterozoic age, overlaying the preceding units. It is composed by slightly metamorphosed cover sediments.

- Proterozoic Granites, intrusive in the latter units and well represented by Carajás Granite in the region.

From Proterozoic to Recent, the alone existent geological records are formed by lateritic and gossanic formations, besides latosols on the top of plateaus, slopes and valleys.

4. Geomorphology

The Serra dos Carajás region is composed by two large geomorphological domains: the first one, related to Serra Norte and Serra Sul plateaus, which give rise to the so called Serra dos Carajás, and the second one, formed by regional lower and slightly undulated surface.

The plateaus present irregular outlines, steep slopes and flat top surface (Fig. IV.3), reaching 600 to 800 m and 650 m as mean altitude. They were sculpted over older mature lateritic formations where the Al, Fe, Mn and Au ore deposits are found. These plateaus (Boaventura et al., 1974) are part of the "Planalto Dissecado do Sul do Pará" (Sul Americana Surface) as a product of Tertiary pediplanation by re-elaboration of a Cretaceous or pre-Cretaceous pediplain. The regional lower surface, 350 m mean altitude, represents the dissection of the older Sul-Americana Surface, as a consequence of very fast new tectonics uplifts, which favored the strong erosion processes, leading to a new pediplain - Velhas Surface - during Plio-Pleistocene. Over this surface, immature laterite profiles have been established.

II. Ore deposit presentation

The N5 bauxite deposit is located in the northwestern part of the N5 plateau, indicated by block A (Fig. IV.2), encompassing an area of 15

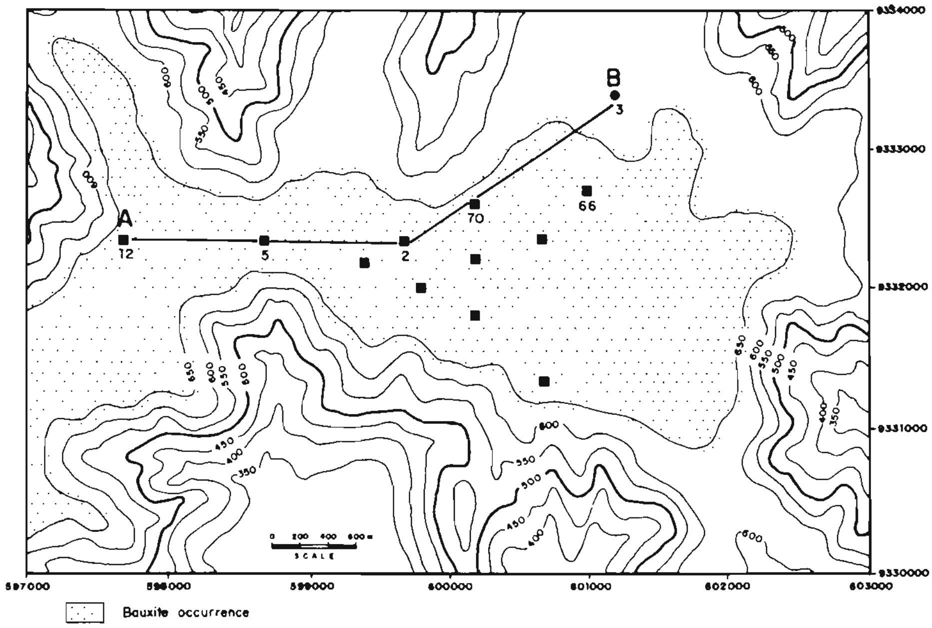


Figure IV.3 - Detailed topographic map of the main bauxite body (A area) showing the investigated pits and drill hole 3.

km^2 area. The block B only contains a low grade bauxite. The central part of the ore (6°10'S and 50°15'W) is 19 Km far from Carajás airport (which is able to operate day and night 727 Boeing type aircrafts) and 30 km from Parauapebas city. The connection between these places is made by well paved road.

The N5 ore deposit is cover-free (Figs. IV.3 and IV.4), turning its mining less expensive. Washing of finest fractions is also unnecessary, what does not occur with Amazon bauxites.

Docegeo, the owner of N5 bauxite deposit, evaluated about 49 million tons raw ore, with 4.2 m thick and occupying 10 km^2 (Alves, 1988).

The average chemical composition of the bauxite ore exhibits low contents of reactive SiO_2 (1.7%), only 34.9% of available Al_2O_3 and high contents of Fe_2O_3 (25%) and organic carbon (1.5%). The latter inhibits alumina production (Alves, 1988). These chemical characteristics indicate only a metallurgical grade for N5 bauxite ore deposit. Table 1 presents the chemical composition through a typical ore profile.

The N5 bauxite deposit is mainly constituted by gibbsite, besides great amounts of hematite, goethite and Al-goethite. Anatase and kaolinite are just small accessories.

III. Lateritic body

1. Lateritic Horizons

The N5 bauxite is settled on the top of a thick lateritic profile

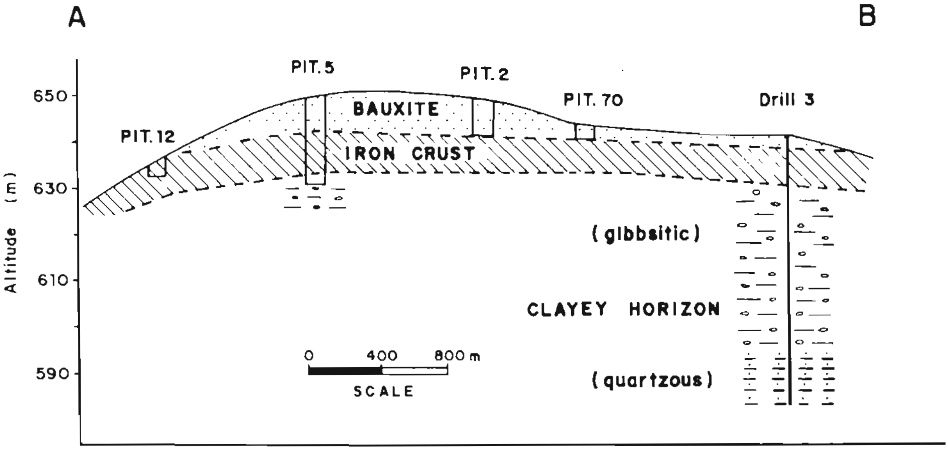


Figure IV.4 - Geological section A-B along the N5 plateau (A area).

where the following horizons were identified (Fig. IV.4): bauxite (in the top), iron crust, clayey horizon and parent rock.

- Bauxite Horizon composes the ground surface and in depth goes into a gradual contact toward the underlying iron crust (Fig. IV.3). Its mean thickness is 4.2 m. The horizon may be divided in two zones: a yellow upper bauxite, with about 2.5 m thick; and a red lower bauxite, 3.5 m thick (Pit 66, Table IV.1), with relicts from the underlying iron crust.

- Iron Crust is compact, massive and cavernous, has dominant red and yellow colors, random distributed, resembling preterit features of mottled horizon. It is found between bauxite and clayey horizon, where the lower contact is also gradual. Its actual thickness is about 10 m.

- Clayey Horizon is a very thick horizon (49 m in drill hole 3, Fig. IV.4), outcropping only in the plateaus slope. It is also divided in two zones: a yellowish upper zone, 36.6 m thick, formed by placoid nodules of aluminous hydroxide immersed in a clayey matrix; and a lower purple to brown zone, with manganesiferous black spots, quartzous and more than 11 m thick.

- Parent Rock in N5, drill holes did not reach fresh rock, although drill hole 3 arrived near. In a neighbor area (N4 plateau), several drill holes-after cross a clayey horizon similar that described in N5-reached basaltic rocks from Grão Pará Group, which will be demonstrated in this work to be also the parent rock for the N5 lateritic formations.

- The basalts, although hydrothermally altered, still exhibit partially preserved their textures and mineralogical composition. Plagioclases are transformed to sericite, epidote and calcite, while pyroxenes are al-

Table IV.1 - Chemical composition of the N5 raw bauxite ore (pit 66)

HORIZONS	DEPTH (m)	LOI	Al_2O_3 (A)	SiO_2 (R)	Al_2O_3 (T)	SiO_2 (T)	Fe_2O_3	TiO_2
YELLOW BAUXITE	0 - 0.5	27.4	35.2	2.2	46.2	2.6	20.0	3.8
	0.5 - 1.0	26.2	36.1	2.1	47.0	2.6	20.2	4.0
	1.0 - 1.5	25.8	37.2	2.1	47.6	2.6	20.2	3.8
	1.5 - 2.0	25.9	37.6	1.6	48.0	2.7	20.2	3.2
	2.0 - 2.5	25.7	38.0	1.6	46.6	1.8	21.3	4.6
RED BAUXITE	2.5 - 3.0	25.5	37.3	1.5	47.2	1.6	21.1	4.6
	3.0 - 3.5	25.9	38.5	1.2	47.5	1.1	21.5	4.0
	3.5 - 4.0	25.4	38.2	1.1	47.9	1.0	21.7	4.0
	4.0 - 4.5	25.7	38.1	1.1	48.3	0.9	21.5	3.6
	4.5 - 5.0	25.4	39.4	1.0	48.4	0.8	21.8	3.6
	5.0 - 5.5	25.4	39.7	0.8	47.8	0.6	22.2	4.0
	5.5 - 6.0	25.3	38.6	0.7	47.9	0.6	22.0	4.2
RED IRON CRUST	6.0 - 6.6	21.7	31.2	1.0	40.1	0.6	34.6	3.0
AVERAGE CHEMICAL COMPOSITION (N5 ORE DEPOSIT)			**34.9**	**1.7**	**25.0**	**3.9**		

Modified from Alves (1988). A: available; T: total; R: reactive.

tered to hornblende, tremolite-actinolite and chlorite. Quartz also occurs as disseminations or veins. Chlorite, quartz and calcite form amygdales; zircon, opaques (ilmenite) and tourmaline are the most common accessories.

2. Mineralogy

The N5 lateritic body is composed by gibbsite, hematite, goethite, Al-goethite, anatase and kaolinite, as lateritic minerals; quartz, zircon, ilmenite and tourmaline, as resistates and accessories (except quartz). Other parent rock minerals, unstable ones, were only detected in the base of profile together with neoformed 2:1 clay minerals.

The bauxite horizon, as mentioned before, is constituted by gibbsite, goethite, hematite and small amounts of anatase and kaolinite. Al-goethite domains in the yellowish zone and hematite in the reddish one.

The iron crust is mostly formed by hematite and gibbsite, besides kaolinite and anatase. This mineralogy diverges from those of the bauxite horizon only in the minerals proportions.

In the clayey horizon, upper zone, kaolinite domains, with high contents of hematite, goethite and gibbsite and smaller amounts of anatase, while its lower zone diverges by the absence of gibbsite and presence of quartz (up to 30%). In this way, the upper zone is called gibbsitic and the lower quartzous.

Figure IV.5 shows the distribution of the main minerals throughout N5 lateritic profile, based on data from pits and drill hole 3. The mineral distribution is compatible with great part of Amazon lateritic profiles: from base to top it portrays the accentuated decreasing in quartz and kaolinite contents and the increasing of hematite, goethite and gibbsite. The most marked difference is the gibbsite domain toward the top of the profile, while hematite decreases. The Amazon bauxite covers like Belterra Clay, correlated to N5 bauxite deposit by Kotschoubey et al. (1989) and Costa (1990), although with abundant gibbsite, it is substituted by kaolinite, which makes it a little important aluminum ore.

3. Geochemistry

The chemical composition of the horizons from N5 lateritic body is presented in Tables IV.2 and IV.3. Table IV.2 shows the chemical composition of the composed profile, based on N4 basalts (fresh and partially weathered), and clayey horizon, iron crust and bauxite horizon from N5 body (drill hole 3 and pits). The upper bauxites horizon presents low

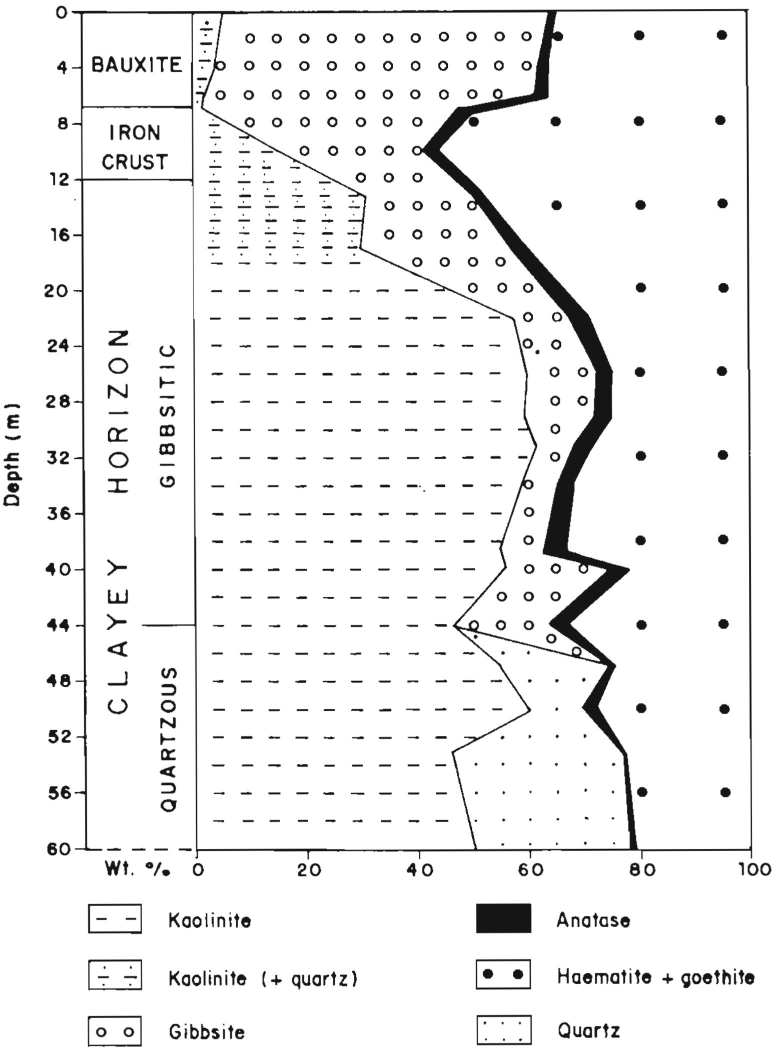


Figure IV.5 - Mineralogy distribution along the lateritic profile of N5 Plateau (drill hole 3).

contents of SiO_2 and Al_2O_3 and high Fe_2O_3 and TiO_2 contents, compatible with an origin from basalts. The contents of SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 in the profile, from basalts until the crust (Fig. IV.6) suggest continuous lateritic evolution from basaltic rocks, with depletion on SiO_2 (and also MgO, CaO, Na_2O and K_2O) and retention of TiO_2, Fe_2O_3 and Al_2O_3. It may be better explained by the chemical composition distribution along the drill hole 3 profile (Table IV.3), which is similar to the com-

Table IV.2 - Average chemical composition of basalts and weathered basalts from N4 plateau and the lateritic horizons from N5 plateau.

	Wt. %	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5 A2	PF	(N)
N5 Plateau												
Bauxite		2,39	2,55	43,41	25,41	<0,01	<0,01	<0,01	<0,01	0,68	25,11	(27)
Iron Crust		6,15	1,77	38,25	46,93	<0,01	<0,01	<0,01	<0,01	0,30	16,19	(16)
Clayey	(1)	25,09	2,05	26,95	31,96	<0,01	<0,01	<0,01	<0,01	0,46	13,55	(22)
horizon	(2)	46,90	1,20	20,95	22,43	0,25	<0,01	0,29	<0,01	0,51	7,47	(4)
N4 Plateau												
Weathered	(3)	32,04	1,44	25,72	24,60	0,13	0,39	<0,01	<0,01	0,83	13,37	(5)
basalts	(4)	45,73	0,70	18,58	15,76	4,02	4,24	1,08	1,02	0,40	13,45	(5)
Basalts		51,70	0,61	14,21	12,67	6,49	6,72	3,16	2,16	0,37	2,28	(8)
Earth Crust	(5)	60,32	0,95	15,55	8,04	3,45	5,81	3,18	2,52	0,43		

(1) - gibbsitic clayey horizon; (2) - quartzous clayey horizon; (3) - deep weathered basalts; (4) - light weathered basalts; (5) - Taylor (1976); (N) - number of samples.

posed profile.

Table 4 shows that the chemical composition of N5 bauxites is comparable with those from Tucuruí, also derived from basalts, and quite different from the large bauxite deposits from Paragominas, derived from sediments.

Trace Elements. Only the following trace elements were analyzed: Ni, Co, Cr, Mn, Zr, Y and Nb. Their contents are presented in Tables IV.5 (composed profile) and 6 (N5 profile, drill hole 3). The upper horizons (bauxite and crust) still present relatively elevated Ni, Co and Cr contents, comparable or higher than bauxites derived from basalts in Tucuruí (Souza, 1989), but very high if compared with Paragominas bauxites (Table IV.6) (Kronberg et al., 1982). The trace element contents in clayey horizon are also high and compatible with a basalt derivation. Both composed and drill hole 3 profiles show equivalent trace element contents.

Table IV.3 - Chemical composition of the lateritic profile along drillhole 3.

Wt. %	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5	PF	TOTAL
BAUXITE											
0,0 - 2,5 (m)	3,25	4,20	50,73	15,74	<0,01	<0,01	<0,01	<0,01	0,55	26,26	100,73
2,5 - 4,5	0,98	2,70	39,04	37,78	<0,01	<0,01	<0,01	<0,01	0,52	18,26	99,28
IRON CRUST											
4,5 - 7,8 (m)	1,04	2,66	26,63	51,10	<0,01	<0,01	<0,01	<0,01	0,54	16,32	98,29
7,8 - 10,3	8,32	1,43	22,02	56,60	<0,01	<0,01	<0,01	<0,01	0,50	10,88	99,75
10,3 - 13,3	19,10	1,51	21,77	45,65	<0,01	<0,01	<0,01	<0,01	0,62	11,16	99,81
CLAYEY HORIZON											
gibbsitic zone											
13,3 - 17,4 (m)	13,78	1,72	30,54	39,36	<0,01	<0,01	<0,01	<0,01	0,11	14,64	98,57
22,3 - 25,8	26,15	2,45	27,16	31,41	<0,01	<0,01	<0,01	<0,01	0,53	12,10	99,80
25,8 - 28,8	28,00	2,35	32,15	25,19	<0,01	<0,01	<0,01	<0,01	0,82	11,40	99,10
28,8 - 31,4	27,26	2,73	32,75	25,46	<0,01	<0,01	<0,01	<0,01	0,60	11,56	100,36
31,4 - 34,2	28,80	2,68	27,66	28,33	<0,01	<0,01	<0,01	<0,01	0,71	12,38	100,76
34,2 - 38,7	27,28	2,23	24,53	33,06	<0,01	<0,01	<0,01	<0,01	1,18	12,30	100,60
38,7 - 40,2	25,80	1,61	26,84	34,60	<0,01	<0,01	<0,01	<0,01	1,20	10,60	100,80
40,2 - 43,7	25,90	1,55	38,63	22,04	<0,01	<0,01	<0,01	<0,01	1,21	11,32	100,60
43,9 - 46,9	21,60	1,44	28,76	34,60	<0,01	<0,01	<0,01	<0,01	0,76	11,48	98,71
quartzous zone											
47,3 - 49,5 (m)	44,24	1,16	21,80	23,60	0,80	nd	0,67	nd	0,43	7,94	99,90
50,7 - 53,3	44,62	1,51	23,50	23,62	0,11	nd	nd	nd	0,39	7,16	100,90
53,3 - 56,1	49,20	1,10	18,80	22,04	0,01	0,02	0,17	nd	0,60	7,26	99,04
56,1 - 60,6	49,84	1,05	19,70	20,46	0,08	0,02	0,32	nd	0,64	7,54	99,65

Trace element distributions through drill hole 3 profile (Fig. IV.7) are also typical of the lateritic evolution indicated by Ni, Co, and Mn contents, concentrated at the base of clayey horizon, and Cr and Zr, in the top of profile. Quite different is the strong increasing of Nb in bauxite horizon.

Geochemical Balance. Considering the earthy nature of great part of N5 lateritic profile, improper for isovolumetric calculations, geochemical balance was based on Nesbitt (1979) equation, using titanium as the immobile element:

$$\%\ \text{Variations} = \frac{(\text{Conc.x}/\text{Conc.Ti})_{\text{Horizon}} - 1}{(\text{Conc.x}/\text{Conc.Ti})_{\text{Rock}}}$$

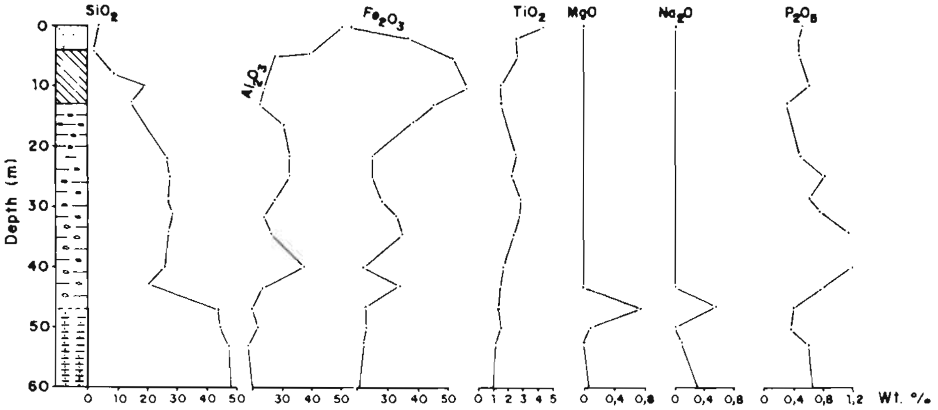


Figure IV.6 - The distribution of the chemical elements contents along the lateritic profile of N5 Plateau (drill hole 3). For legend explanation see Figure IV.4.

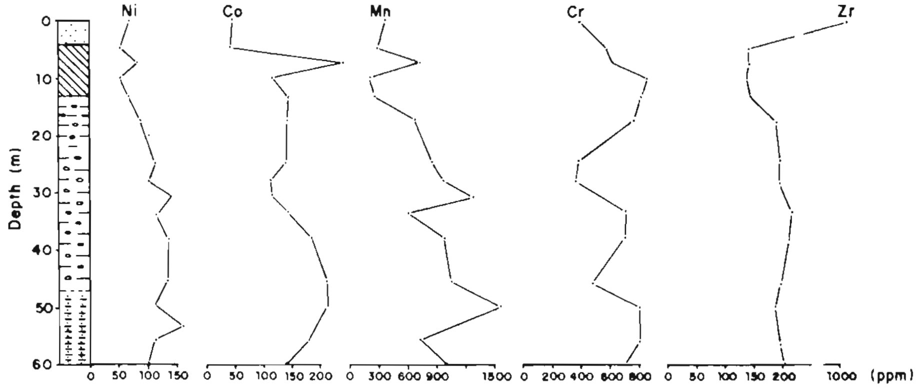


Figure IV.7 - The distribution of the trace elements through the lateritic profile of N5 Plateau (drill hole 3). For legend explanation see Figure IV.4.

where "Conc.x" is the concentration of any chemical element.

Figure IV.8 shows the sequence of gains and losses through the profile. In a general sense, the geochemical evolution is normal, equivalent to those described by Tardy (1969), Chesworth (1979), Monti (1988), Horbe & Costa (1990) and Lemos (1990). The following elements are classically leached upward: Na, K, Mg and Ca (completely leached); Si, Mn, Y and Ni (intermediate leached); and Al, Co Fe and Zr (partially leached). From base to top (crust), as described, the profile evolution

Table IV.4 - Correlation between the mean chemical composition of bauxites from N5 plateau, Tucuruí and Paragominas.

Wt. %	N5	TUCURUí (1)	PARAGOMINAS (2)
SiO2	2,39	0,90	6,48
TiO2	2,55	5,00	1,03
Al2O3	43,41	40,13	50,13
Fe2O3	25,41	31,22	13,67
MgO	< 0,01	0,36	0,03
CaO	< 0,01	0,06	< 0,01
MnO	< 0,01	0,09	< 0,01
K2O	< 0,01	0,03	< 0,01
P2O5	0,68	-	0,03
PF	25,11	21,93	6,00
	(ppm)	(ppm)	(ppm)
Ni	63	35	5
Co	120	29	0,3
Mn	265	277	194
Cr	352	412	6
Zr	789	-	9
Y	31	-	6
Nb	64	-	19
Parent rocks	basalts	basalts	sedimentary rocks

(1) Souza (1983), (2) Kronberg et al. (1982).

Table IV.5 - Average concentration of trace elements of basalts and weathered basalts from N4 plateau, and the lateritic horizons from N5 plateau.

(ppm)		Ni	Co	Mn	Cr	Zr	Y	Nb	(N)
Bauxite		63	120	265	352	789	31	64	(22)
Iron crust		63	144	336	724	298	10	10	(6)
Clayey horizon	(1)	124	188	1055	696	191	15	< 1	(4)
	(2)	118	136	812	541	205	7	< 1	(10)
Weathered basalts	(3)	100	180	2777	144	102	33	< 1	(5)
	(4)	170	232	3160	136	152	16	< 1	(5)
Basalts		83	70	2943	55	77	24	< 1	(8)
Earth Crust	(5)	75	25	250	122	162	31	20	

(1) - gibbsitic clayey horizon; (2) - quartzous clayey horizon; (3) - deep weathered basalts; (4) - light weathered basalts; (5) - Taylor (1967); (N) - number of samples.

Table IV.6 - Trace element contents along the lateritic profile of the drillhole 3.

(ppm)	Ni	Co	Mn	Cr	Zr	Y	Nb
BAUXITE							
0,0 - 2,5 (m)	63	46	352	380	1028	< 1	185
2,5 - 4,5	50	46	261	580	142	48	22
IRON CRUST							
4,5 - 7,8 (m)	83	246	715	630	184	< 1	< 1
7,8 -10,3	50	113	181	830	132	< 1	< 1
10,3 -13,3	66	146	250	805	139	< 1	< 1
CLAYEY HORIZON							
gibbsitic zone							
13,3 - 17,4 (m)	83	146	647	755	183	13	1
22,3 - 25,8	116	146	863	355	221	6	7
25,8 - 28,8	100	113	943	105	172	< 1	< 1
28,8 - 31,4	133	146	1306	380	197	< 1	< 1
31,4 - 34,2	116	113	605	355	195	6	< 1
34,2 - 38,7	133	113	1159	800	221	7	< 1
38,7 - 40,2	133	113	591	800	217	8	< 1
40,2 - 43,7	116	146	532	700	223	5	10
43,9 - 46,9	133	180	954	705	212	18	< 1
quartzous zone							
47,3 - 49,5 (m)	116	213	1000	480	190	10	< 1
50,7 - 53,3	166	213	1545	800	173	13	< 1
53,3 - 56,1	116	180	704	800	197	20	9
56,1 - 60,6	100	146	972	705	206	18	10

until the crust was isochemical for Ti and Zr, almost for Al and Fe. On the other hand, Cr was introduced into the profile or is reflecting its compositional heterogeneity in the parent rock. In fact, Cr contents in N4 basalts show strong variations (40 to 200 ppm), with high parallelism with Fe in the lateritic profile. Toward the top, along the bauxite horizon, Al remains immobile, while Zr, (Nb) and Fe modify their migrating trajectory. Fe enters in the leached elements group, while Zr and Nb experiment strong accumulation. These behaviors indicate a different evolution for the bauxite horizon.

Geochemical Associations. On the basis of correlation matrix obtained from Pearson's correlation coefficients for basalts and horizons from N5 lateritic body, it was possible to identify the following geochemical signatures for each horizon:

- Parent Rock: The most important are Si-Fe$^{(2+)}$-Ca-Na-(Mg), indi-

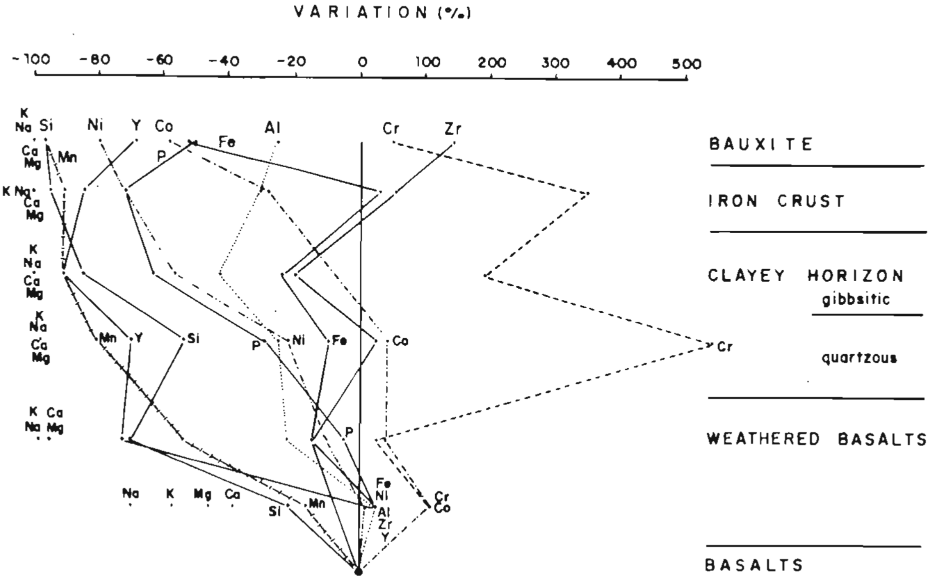


Figure IV.8 - Isotitan geochemical balance through the lateritic profile of the N5 Plateau with basalt as parent rock.

cating pyroxenes and Al-Fe$^{(3+)}$-LOI-Ni-Co-Cr-Zr, alumino-silicates.

- Clayey Horizon (Upper Zone): Shows no more parent rock associations, but only isolated correlation pairs: Fe-PF, Si-P, Ni-Zr. The Si significant negative correlation Si/(Fe, LOI, (Al)) represent the silicates (clay and quartz) replacement by iron and partly Al-hydroxides.

- Iron Crust: Exhibits the geochemical signature, Al-LOI-Zr, related to gibbsite (Al-goethite plus zircon), which correlates negatively with Fe (Fig. IV.9), only represented by hematite. This means that hematite and gibbsite were formed in different steps, which is also related to different mobility of Fe and Al. Another association is Ti-Ni-Co-Mn, characterizing the significant presence of ilmenite. Si does not show any correlation with other elements.

- Bauxite: The more prominent association is Al-Ti-Zr-(LOI)-(Co)-(Ni), similar to those in the crust, representing gibbsite, Al-goethite, and accessory minerals. Fe continues itself only to correlate negatively with this association (Fig. IV.9), as hematite. In this horizon, Si also exhibits no correlation.

This great modification of geochemical signatures show that profile evolution underwent polyphasic and/or polygenetic effects as

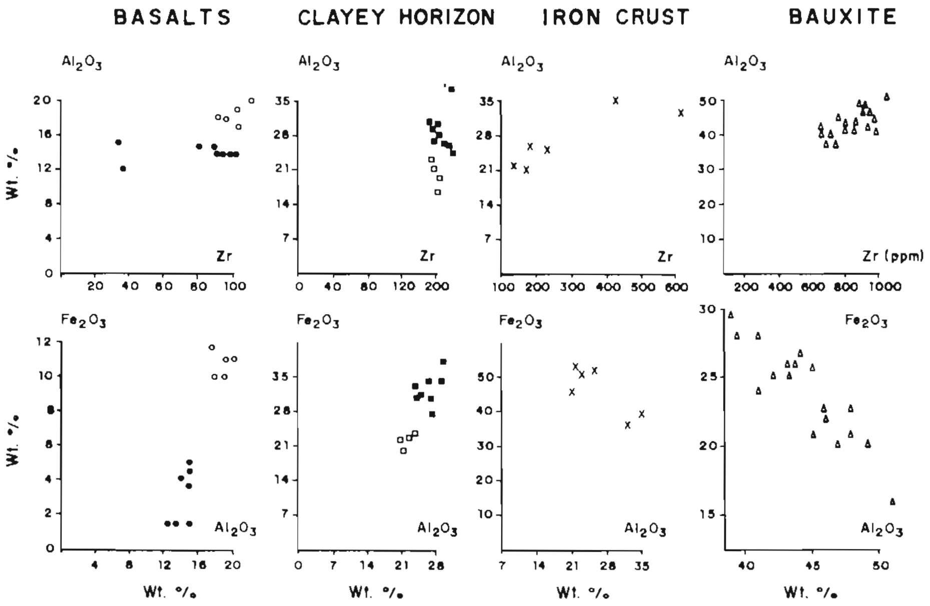


Figure IV.9 - The evolution of the Al_2O_3-Zr and Fe_2O_3-Al_2O_3 correlations from the parent rock up to the lateritic top horizon (bauxite ore body).

suggested by Kotschoubey et al. (1989), based on morphological studies.

IV. Genesis of lateritic body and its bauxite ore deposit

1. Lateritic Body

The N5 lateritic body is part of a large lateritic formation that composes the diverse plateaus from Carajás region, and can be correlated with those from Baixo Amazonas, Paragominas, Gurupi, Pitinga and Cassiporé. These lateritic bodies were afterward affected either by new lateritisation and pedogenesis phases (Kotschoubey et al. 1984; Lucas, 1989; Costa, 1990a), as by sedimentation and erosion (Costa, 1990b).

Lemos (1982), Lemos & Villas (1983), Kotschoubey & Lemos (1985) and Kotschoubey et al. (1989) concluded that N5 derived from lateritic weathering of basaltic rocks from Grão Pará Group. However, they diverge in the origin of bauxite deposit located on the top of profile. Lemos (1982) and Lemos & Villas (1983) concluded for a contemporaneous evolution between crust and bauxites in a lateritic environment. On the other hand, Kotschoubey & Lemos (1985) and Kotschoubey et al. (1989) admit a bauxitisation process posterior to the crust, over the material resulting from mechanical dismantling of this horizon and its partial deposition above it.

Fundamental Profile Formation. The horizon sequence immediately under N5 bauxite deposit represents a classic and complete mature lateritic profile (Costa, 1991), frequently found in Amazon region (Gurupi, Pitinga, Carajás). Kotschoubey et al. (1989) have already identified the normality of this sequence in Carajás. In fact, chemical and mineralogical composition, besides distribution patterns for minerals and different chemical elements contents show that the fundamental profile is complete and mature. The evolution was continuous up to the crust, reinforced by geochemical balance (Fig. IV.8) and by the ternary diagram (Fig. IV.10). The actual crust is an old one, thicker than observed today. It was formed near the surface (Fig. IV.11), at the expense of mottled horizon, inasmuch it does not present evidences of mechanical dismantling and preserves mottling pattern. After the crust establishment, the differentiation of a typical bauxite horizon began, immediately under the crust. Recrystallization of the iron crust occurred during the transformation of goethite to hematite and kaolinite to gibbsite. Therefore, the formation of a typical bauxite horizon under the crust was inhibited, as indicated by its low amount of gibbsite (Fig. IV.5). Probably, this inhibition was caused by fast tectonic uplift experimented by the region during the Tertiary, in a complete desequilibrium with the velocity of hydrolysis reaction (kaolinite + water = gibbsite), which did not permitted the complete consummation of kaolinite. Thus, there was not enough silica leaching favoring gibbsite formation. The actual elevated altitudes from Carajás region corroborate this fact, while the other Amazon bauxite regions, with high available Al_2O_3, but with small thickness, have lower altitudes, between 100 and 250 m (Paragominas, Baixo Amazonas, Gurupi), independently their distance from coast region. Higher quality bauxite deposits are found in altitudes lower than 300 m, as one can observe in Bardossy (1983). The uplift explains the great thickness (39 m) of clayey-gibbsite horizon, and its low gibbsite contents, representative of an unbalanced bauxite horizon. Similar fact is also observed in Pitinga and Cassiporé.

The N5 lateritic profile, by correlation with other Amazon laterites, must have been also formed in Eocene-Oligocene (Kotschoubey et al., 1989; Costa, 1990b).

2. N5 Bauxite Deposit Formation

Evidences that N5 bauxite deposit is product of tropical weather-

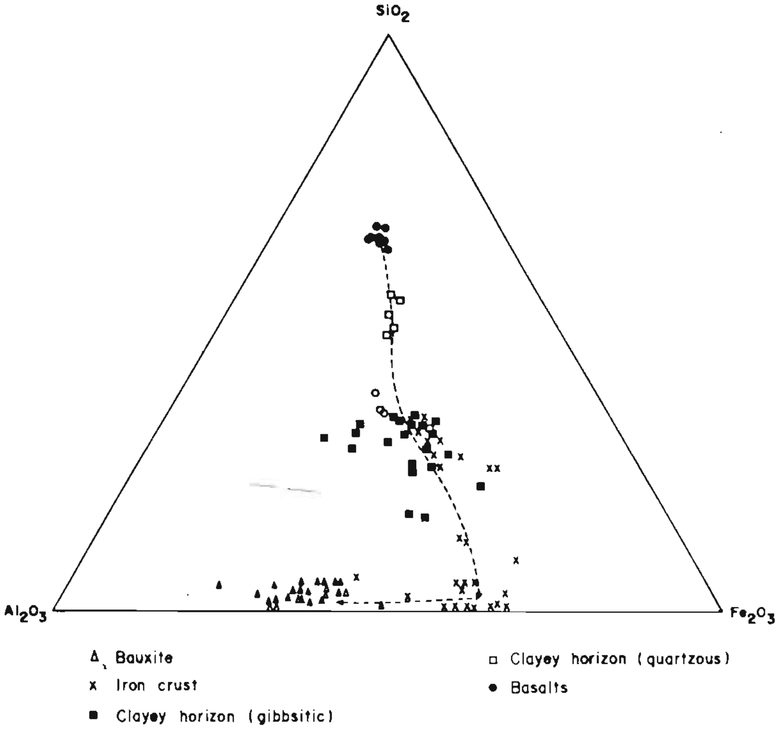


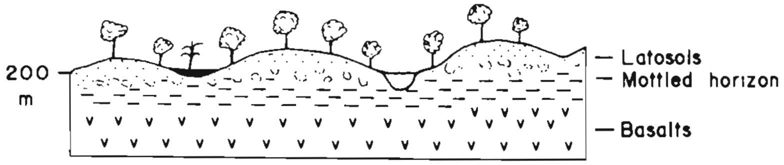
Figure IV.10 - The chemical evolution of lateritic profile of N5 Plateau on the SiO_2-Al_2O_3-Fe_2O_3 diagram.

ing over an immediately underlying aluminous iron crust are very strong:

(1) The profile presents a typical yellow latosol in the upper zone, rich in organic carbon (1.5%), that grades toward a reddish lower zone, resembling a saprolite derived from the crust;

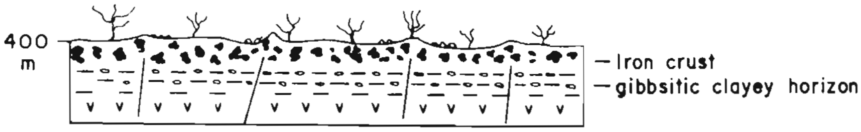
(2) The mineralogical composition of the bauxite is almost similar that one from the crust, only diverging in absolute concentrations from minerals species. The domain of Al-goethite in the yellow zone confirms its latosol nature, and the presence of hematite in reddish zone, its crust derivation. Al-goethite is a common mineral in Amazon latosols (Sombroek and Camargo, 1983; Lucas, 1989; Lucas et al., 1989; Costa, 1990b).

3) the chemical composition of bauxite still presents the high contents of Fe, Al, Ni, Co, Mn and Cr from the crust. The contents of Al, Ti, LOI, Zr and Nb increase gradually, while Fe, Ni, Cr, and (Co, Mn) decrease from crust toward the top of bauxites. Near ground surface Si, Zr, Nb and (Mn) contents experiment significant increasing, if compared with the crust. These geochemical characteristics were observed by Horbe &



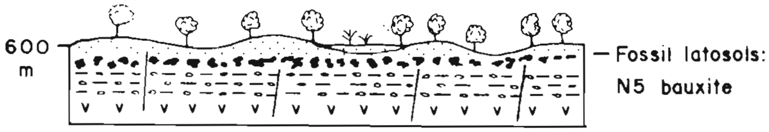
Eocene

Tropical chemical weathering: latosols and deep saprolites



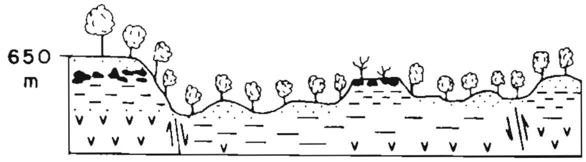
Oligocene

Semi-arid, erosion, iron crust formation over mottled horizon; rapid rising with restraint of the lower bauxite horizon.



Miocene - Pliocene

Physical and chemical weathering of the iron crust: formation of bauxite ore; thickening of restrained lower bauxite horizon.



Actual Landscape: evolution from Plio-pleistocene to Recent

Neo-tectonics with block faulting: denudation, peneplenation, immature lateritisation, alluvium deposits, actual chemical weathering.

Figure IV.11 - Schematic evolution of N5 lateritic body (Carajás) during Cenozoic.

Costa (1990) in laterites from Pitinga. Similar geochemical pattern was used by Pasquali & Lopez (1982) to distinguish lateritic profiles from savannahs and tropical forest.

(4) Geochemical balance, as well as the diagram from figure 8,

show that, from parent rock to the iron crust, the profile underwent geochemical changes, discordant with a continuos lateritic evolution;

(5) Geochemical balance from bauxite ore profile, with the crust as the parent rock, shows a typical weathering pattern with high deferruginisation and desilication, where Al, Ti and P are almost immobile (Fig. IV.12). Al and Ti confirm their tendency to immobility in all the N5 profile, what was also observed by Horbe & Costa (1990) in Pitinga. Mn and Co are similarly mobile, likewise Fe and Cr, while Zr, Nb and Y present absolute enrichment.

In this way, after establishment of the fundamental profile, with its lower unbalanced bauxite horizon, and the exposition of the crust to a new phase of intense tropical weathering, an earthy gibbsite latosol was formed (Fig. IV.11). The crust was initially dismantled to a saprolite, and then weathered until a latosol, in the following way:

The very low silica contents (1 to 2%), the opposite of major Amazon lateritic crusts and bauxites (6 to 8%) do not permit kaolinite neoformation and accumulation, probably because the vegetation might not dispose of silica to accumulate it in the profile.

The formation of this fossil latosol profile may have already initiated in Miocene (Fig. IV.11), as part of a new denudation process retaken over a Pre-Cretaceous surface as a consequence of tectonic reactivation, inducing a new pediplain formation (Velhas Surface) com-

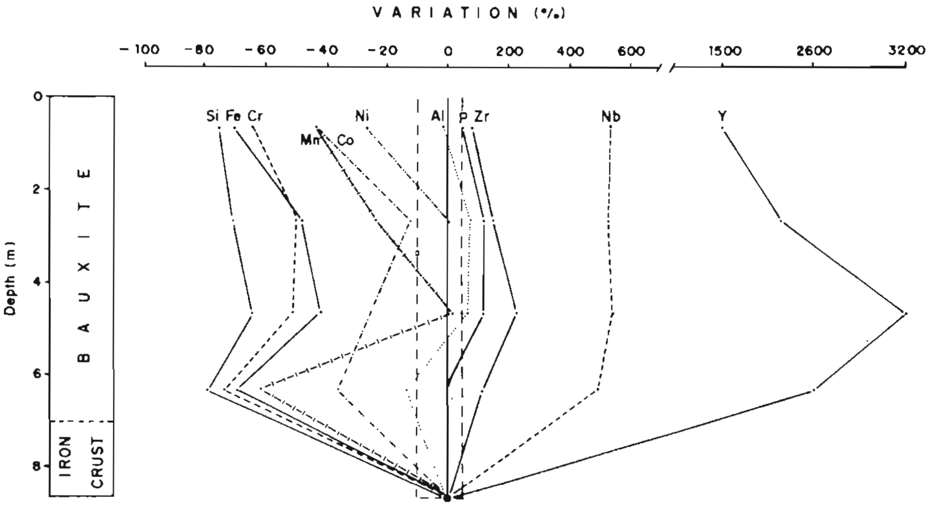


Figure IV.12 - Isotitan geochemical balance through the bauxite horizon of N5 Plateau with iron crust as parent rock.

pleted in Pleistocene.

The preservation of latosols like these, common over plateaus in Amazon, which establishment still began in Miocene-Pliocene, (Fig. IV.11) was probably favored by forest refuges in these areas that survived during the frequent climatic changes in the Tertiary.

Acknowledgments

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BAUXITE OF THE QUADRILÁTERO FERRÍFERO AND CENTRAL MANTIQUEIRA PROVINCE

CHAPTER V - THE BAUXITE OF THE QUADRILÁTERO FERRÍFERO

CHAPTER VI - THE BAUXITE OF CATAGUAZES

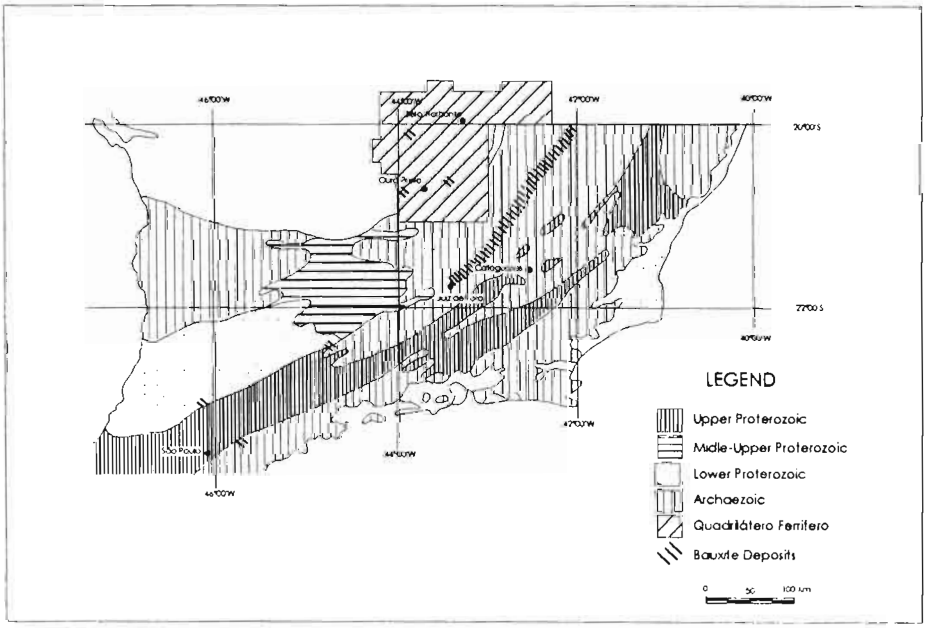
CHAPTER VII - THE BAUXITE OF NAZARÉ PAULISTA AND ASSOCIATED DEPOSITS

BAUXITE OF THE QUADRILÁTERO FERRÍFERO AND THE CENTRAL MANTIQUEIRA PROVINCE

The region refers to the deposits formed on Precambrian rocks of the Quadrilátero Ferrífero region and the central part of the geomorphological province called Mantiqueira (Hassui & Almeida, 1984). Despite of the wide lithological variation, it is possible to distinguish two different rock types associated with the bauxite deposits. The first one is constituted of metasedimentary rocks that occur in the Quadrilátero Ferrífero region, located in the central part of Minas Gerais State. The other one is constituted of a great variety of metamorphic rocks of amphibolitic and granulitic grades, associated with granitic-gneissic rocks. This second type occurs in a large and extensive zone, nearly parallel to the coast, that goes from the northeast of São Paulo State up to Espírito Santo, reaching also the southern part of Bahia State.

The different bauxite deposits of this region were studied as concerning their morphological and petrological characteristics, as well as their genetic aspects.

Thus, the area of Cataguazes was selected as representative of the bauxite deposits of the southeastern part of Minas Gerais State.



These deposits form an aluminium belt, extending from São João do Nepomuceno up to the Northeast of Cataguazes.

In the region of the "Quadrilátero Ferrífero", where the bauxite is distributed in various small deposits, three of them, Morro do Fraga, Vargem dos Óculos and Macaquinho, were selected as representative of the different types occurring in the region.

It was also included the deposit of Nazaré Paulista, Curucutú and Mogi das Cruzes, situated in São Paulo State, representing the bauxite associated with the granitic-gneissic rocks of "Serra do Mar".

Chapter V

THE BAUXITE OF THE QUADRILÁTERO FERRÍFERO

B. Boulangé, A. Carvalho, C.A.C. Varajão, A.F. Varajão

The "Quadrilátero Ferrífero", located in the central part of Minas Gerais state, Southeast Brazil, covers an area of nearly 7,000 km^2. It is a mountainous Precambrian region, with altitudes from 650 to 2,000 m. The bauxite reserves of this region are estimated to 10 million tons, distributed in 24 small deposits, which ranges from 150 to 1,500 thousands of tons. Considering both the geomorphological aspects and the geological situation, the deposit types have been interpreted differently in the various studies carried out in the region. The majority of the studies (Guimarães, 1945; Vaz, 1945; Lacourt, 1947; Dorr, 1969; Moore, 1969; Maxwell, 1972) suggested for the bauxites an autochthonous evolution from clayey phyllites and dolomites, while in a few others (Fleischer et al., 1968; Fleischer & Oliveira, 1969), the deposits were considered as allochthonous. On the other hand, in all these studies, it was mentioned the presence of a discontinuity between the substratum and the mineralized layers, which has been explained as a result of bauxitisation of either lacustrine clayey sediments inside depressions (Varella & Rosales, 1977; Büchi et al., 1982), or volcanic acid rocks (Dorr, 1969).

I. Regional aspects

The "Quadrilátero Ferrífero" forms the southern end of the folded belt of São Francisco Shield (Fig. V.1). The stratigraphic series overly a granite-gneissic basement that is the central outcrop in the southern part of the "Quadrilátero Ferrífero". These series are constituted by 3 great lithostratigraphic units (Harder & Chamberlin, 1915; Dorr, 1969; Ladeira, 1980):

- *Rio das Velhas Supergroup* forming a greenstone belt that includes the phyllitic and quartzitic formations of Nova Lima and Maquiné groups, the ultramaphic rocks on the eastern border and the bearing gold greenschists on the south.

- *Minas and Itacolomi Supergroups* formed by thick units of Proterozoic metasedimentary rocks. The Minas Supergroup has the most important deposits of iron, manganese and aluminum. The general metamorphic grade is lower than the greenschist facies, increasing from west to east.

The bauxite deposits are generally associated with the Itabira Group, included in the Minas Supergroup, and containing two units: Cauê and Gandarela formations. The main constituent of Cauê formation are the itabirites, associated with dolomitic and amphibolitic facies, intercalated with phyllites and marble. The Gandarela formation is constituted by dolomites, dolomitic phyllites, dolomitic itabirites and phyllites. Pires (1979) postulated that the base of Gandarela Formation would be formed by a magnetite-chlorite-schist, originated from mafic volcanic rocks, and by dolomitic lens, suggesting an environment similar to the recent reefs. It has to be remarked that the presence of volcanic rocks in the Minas Supergroup has been mentioned quite often (Guimarães, 1935, 1951, 1964; Guild, 1957; Simmons, 1958; Johnson, 1962; Dorr, 1969).

On the other hand, the occurrence of sedimentary deposit of Tertiary or Quaternary age has been reported in the "Quadrilátero Ferrífero". They constitute the lacustrine basins of Gandarela and Fonseca. Other sedimentary deposits occur as well in other regions, especially in Gandarela, Macacos and Rio Acima Quadrangles.

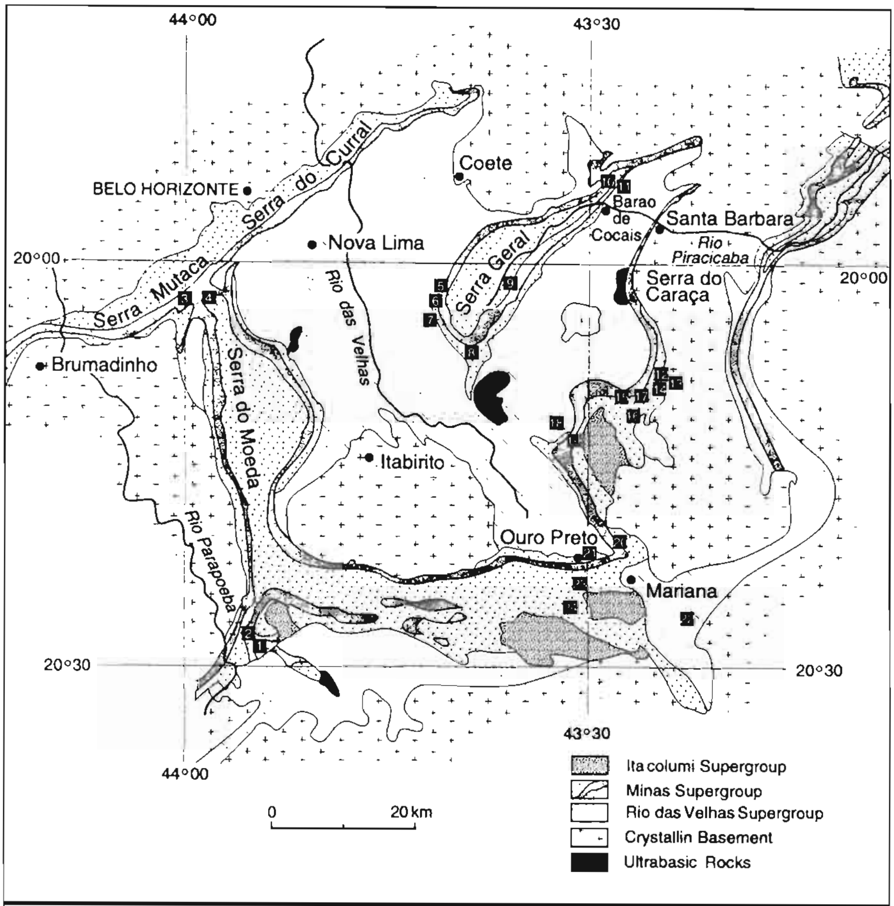
The geological structure pattern in this iron rich region results of a complex tectonic, having three main trends (north, east and south) and being constituted of three orogenetic phases. The first phase (2,700 m.y.) is younger than the deposition of Rio das Velhas Supergroup, while the second and most important one (2,000 m.y.) affected the Minas Supergroup and is equivalent to the Transamazonic Cycle. The last phase (500 - 600 m.y.) corresponds to the Brazilian Cycle (Brito Neves et al., 1979; Cordani et al., 1980; Uhlein et al., 1986).

The hydrological system is superimposed upon the geological structure. The main rivers are the Paraopeba in the west and Velhas in the center, which flows toward the São Francisco river. The Piracicaba and Gualaxo rivers drain the eastern part of the "Quadrilátero Ferrífero".

The present climate is of semi-tropical type. The mean temperatures vary from 14 to 21°C and it is rarely higher than 30°C. The annual mean rainfall ranges from 1,500 to 2,000 mm and increases from northwest to southeast; the months of June and July are completely dry and December and January are the most rainy months.

According to King (1956) and Dorr (1969), the geomorphological evolution of the "Quadrilátero Ferrífero" was characterized by the development of four surfaces placed at different levels, having different ages:

- the Gondwana surface (Lower Cretaceous), with altitudes varying from 1,500 to 1,600 m,
- the Post-Gondwana surface (Upper Cretaceous), between 1,200 and 1,400 m,



1 - Casa da Pedra
2 - Serra da Bandeira
3 - Jardine Canada
4 - Vargem dos Oculos
5 - Fazenda do Lopes
6 - Maquiné
7 - Gandorela
8 - Vigario da Vara
9 - Fazenda do Vargem
10 - Dois Ircuaos
11 - Fazenda do Sape
12 - Faria
13 - Macaquinho
14 - Fazendão
15 - Morro da Arataca
16 - Morro da Fraga
17 - Cata Preta
18 - Batatal
19 - Canta Historia
20 - Serra de Antonio Pereira
21 - Serra da Brigida
22 - Morro do Cruzeiro
23 - Tesoureiro
24 - Moujolo

Figure V.1 - Geological map of the Quadrilátero Ferrífero (modified after Dorr & Barbosa, 1963) and location of the bauxite deposits.

- the Sul-Americana surface (Oligocene-Miocene), with altitudes from 850 to 950 m,

- the Velhas surface (Pliocene), forming the central part of the "Quadrilátero Ferrífero" with an average altitude of 750 m.

From the beginning and up to now, the existence of these surfaces has been a matter of controversy (Varajão, 1988). Braun (1971), just after the proposal of Dorr (1969), has remarked that it would be very unlike that the rest of the Gondwana surface would be preserved after the intense erosional process that happened in the post-Gondwana period. In any case, the idea of a control of the topography by the lithological structure has been well accepted.

With regard to the general morphological features, it is possible to distinguish three units:

- the summits and the upper part of the higher topography, with altitudes over 1,500 m;
- the hill slope, corresponding to the intermediate unit, with altitudes ranging from 800 to 1,400 m;
- the depressions presenting altitudes varying from 1,200 to 1,400 m.

It has to be remarked that some other geomorphological units can be found in the "Quadrilátero Ferrífero". That is the case of a large depression, occurring in its central part, that was cut down by the Rio das Velhas, where the average altitude is about 800 m. The are also, in the external border of the "Quadrilátero Ferrífero" some small plateaus, in a rather low topographic position (about 900 m).

II. Classification of the bauxite deposits

The most part of the studies of the bauxite deposits, that normally followed their exploitation, were carried out taking into consideration particularly the aspects associated with the topographic positions, and consequently, with the erosional surfaces and their ages (Vaz, 1945; Guimarães, 1945; Guimarães & Coelho, 1945; Lacourt, 1947; Fleischer & Oliveira, 1969; Dorr, 1969; Moore, 1969; Maxwell, 1972; Ferreira, 1983). Recently, a study was carried out by Varajão (1988) and despite not presenting a detailed petrographic analysis, it represents a good inventory of the deposits of this region.

Based on the knowledge accumulated so far, a classification of the bauxite deposits of "Quadrilátero Ferrífero" is proposed here, taking into consideration both the geomorphological and geochemical aspects. As concerning the geomorphological aspects it was observed that the deposits were associated to 4 different units: high plateaus; hill slope; depressions and low plateau. The geochemical aspect refers to the average chemical composition of each deposit plotted on ternary diagram SiO_2-Al_2O_3-Fe_2O_3 (Fig. V.2), based on chemical analysis from regional mining companies (Table V.1). It can be observed that the deposits have a tendency to be distributed in 4 groups that correspond to the different morphologies mentioned above.

Thus, based on these two aspects, the bauxite deposits of the "Quadrilátero Ferrífero" were classified in 4 different types: the high plateau bauxites - Type I; the hill slope bauxites - Type II; the depression bauxites - Type III, and the low plateau bauxites - Type IV.

1. Type I - High Plateau Bauxites

These deposits are all situated in a high topographic position,

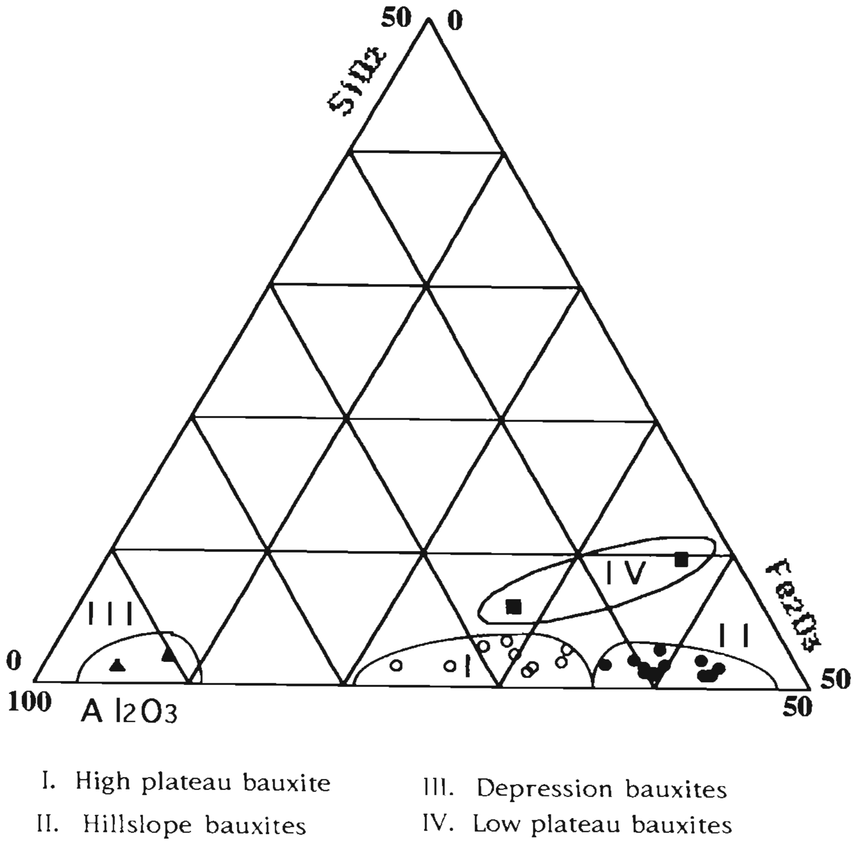


Figure V.2 - Diagram SiO_2 - Al_2O_3 - Fe_2O_3 allowing to range the Quadrilátero Ferrífero bauxite deposits on function of its main chemical components.

forming either the summit of a slightly tilted plateau or a part of a slope of a higher topography:

Serra do Batatal: 1840 m
Gandarela: 1640 m
Maquiné: 1600 m
Conta História: 1550 m
Vigário da Vara: 1510 m
Fazenda do Lopes: 1510 m
Serra da Bandeira: 1500 m
Serra da Brígida: 1490 m

The average chemical composition shows that these bauxites, with 47% Al_2O_3, are very poor in silica (1,5% SiO_2), but have a rather high content of iron (22% Fe_2O_3).

2. *Type II - Hillslope Bauxites*

These deposits occur in various altitudes and are also distributed on the morphological surfaces, except for the high plateau. They are normally protected by the itabiritic wall (Itabira Group) of the folded series of Minas Super-Group.

Tesoureiro: 1400 m
Jardim Canada: 1350 m
Monjolo: 1070 m
Morro do Arataca: 950 m
Cata Preta: 930 m
Casa da Pedra: 1350 m
Serra Antº. Pereira: 1220 m
Morro do Fraga: 1020 m
Dois Irmãos: 950 m
Fazendão: 890 m
Fazenda do Sapé: 830 m

The average chemical composition shows bauxites with 43% Al_2O_3, very low silica content (< 2% SiO_2) and a high iron content (29% Fe_2O_3).

3. *Type III - Depression Bauxites*

This type of deposit is quite rare, and up to now only 2 examples are known: Vargem dos Óculos (1350 m) and the foot slope of Morro do Fraga deposit (990 m). The old deposit of Morro do Cruzeiro (1210 m), already completely exploited, considering its description given by Guimarães & Coelho (1945), could be added to this group. But there is no chemical data to do so.

These bauxites contain a very high amount of alumina (56% Al_2O_3), together with 5% Fe_2O_3 and 1,2% SiO_2.

4. *Type IV - Low Plateau Bauxites*

This type of deposit occurs on the plateaus situated in the external border of the "Quadrilátero Ferrífero", and includes the deposits of

Table V.1 - The bauxite deposit types of the Quadrilátero Ferrífero and its chemical composition.

	Type	N°	Location	SiO2	Al2O3	Fe2O3
High plateau bauxite	I	2	Serra da Bandeira	2	43,6	22,3
		5	Fazenda do Lopes	1,1	53,5	16
		6	Maquiné	2,2	48,7	19,3
		8	Vigario da Vara	1,3	45,9	23,2
		18	Batatal	1,1	46,8	21,9
		19	Conta Historia	0,7	41,1	31,2
				0,96	43,65	15,68
				0,67	40,5	21,86
				1,09	38,57	23,76
Hillslope bauxite	II	1	Casa da Pedra	1,5	41,1	25,7
		3	Jardim Canada	1,3	42,6	29
		7	Gandarela	2,9	47,9	20,5
		10	Dois Irmaos	1,2	40,4	31,8
		11	Fazenda do Sape	1,6	40,7	30,6
		15	Morro da Arataca	0,7	41,3	31,9
		16	Fraga	0,9	48,9	31,5
				0,7	43,08	19,95
		17	Cata Preta	1,2	48,9	31,5
		20	Serra de A. Pereira	2,2	43,2	28,8
		21	Serra da Brigida	1,8	48,2	21,1
		23	Tesoureiro	1	37,1	31,7
		24	Monjolo	0,7	43,2	28,4
Depression bauxite	III	4	Vargem dos Oculos	1,2	59	5
		16	Fraga	1,1	57,5	3
		22	Morro do Cruzeiro	1,2	44,7	25,8
Low plateau bauxite	IV	12	Faria	7,4	40	27,5
		13	Macaquinho	2,4	48,1	20,4
		14	Fazendao	0,8	43,3	28,6

Faria (920 m) and Macaquinho (920 m) .

These bauxites, with 46% Al_2O_3 and 23% Fe_2O_3, are separated from the other types by the higher silica content (5 to 7% SiO_2).

III. Profiles characteristics

The various bauxite deposits of the "Quadrilátero Ferrífero", as mentioned previously, are distributed in 4 different types, and for each of them, the most typical deposit was selected:

Type I: Batatal deposit
Type II: Morro do Fraga deposit

Type III: Vargem dos Óculos deposit
Type IV: Macaquinho deposit

These various types of bauxite deposits were studied in different degrees of detail, depending on the peculiar characteristics of each one. Thus, the deposit of Vargem dos Óculos (Type IV), presenting a geomorphological setting completely different, as compared to the other deposits, was object of a detailed study (Varajão A., 1988; Varajão et al., 1989; Boulangé & Carvalho, 1991). The bauxite of Morro do Fraga (Type II), considering its abundance and the easy access, was also studied with a certain detail, particularly in its morphological and petrological aspects (Varajão C., 1988). For the rest of the deposits, only a general study, aiming its characterization, was carried out.

1. Type I . High Plateau Bauxite - Batatal Deposit

The deposit of Batatal, being exploited for 10 years, is located in the southern end of Serra Geral, which forms the eastern ridge of the "Quadrilátero Ferrífero" (Fig. V.1). The deposit, with a thickness varying from 5 to 10 m, occurs on a plateau, showing a smooth declivity to the east, with altitudes between 1,840 and 1,820 m, covering an area of 90,000 m^2. According to Maxwell (1972), the bauxite was supposed to lay on the Itabira Group rocks but further prospection seems to indicate that the bauxite could be originated from the phyllites of Batatal formation (Büchi & Menezes, 1982).

Recently, a profile of a shaft located in the upper part of the plateau was observed concerning the morphological and micromorphological aspects. This study (Varajão et al., 1989) allowed to establish the complete profile that shows, from the top to the bottom, the following facies:

Ferruginous massive bauxite (1 m): a red massive alumino-ferruginous crust, with a porous and vacuolar structure. Locally, this crust present a nodular aspect, where the nodules of the crust are embedded in a porous and vacuolar clear matrix. This layer is constituted mainly of gibbsite, hematite, small amount of goethite associated with the matrix, anatase and quartz. As for the chemical composition, this horizon is constituted by 46,5% Al_2O_3, 26,5% Fe_2O_3 and 2,8% TiO_2.

Mottled bauxite (4 m): a hard massive bauxite, made up of dark red volumes with hematite and gibbsite, sometimes nodular, that changes into brown yellow to beige volumes with gibbsite and goethite. This horizon presents an upper part (1 m) richer in Al_2O_3 (54%) with 23% Fe_2O_3 and 2,3% TiO_2, as opposed to the lower part that shows .41% Al_2O_3, 30% Fe_2O_3 and 2,6% TiO_2.

Mottled clay (2 m): an horizon formed by small red bauxite volumes (nodules), with hematite and gibbsite, embedded in a kaolinitic matrix, with a small amount of goethite. It seems that the bauxite nodules are relicts in continuity with the matrix, underlying the resilication process, associated with a strong deferruginisation. The average chemical composition shows 30% Al_2O_3, 14% SiO_2 and 10% Fe_2O_3, with more than 3% TiO_2. The high content of TiO_2 of this clay horizon confirms this transformation, that is followed by a residual Ti accumulation in the form of anatase. This transformation process intensifies the existing discontinuity between this horizon and the basal clay.

Kaolinitic basal clay, where the presence of muscovite and sericite underlines the original phyllite schists.

The micromorphological study of the bauxite profile has shown that it was submitted to several successive phases of reorganization, indicating a very long geological history. Hereby, the original structures were completely removed, resulting in a discontinuity between the bauxite profile and the basal weathered phyllite. As a consequence, it is difficult, in the present step, to precise if the parent rock is the basal phyllite.

2. Type II. Hillslope Bauxites - Morro do Fraga Deposit

The bauxite deposit of Morro do Fraga is located in the eastern border of the "Quadrilátero Ferrífero" (Fig. V.1), 7 km far from Santa Rita Durão District. According to Maxwell (1972), this deposit is situated on the inverted limb of Santa Rita syncline, constituted by the Itabira Group formations. Under the topographical point of view, the deposit is situated on the slope of a small basin, with altitudes between 1050 m and 975 m. This basin is limited by a crest line formed by a subvertical itabirite layer, covered by an iron crust that protects it against the erosion.

According to their position on the above morphology, two different profile types can be distinguished: the profiles situated on the slope and the one situated in the depression. In the profiles on the slope, it was observed that the basal clay is covered, from the bottom upwards, by the following sequence of facies: massive bauxite, alumino-ferruginous crust and nodular horizon (Fig. V.3).

Massive bauxite. It is an homogeneous bauxite with a hard, dark red, porous and vesicular facies, having a thickness of 4 m in the back slope and 8 m in the foot slope. It is formed by dark red volumes constituted by hematite and gibbsite. These irregular volumes are separated from each other by volumes of saccharoid well crystallized gibbsite,

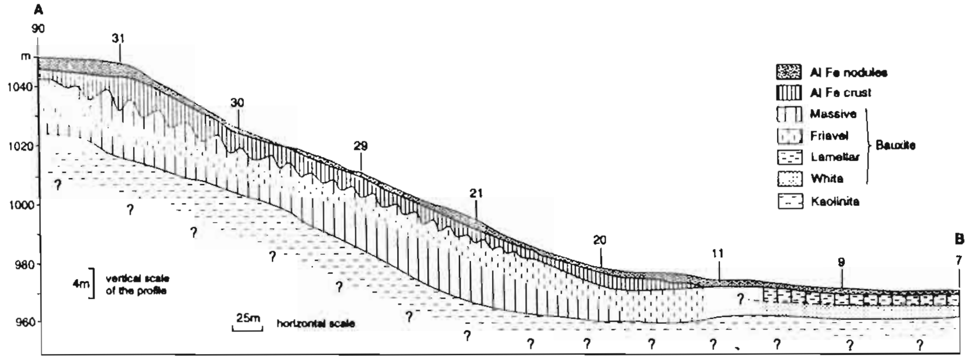


Figure V.3 - Topographic sequence of the Morro do Fraga bauxite deposit.

delimiting voids that are partially or completely invaded by dark ferruginous products. Vertically upwards, the density and the pores size increase and isolate bauxite volumes, resulting in a friable facies. Towards the back slope, close to the itabiritic walls, the pores impregnation by ferruginous products is rather important. The pores and vesicles are partially filled by a gray, argillomorphic and very humid product, that becomes readily dark when exposed (observed in a quarry front). It is a ferrihydrate that changes directly into hematite. In the foot slope, on the contrary, a deferruginisation takes place, underlined by a discoloration of the dark red volumes which are isolated within a light to brownish red matrix, constituted by gibbsite and goethite. This horizon presents Al_2O_3 content varying from 40% in the massive facies to 50% in the friable facies, 20% Fe_2O_3, less than 1% SiO_2 and less than 2% TiO_2.

Alumino-Ferruginous crust. This horizon, having thickness of 1 to 2 m, presents an irregular lower limit with the massive bauxite. This facies presents a goethitic matrix enveloping relicts of massive reindurated bauxite. The alumino-ferruginous horizon differs from the previous one by the porous dimension and the absence of gray ferrihydrate precipitate. The presence of goethite in the matrix is only associated with vertical migration and not with lateral flow coming from the back slope. The chemical composition of this horizon is very similar to the subjacent bauxite (40% Al_2O_3 and 20% Fe_2O_3).

Nodular horizon. This horizon, with a thickness of 0,5 to 1 m, is formed by subspherical nodules of alumino-ferruginous crust, with a diameter of 10 cm. The chemical composition is characterized by an increase of Fe_2O_3 content (25%) and a relative increase of Al_2O_3 (45%).

Towards the back slope the nodules are cemented by a ferruginous product and form locally a pseudobrecciated crust.

In the lower part of the area, in the depression bottom, the nodular horizon and the alumino-ferruginous crust form only one horizon, hardened and rich in Fe_2O_3 (35%), having in the upper part (2 m) goethitic lamellae. These lamellae become less important and disappear completely downwards giving place to a gray to white argillomorphic bauxite horizon (2 m). This gray bauxite is very rich in Al_2O_3 (57%) and has a low content of iron Fe_2O_3(3%). On the other hand, the high value of TiO_2 (4,5%) suggests that this bauxite was submitted to a deferruginisation process and a consequent TiO_2 residual accumulation (Boulangé & Carvalho, 1989). Considering its characteristics, this profile is better classified as type III.

The Morro do Fraga bauxite deposit, situated on a slope, shows various geochemical mechanism according to the geological and morphological condition. Hence, the alteration process affects at the same time the itabirite and the phyllite layer. But, in the former, it progresses slowly and gives origin to a ferruginous crust while in the phyllite it forms bauxite and the process goes deeply. As a consequence of this differential erosion, the topography is reinforced with the itabirites forming the crest line and the bauxites laying on the slope.

A great amount of iron is liberated by the itabirites. It moves down, it is fixed as ferrihydrate and it changes into hematite as soon as the profile is submitted to desiccation. However, this mechanism does not occur in the surface, where the previously formed bauxite is submitted to a breaking down and a nodulation. The fragments were mechanically transported and deposited in the depression. Here, under hydromorphic conditions, the bauxite suffers an intense deferruginisation, giving origin to a gray to white argillomorphic bauxite, with no trace of resilication and rich in residual TiO_2 (4,5%) as anatase.

On the other hand, the amount of iron available in the slope, and get moving, is redistributed as lamellae in the upper part of the profile. This distribution marks well the water table movement in this depression.

3. Type III. Depression Bauxites - Vargem dos Óculos Deposit

Description of facies. The deposit of Vargem dos Óculos are of two types: kaolinite deposit and bauxite deposit. They are located at 15,5 Km of Belo Horizonte in the vicinity of the road leading to Rio de Janeiro, and cover an area about 50 ha (Fig. V.1). They are situated in the Moeda syncline trough, west border of the "Quadrilátero Ferrífero", and are developed on Precambrian Itabira Group rocks. The morphology is very similar to the Morro do Fraga deposit. Thus, an itabiritic crust forms the crest line bordering a large depression, where the deposits of kaolinite and bauxite are situated.

The profiles of kaolinite and bauxite deposits are very similar, their difference being only the thickness of the different facies. The study of the open cut mine samples and drill hole cores leads to establish a typical profile, with three major units (Varajão et al., 1989), that are, from the bottom to the top (Fig. V.4): lower clay unit, middle bauxite unit and covering unit.

The lower clay unit. This facies, not well developed in the bauxite deposit, at least in the exposed area, but very thick in the kaolinite deposit (more than 12 m), is constituted, from the bottom to the top, by two facies, with gradational contacts:

a. Massive kaolinite facies. This facies can be observed only at the bottom of the visible profile in the kaolinite deposit. It occurs as block fragments (50 cm large) bounded by a network of narrow cracks (1 mm) with a red argillo-ferruginous coating. The kaolinitic fragments are compact and are made up by a quartzous skeleton embedded in a kaolinitic matrix. The quartz (less than 5% and smaller than 3 mm) is fractured, showing dissolution features on their edges and sometimes a red ferruginous coating (hematite) in the fissures. The kaolinite matrix is brownish to white, with a better crystallization in the white zones.

b. Kaolinite with ferruginous zonation facies. This facies, with a thickness about 12 m in the kaolinite deposit, is more fragmentary than the previous one and independently of the cracks. Ferruginous zonations are developed in the kaolinitic fragments. This zonation is expressed by the alternation of red ferruginous and white kaolinitic lineations, that develop in a meter scale and are independent of fractures. These lineations are abundant in the upper part and are reduced to scattered spots downwards. The ferruginous zonations give a pink yellow color at the matrix, suggesting that iron is been removed from the present profiles with possible transformation of hematite into goethite.

Transition facies. This facies, with thickness to 3 m in the kaolinite deposit, was observed only in the lower part (0.50 m) of the bauxite deposit. It is characterized by a greater amount of alumino-ferruginous nodules embedded in a kaolinitic and gibbsitic matrix. The nodules are formed by gibbsite, quartz, hematite-gibbsite-quartz association and hematite with ferruginous halos, gradually disappearing into the matrix. The gibbsite shows irregular outline embayments of dissolution that put

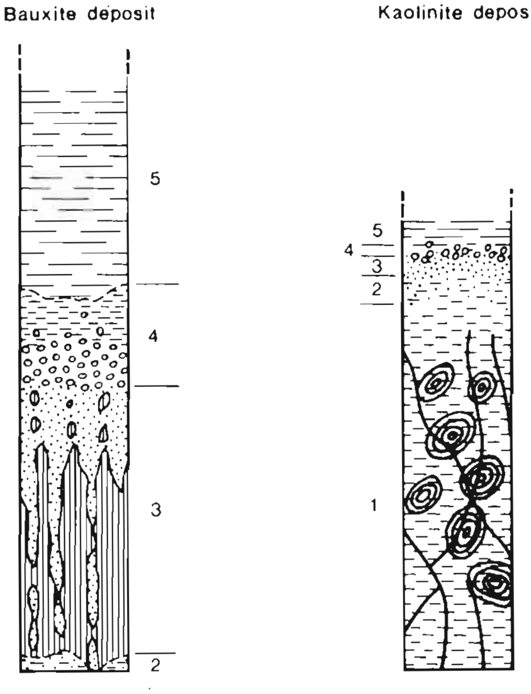


Figure V.4 - Schematic section of the bauxite deposit and kaolinite deposit of Vargem dos Óculos (Quadrilátero Ferrífero).

the gibbsitic and the kaolinitic matrix side by side. These nodules, sometimes with internal voids, could be relicts of an older alumino-ferruginous crust or bauxite. All the nodules show gradual transition with the yellowish brown matrix. Nodules and matrix are also submitted to a new deferruginisation that leads to the formation of kaolinitic matrix with few ferruginous relicts. This unit seems to result from the degradation of an older bauxitic crust that itself was submitted to a great accumulation process of aluminum and iron. The degradation process is characterized by a deferruginisation of the alumino-ferruginous nodules and an iron redistribution in the ferruginous bands and by a resilication observed in the gradual contact between the well crystallized gibbsite and kaolinitic matrix.

Bauxite horizon. Rather thin in the kaolinite (1 m), this unit can reach 3 m thick in the bauxite deposit. In the lower part, it is constituted by an association of red volumes embedded in yellow volumes. Both are cut down by white volumes, appearing as vertical pockets in the middle part and getting coalescent to form wholly the upper part. The red volume is formed by irregular shaped and sometimes coalescent nodules with mainly hematite-gibbsite mineralogical composition; the gibbsite is in close association and indistinguishable from the hematite and also appearing coating cracks and voids. The edges of the nodules show a gradual transition with yellow zones of which the mineralogical composition is mainly goethite and gibbsite. In the middle part, it can be observed a clear contact between the alumino-ferruginous nodules and the white volumes. Under the microscope, at the edges of these vertical pockets, it seems that the white gibbsitic matrix results from the deferruginisation of the alumino-ferruginous nodules that is complete in the upper part. Then the bauxitic facies is formed by small relicts of well crystallized gibbsite embedded in a cryptocrystalline gibbsite.

In the kaolinite deposit, this facies is reduced to a thin horizon of red alumino-ferruginous relict nodules embedded in a white gibbsitic matrix.

Ferruginous nodular facies. This facies, with a thickness varying from 0.5 to 2.5 m in the bauxite deposit, is represented only by some dispersed nodules in the kaolinite deposit. In the bauxite deposit it is characterized by irregular shaped nodules, with variable size (3 to 10 mm), cemented by a red yellow matrix and forming a crust. Some indentations of these crusts go into the subjacent white bauxite, showing a progression of the ferruginisation downwards. The nodules are either a hard, dark red compound, mainly constituted of hematite and gibbsite, or a friable, pink yellow compound with gibbsite, hematite and goethite. These nodules have the same structures as the alumino-ferruginous ones of the bauxitic facies and are surrounded by a goethitic-gibbsitic cortex.

In the upper part, this facies shows relict fragment nodules composed of hematite, goethite, gibbsite and quartz. The middle bauxitic unit is characterized by the presence of relict nodules of an older alumino-ferruginous formation that give evidence of deferruginisation process, going, even, with resilication process, as observed in the kaolinite deposit.

Covering Unit. The unit is barren, presenting clear sedimentary features. Two superimposed layers include nodules of ferruginous crust, bauxite and itabirite, that is oriented parallel to the bedding. It can be observed, in the interstitial voids of these sediments, gibbsite coating that indicates a permanent dependence on the alumino-ferruginous crust situated at the low slope.

Chemical Composition

The deposits of kaolinite and bauxite of Vargem dos Óculos present the same sequence of horizons and so, for the chemical composition, the samples were grouped according to the facies, regardless the type of deposit: I. lower kaolinite, II. lower transitional zone, III. bauxite, IV. ferruginous zone and upper transitional zone. The covering layer, being completely barren, as concerning the mining point of view, is not considered in this discussion. The chemical composition for the different facies are shown in Table V.2.

Major Elements. The diagrams SiO_2-Al_2O_3-Fe_2O_3 (Fig. V.5) and TiO_2/Fe_2O_3 (Fig. V.6) were obtained from the results of the chemical analysis (Table V.2) and give a better idea of the chemical variation for the different facies.

As concerning the low clay (I), analyzed only in the kaolinite deposit, it can be observed that their samples are grouped close together which means that they are very homogeneous.

In the lower transitional zone, in both kaolinite and bauxite deposits, it seems that the points are very scattered. Nevertheless, it can be noticed that some samples are closer to the subjacent clay (Vk5), while other ones are nearer to the bauxites (Vk51b and Vb12-13). In the former, where the petrographic analysis has shown evidences of resilication, an increase of TiO_2 content is observed.

In the bauxite, it can be observed (Fig. V.6) that the TiO_2 amount increases, while the Fe_2O_3 content decreases. This result indicates that the deferruginisation process, identified in the petrographic analysis, led to a residual accumulation of titanium and alumina, probably by a volume reduction.

In the upper part, as observed in the petrographic analysis, the bauxite undergoes a ferruginisation process, that results in a relative decrease of TiO_2 content. This observation is valid for both, the red bauxites, not submitted to deferruginisation, and the TiO_2 rich white bauxites, that underwent deferruginisation.

Thus, the detailed analysis of the major elements variation makes possible to set the various steps of the supergenic history of the deposits. By no means it is possible to assure the affiliation between bauxite and the basal kaolinite. However, the discontinuity, put in evidence in the transitional zone, was masked by the deferruginisation and resilication processes. In any case, considering its relative horizontal settlement, it seems to be of sedimentary origin.

Table V.2 - Chemical analysis of the kaolinite deposit (vk) and bauxite deposit (vb) of Vargem dos Óculos (Quadrilátero Ferrífero).

	Massive kaolinite				Transition facies			Bauxite			Ferruginous nodules			
	VK 1	VK 2	VK 3	VK 4	VK 5	VK 51a	VK 51b	VK 52a	VK 52b	VK 53	VK 54a	VK 54b	VK 55a	VK 55b
SiO2	42.61	43.25	43.17	42.48	40,21	14.55	23,89	8.10	6.15	3,19	5.87	3,57	3.47	2,25
Al2O3	37.83	38.01	37.88	37,43	34.95	22,50	42.89	39.66	59,05	56.86	34.09	22,82	27,22	54,68
Fe2O3	1.02	0,89	0,93	1,21	5.17	46,19	2,91	26,05	2.88	5,82	33.85	50,45	47,73	12,91
TiO2	2,57	2.36	2.60	2.50	2,50	2,31	4,35	3.12	3.92	3,78	2.19	1,45	2,16	2,58
H2O+	13.77	13,97	13,87	13,92	13,90	12,02	20,00	20,35	26,22	26,25	19,55	17,82	16,80	25,02
H2O-	0,55	0,35	0.40	0,42	0.25	0,52	0,20	0,32	0,10	0,15	0,40	0,70	0,87	0,35
Mn	0,01	0,01	0,02	0,01	0,02	0.02	0,03	0,02	0,02	0,02	0,02	0,01	0.02	0.03
Total	98,36	98,84	98,87	97,97	97,00	98,11	94,27	97,62	98,34	96,07	95,97	96,82	98,27	97,82
Cr	314	266	253	259	286	224	274	296	338	352	199	196	191	149
Ni	34	84	79	79	65	29	38	18	18	7	9	10	8	7
Sr	62	108	117	119	111	81	7	113	10	80	72	50	47	7
Ga	71	72	72	71	75	75	75	92	98	97	55	69	43	60
V	139	136	136	165	274	687	126	221	129	138	387	2355	422	140
Zn	30	54	64	59	48	102	28	54	16	18	70	98	87	33
Zr	313	300	319	315	315	264	510	393	492	494	291	320	308	330
Nb	49	39	43	93	40	40	86	58	76	75	40	44	40	49
Y	26	26	28	24	24	18	48	28	49	5	18	17	16	30
La	47	63	70	69	81	52	93	74	68	100	37	32	28	57
Ce	147	150	160	162	160	92	174	129	144	179	62	55	49	110
Nd	43	49	65	58	63	31	56	44	40	50	19	16	14	25
Sm	10,00	11,00	15.00	12,00	13,00	6,00	11,00	8,40	7,80	8,30	3,40	3,20	2,80	5,30
Eu	2,10	2,40	2,80	2,60	2,60	1,00	2,00	1.50	1.50	2,60	0.60	0,60	0,50	1,10
Gd	4,80	6,00	6,20	5,00	4,40	2,60	5,60	3,60	3,90	5,90	1.50	1,30	1,50	3,30
Dy	7,00	9,00	10,00	8,40	7,30	2,80	5,40	4,00	3,90	5,20	1,50	1,50	1,30	3.50
Yb	2,40	2,10	2,30	2,00	2,30	2,30	4,50	3,20	3,20	5,00	1,10	1,10	1,30	3,60

	Transition facies			Bauxite					Ferruginous nodules			
	Vb 14	Vb 13	Vb 12	Vb 1	Vb 2	Vb 3a	Vb 3b	Vb 4	Vb 5a	Vb 5b	Vb 6	Vb 7
SiO2	5,83	9,47	7,49	1,66	1,62	2,05	1,13	1,60	2,16	1,26	4,44	4,17
Al2O3	55,79	47,29	46,55	53,91	54,05	41,68	63,25	62,19	23,13	58,10	22,88	25,90
Fe2O3	8,02	16,67	18,90	14,94	14,72	31,15	2,44	3,35	54,89	8,76	55,11	44,85
TiO2	2,52	2,61	2,92	3,36	3,42	2,54	4,15	3,91	1,18	3,65	1,25	3,10
H2O+	27.02	23,75	23,42	27,00	26,92	22,40	30,05	30,47	17,50	28,45	16,15	19,25
H2O-	2,40	0.27	0.42	0,17	0,15	0,45	0,02	0,01	0,80	0.07	0,72	1,65
Mn	0,01	0,02	0,02	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02
Total	101,59	100,08	99,72	101,06	100,89	100,28	101,05	101,54	99,67	100,30	100,56	98,94
Cr	251	303	319	366	378	348	385	346	312	275	290	291
Ni	2	8	1	1	4	1	1	1	2	1	2	1
Sr	100	103	108	135	128	91	136	109	40	89	44	53
Ga	80	105	110	93	122	118	101	101	105	95	114	150
V	222	268	340	520	323	665	171	208	1510	280	1248	381
Zn	13	22	21	14	13	16	8	8	23	12	25	32
Zr	537	715	556	530	328	440	761	735	624	741	307	560
Nb	47	60	47	45	12	38	71	64	51	69	21	50
Y	41	54	41	40	18	32	56	52	46	56	19	40
La	57	68	67	77	74	51	80	48	28	59	29	36
Ce	104	122	123	140	140	98	142	100	48	110	50	63
Nd	37	44	43	47	45	32	51	29	18	35	16	23
Sm	7.30	8,50	8,44	8,92	8,62	6,44	9,91	5,55	3,60	7,11	4.07	4.82
Eu	1,26	1.50	1,42	1,45	1,50	1,13	1,67	1,06	0,68	1.43	0.72	0.91
Gd	4.19	4,24	4,94	4,97	5,00	3,83	5.80	3,37	2,04	10,70	1,98	4.72
Dy	4,86	4,77	5,79	5,72	5,51	4,51	7,06	4.15	2,30	15,40	2,35	3,33
Yb	3,18	3,50	4.03	4,23	4,00	3,25	4,75	2,60	1,81	11,90	2,16	3,81

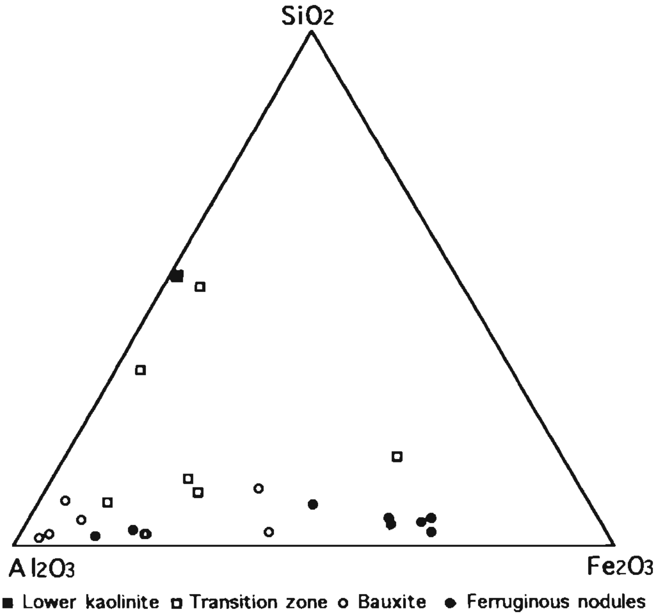


Figure V.5 - Diagram SiO_2 - Al_2O_3 - Fe_2O_3 of the main facies of Vargem dos Óculos deposits.

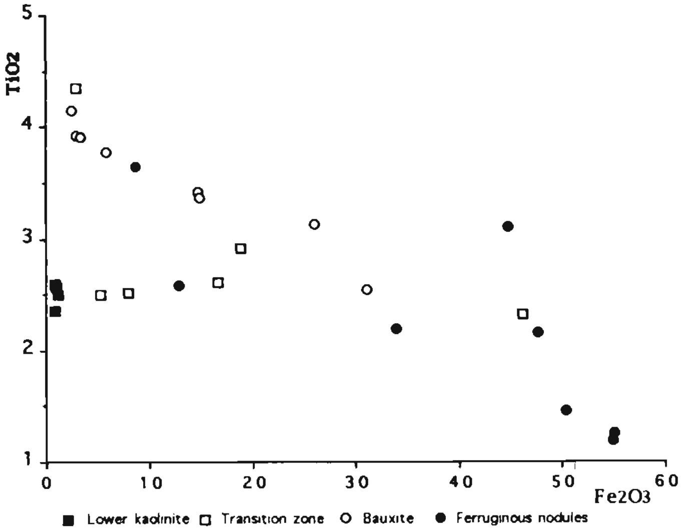


Figure V.6 - Relationship Fe_2O_3 vs TiO_2 of the main facies of Vargem dos Óculos deposits.

Trace elements. The results, concerning the trace elements for the bauxite and kaolinite (Table V.2), show that certain elements (Zr, Nb and Y) present a behavior similar to titanium. Thus, the white argillomorphic bauxite and the transitional clay zone underlying the bauxite horizon, which are richer in titanium, present also a higher content of these elements (up to 760 ppm), that would be submitted to a residual concentration. Despite not having been analyzed, it is known that the zircons contain the analyzed Nb and Y (Murali et al., 1983; Hinton & Hupton, 1991).

The gallium contents follow as well the Ti behavior, but their correlation is not as good as the one for Zr and with a larger difference between the bauxite and the kaolinite deposits.

On the other hand, vanadium and, in a less extension, chromium present a behavior close to the iron one. Thus, the higher values of vanadium correspond to the more ferruginous facies, regardless the deposit type, indicating that V follows iron throughout the different steps of the supergenic cycle.

Rare Earth Elements. The Rare Earth Elements analyses for the bauxite and kaolinite deposits are shown in Table V.2, and the Fig. V.7 presents the diagrams of their distribution, normalized to chondrites. It can be observed that the bauxitic horizons, the subjacent ferruginous nodules and the lower transitional horizon present very similar distribution. For the last two horizons, the REE contents are very close (ΣREE =200 to 300 ppm) with a ratio Lach/Ybch varying from 10 to 15. On the contrary, in the ferruginous nodules, the ΣREE decreases (100 to 200 ppm) and the ratio Lach/Ybch is lower than 10, at least for the bauxite deposit. It is noticed that, during the ferruginisation, there is a slight increase of heavy REE as compared to the light REE.

The distribution of the REE for the low clay, as compared to the overlaying horizons, is rather different, with a higher content (ΣREE about 300 ppm) and with a ratio Lach/Ybch normally over 20. This result point out also the existence of a discontinuity between the lower clay and the bauxite horizons.

As for the parent rock, not identified in the area, the results of the REE distribution in a rhyodacite from the Paraná Basin (Piccirillo & Melfi, 1988) was used for comparison. A good correlation was found, reinforcing the idea of a volcanic origin for the kaolinite and bauxite deposit.

The chemical analysis as a whole, has shown that, in both bauxite and kaolinite deposits, a continuous gradation exists between the

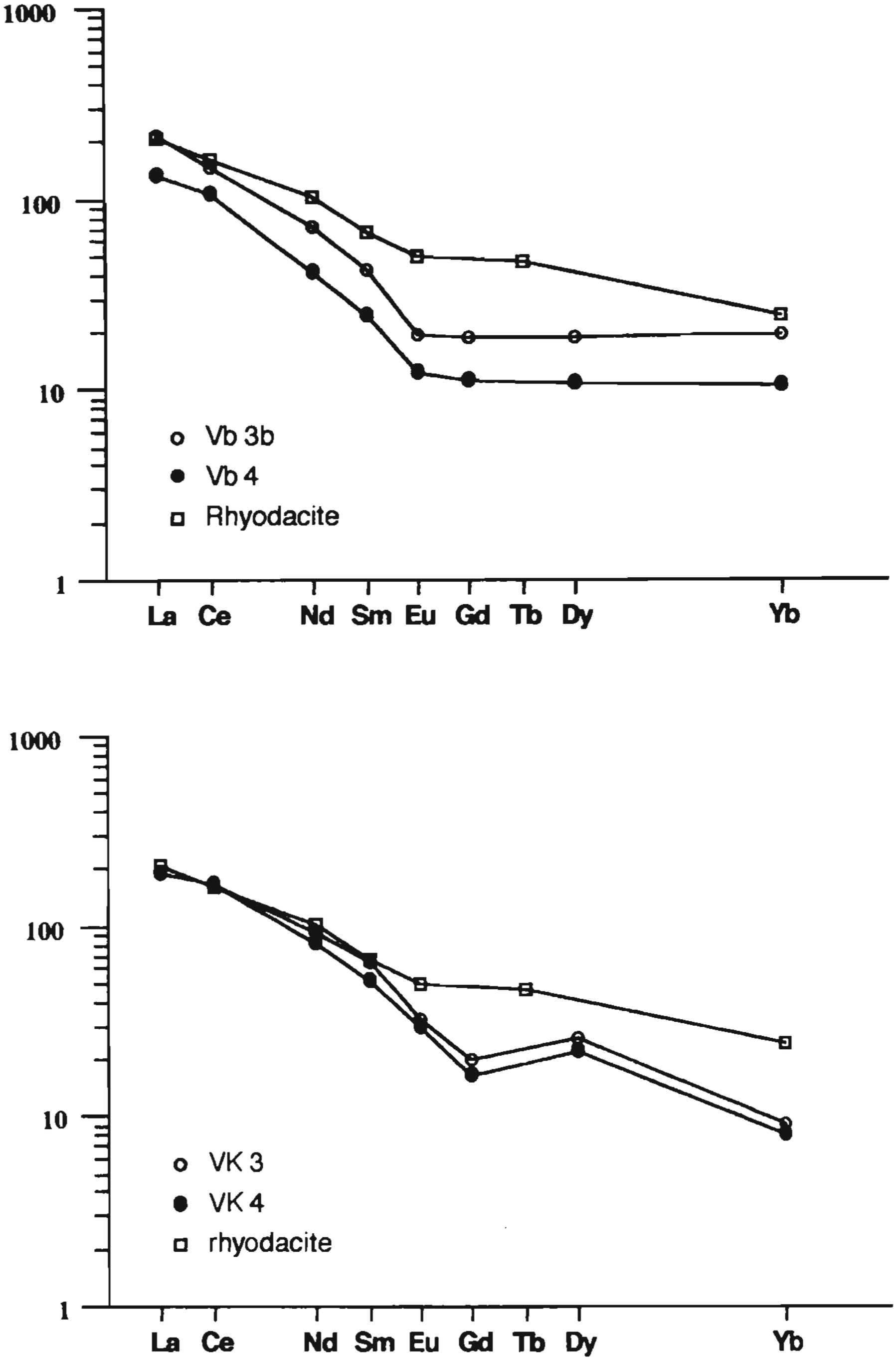


Figure V.7 - Representative chondrite-normalized REE abundances for bauxite deposits (vb) and kaolinite deposit (vk) of Vargem dos Óculos. For comparation, REE abundance for rhyodacite from Piccirillo & Melfi (1988).

bauxite submitted to resilication and the lower transitional clay horizon, as well as, between the bauxite submitted to a strong ferruginisation and the overlaying ferruginous nodules.

On the other hand, it was also shown a discontinuity between the three upper units and the underlying kaolinite.

As considering the REE signature, one can say that both kaolinite and bauxite deposits would be formed by the transformation of a parent rock of volcanic type.

4. Type IV. Low Plateau Bauxite - Macaquinho Deposit

The Macaquinho bauxite deposit is located in the eastern part of the "Quadrilátero Ferrífero", 11 km far from Santa Rita Durão. It is situated in the southern edge of "Chapada do Canga", a large plateau, with altitude of 900 m, capped by an argillo-ferruginous crust (Fig. V.1). According to Maxwell (1972), this crust would probably be developed on sediments of Fonseca Formation, which are Eocenic in age (Lima & Salard-Cheboudaeff, 1981).

The deposit is rather uniform as concerning both the thickness (6 m) and the facies distribution. It presents, from the bottom to the top, the following facies: friable bauxite, alumino-ferruginous crust and nodular facies.

Friable bauxite. This facies is a reddish brown blocky bauxite with a thickness of 4 m. These blocks (> 10 mm) are constituted by nodules embedded friable matrix. The nodules (< 2 mm), having irregular shape, are formed by small rounded gibbsitic white volumes (0,3 to 0,5 mm), disseminated in a brown ferruginous matrix, mainly goethitic. The matrix enveloping the nodules is very porous and it is also formed by gibbsite and goethite. The pores are coated with ferruginous and gibbsitic cutans. The nodules and the matrix are relatively rich in quartz grains (1 to 5%), having diameters up to 0,5 mm and presenting dissolution features. This bauxite contains nearly 49% Al_2O_3, as gibbsite, and about 18% Fe_2O_3, mainly as goethite.

Alumino-ferruginous crust. This crust is formed, in the lower part, by a massive facies (1 m) and, in the upper part, by a lamellar facies (0,5 m). Both facies are heterogeneous and constituted by an association of brownish red volumes and white volumes. Its matrix is rather similar to the one of the bauxite, with more intense ferruginisation. This crust contains about 35% Fe_2O_3 and 32% Al_2O_3 mainly as gibbsite and goethite, in its lower part, and gibbsite, hematite and goethite, in its upper part.

Nodular facies. This facies is originated by the dismantling of the alumino-ferruginous crust forming a nodular horizon. The nodules are nearly rounded and with size varying from 1 to 3 cm.

As considering their morphological and chemical characteristics, the Macaquinho deposit type is totally different as compared to the other deposits of the "Quadrilátero Ferrífero". Despite the lack of reliable analytical data, the facies sequence, the high silica content associated to the presence of quartz, would allow to consider these bauxites as close to the Porto Trombetas deposit, developed on sediments. This fact reinforces the hypothesis of Maxwell (1972), who considered these bauxites as formed on the Tertiary sediments of Fonseca Formation.

IV. Discussion

The bauxite deposits of the "Quadrilátero Ferrífero" are grouped into 4 different types: the high plateau bauxites (Type I); the hill slope bauxites (Type II); the depression bauxites (Type III) and the low plateau bauxites (Type IV). The majority of the deposits were formed on metasedimentary rocks, except for the type IV, that were originated from sedimentary rocks.

The Figure V.8 shows a diagram with the distribution of the various deposits, according to their altitudes. It can be observed that the type I bauxites occurs always in altitudes higher than 1,500 m, while the type II deposits can be found in altitudes ranging from 1,400 to 800 m. The type III, despite having very few examples, can be associated with the depressions in different altitudes , but always related to hill slope bauxite of type II. The type IV deposits occurs only on a lower surface (900 m), at the external position of the eastern border of "Quadrilátero Ferrífero".

The bauxite of the higher plateaus shows, in general, no evidence of a relationship between the bauxite and the underlying rock and, as a consequence, an allochthonous origin cannot be completely discarded.

As a matter of fact, the deposit of Conta História presents also a clear discontinuity between the bauxite and the underlying hematitic itabirite. This discontinuity is underlined in the foot-wall of the bauxite, by a thin layer of goethite. This plateau is tilted towards the west and the iron and aluminum content show a variation, according to this inclination. Thus, the more aluminous facies are situated upwards, while the more ferruginous ones are downwards. The upper part of the plateau

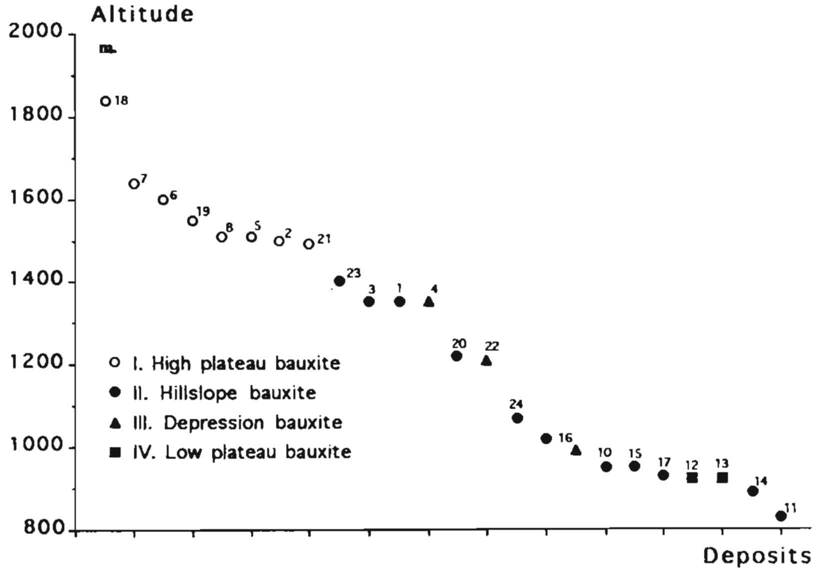


Figure V.8 - Heigh distribution of the Quadrilátero Ferrífero bauxite deposits.

constitutes a cliff, several tens of meter high, certainly related with a fault.

In this case, as well as in the Batatal plateau, it is quite possible that a tectonic event associated with an intense mechanical erosion, following the bauxitisation process, could be responsible for a topographic inversion that placed the recent plateaus in a relatively higher position. But, as considering the analysis carried out by Braun (1970), it seems to be quite difficult to accept these bauxites as correlated material developed on the Gondwana surface. Nevertheless, as for their different characteristics, these bauxites can be considered as the most ancient deposits of "Quadrilátero Ferrífero". They could be associated with a bauxitic alteration process occurring during the post-Gondwana cycle, described, by Braun (1970), as a period having a humid climate, a tectonic stillness and a paralic sedimentation with abundant fossils.

The beginning of the "Sul Americano cycle", in the upper Cretaceous, was marked, in other regions, as for example, the coastal basins, by an intense erosional activity, the formation of Barreirinhas and Paraíba do Sul grabens (see chapter Passa Quatro) and the uplifting of Serra do Mar and Mantiqueira ridges. In the "Quadrilátero Ferrífero", during this erosive period, new slopes were elaborated, cutting down the phyllites of Minas Supergroup, leaving in a high position the bauxite plateaus, as well as the itabiritic crest lines. At the same time, the sediments removed from the "Quadrilátero Ferrífero", specially by the penetration of Rio das Velhas or Rio Piracicaba, were deposited in the outermost zones to form the Fonseca Sediments, dated mid to upper Eocene by Lima & Salard-Cheboudaeff (1981).

Thus, it was after this erosive event that, between the end of the Eocene and the Pliocene, an intense bauxitisation period has occurred. Consequently, the phyllites were submitted to a bauxitisation process, forming a series of deposits, qualified as hill slope bauxite (type II), that are distributed within the altitudes of 1,640 m (Gandarela) and 830 m (Fazenda do Sapé). It was also during this period that certain sedimentary zones of Fonseca Formation have undergone a bauxitisation process (type IV deposits - Macaquinhos and Faria).

The profiles of the hill slope area, like Morro do Fraga, were normally formed by an "in situ" alteration of the inter stratified phyllites of Minas Group. These deposits are associated with itabiritic walls that forms the surrounding morphology. On the top of this itabiritic crest, a lateritisation process formed an iron crust, locally named "canga". The iron, liberated from the itabirite, occurring in the upper part of this slope, moves down as ferrihydrate and it is changed into hematite as soon as the profile is submitted to desiccation. Consequently, the hill slope bauxites are frequently very rich in iron.

On the other hand, the itabiritic crest lines, as well as the bauxitic hill slope, can dominate closed depressions, that are very common in the Moeda syncline. Some of them are completely closed, while others are totally opened by the regressive erosion due to the cutting down of Rio das Velhas. However, the depression of Vargem dos Óculos is only partially opened. In this case, the regressive erosion that cut down through the bottom deposits has preserved part of the hill slope.

In the depression of Vargem dos Óculos (Fig. V.9), it can be found iron crusts, forming the crest line and relicts products, and sometimes, even bauxites, scattered on the slope. Despite not have been studied, it seems that they were the result of a bauxitisation process. The bauxites would be of the same type of those of Morro do Fraga deposit

The study carried out on the bauxite and kaolinite deposits that occurs in Vargem dos Óculos has shown the presence of a discontinuity in the profile, between the lower kaolinite layer and the bauxitic layers, which is marked by deferruginisation and resilication of the bauxite. It was also noticed that this discontinuity was probably due to a process involving an alluvial/colluvial sedimentation.

Thus, at the same time of the bauxitisation or during the period of

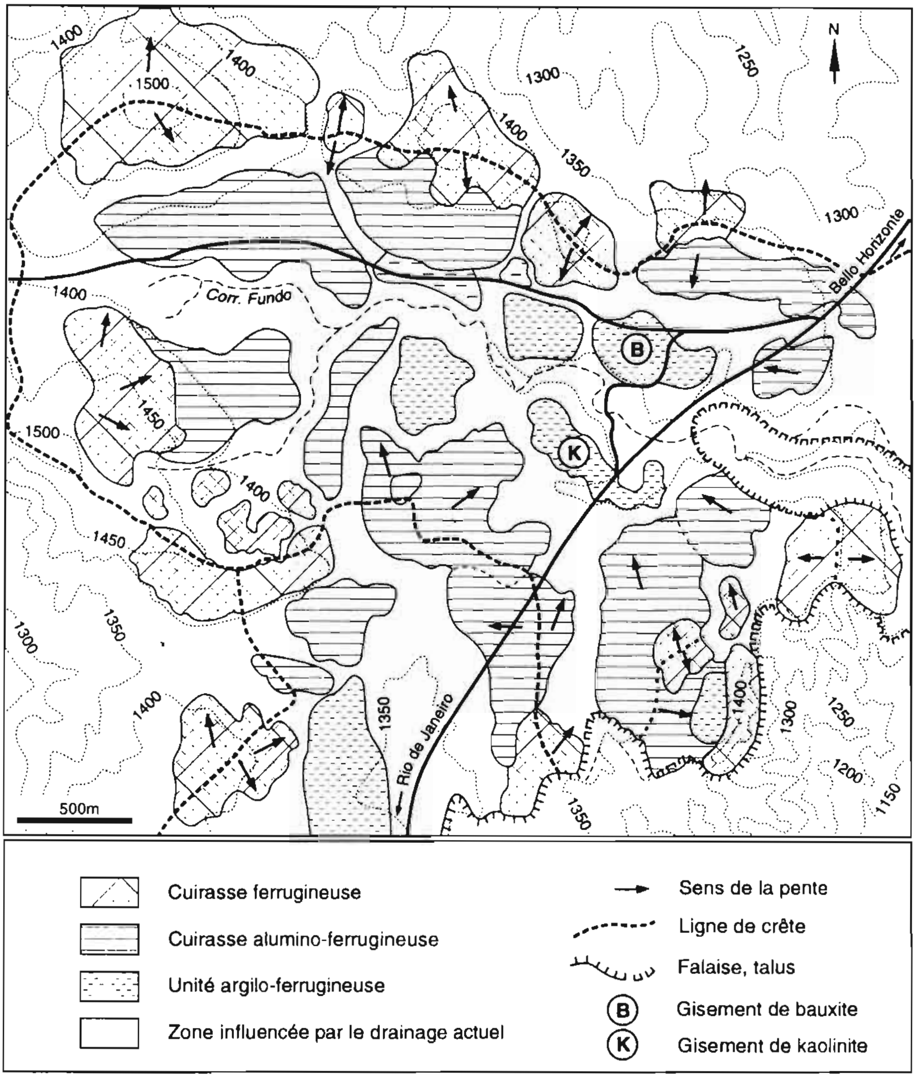


Figure V.9 - Schematic geomorphological map showing the distribution of the surficial formations in Vargem dos Óculos area.

a later mechanical erosion phase, the bauxite fragments removed from the slope were sedimented in the depression bottom, on the weathered kaolinite. The fact that very few bauxite was left on the slope would be an evidence that the mechanical erosion was quite strong. The bauxite deposit was later covered by the barren unit, constituted mainly by kaolinite and ferruginous nodules coming from the iron crust and presenting clear evidences of sedimentation.

Under this thick covering layer, the bauxites, previously deposited, were submitted to a degradation process. In the lower part, in the contact with the clay layer, the hydromorphic condition led to an important deferruginisation. Additionally, the silica supplied by the alteration of the itabirites, would favor the resilication process. The latest was much more accentuated in the kaolinite deposits, that occupy the lower part of the depression, and less developed in the bauxite deposits closer to the north slope.

In the upper part, an iron crust was developed and it still progress presently in the bauxite which is marked by clear signs of ferruginisation. The upper part of this crust, under the barren cover, is submitted to deferruginisation.

As concerning the parent material of the bauxite deposits of "Quadrilátero Ferrífero", its identification was rather difficult, particularly considering that the profiles were deeply modified by the successive aluminous and ferruginous accumulations, masking completely the evidences of the original rock. Nevertheless, the field observations and the laboratory data of the studies carried out recently (Varajão C., 1988) seem to indicate that, except for the type IV, the bauxite deposits were formed from metapelites, probably dolomitic phyllites.

However, in the case of Vargem dos Óculos deposit, the parent material seems not to be of the same kind. As a matter of fact, the origin of the deposits has been always a matter of controversy, nevertheless, a consensus about the allochtonous origin of the parent material was apparently achieved. Thus, for Pomerene (1964), these deposits were formed by an "in situ" evolution of alluvial sediments, that, according to Souza (1983), were derived from carbonated phyllites. Considering their topographic situation, the sediment was interpreted as deposited in paleo-playas (Barbosa & Rodrigues, 1965; 1967) or in karstic depressions (Barbosa, 1980; Dorr, 1969; Fleischer & Oliveira, 1969). Dorr (1969) interpreted the high Ti values as an evidence of a contribution of volcanic material in the sediments. On the other hand, Barbosa & Rodrigues (1965) suggested the climatic and hydric variations as the responsible for the formation of the different facies of the deposits. However, it has to be considered that these studies were mainly based on global analysis of the horizons observed in the deposits.

Recently, detailed studies carried out in the area (Varajão A., 1988; Varajão et al., 1989; Boulangé & Carvalho, 1991) allowed to have a better idea about the origin and the evolution of these deposits.

The complex evolution of the different products deposited in the depression bottom, finish by removing completely the limits of any sedimentation that could exist between the bauxite and the underlying clay layer. As a matter of fact, this discontinuity, shown by the petrographic and chemical analysis, is actually of sedimentary origin. Thus, it seems that the parent rock of the hill slope forming the bauxite and the one of the bottom depression originating the kaolinite are identical, and the RRE signature would be the proof of it. Additionally, this signature, close to the one for rhyodacite, would confirm the idea of Dorr (1969) that the parent rock would be of volcanic type.

There is no real evidences concerning the origin of these volcanic rocks. They could be contemporaneous to Cauê and Gandarela formations, or a result of a thrusting affecting the volcanites of Nova Lima group during the Transamazonic cycle, or even of a late paleo-Eocene eruption marking the beginning of Sul Americano cycle. The opening of the depressions and its mechanical erosion has either erased any trace of the alteration or preserved some relict islet of bauxite in the slope and/or the bottom deposits. These events would correspond to the beginning of Velhas cycle (Pliocene).

Evaluating the period of the bauxitisation process in the "Quadrilátero Ferrífero" is not an easy task. However, taking into consideration that deposits of the same type are formed at the same age, it is reasonable to admit that the different altimetric levels were already present at the time of the bauxitisation.

Actually, the fact that the majority of the bauxite deposits of the "Quadrilátero Ferrífero" presents nearly the same sequence of facies and with the same characteristics, independently of their topographic situation, seems to indicate that they were originated under the same geological conditions. Thus, they would be formed by a bauxitisation process that occurred after the topography evolution, in different levels. Evidently, the process would happen later than the deposition of Fonseca Formation (Eocene) and, consequently, the bauxites of "Quadrilátero Ferrífero" would be formed in a post-Eocene period, probably associated with the Sul Americano cycle. The opening of the depressions and its mechanical erosion has either erased any trace of the alteration or preserved some relict islet of bauxite in the slope and/or the bottom deposits. These events would correspond to the beginning of Velhas cycle (Pliocene).

On the other hand, the association between the type I deposit and the post-Gondwana surface could be interpreted as an evidence of an older bauxitisation period, that would precede the topographic evolution that would be contemporaneous to the "Sul Americano" cycle.

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Chapter VI

THE CATAGUAZES BAUXITE DEPOSIT

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The studied bauxite deposit occurs mainly in the south eastern part of Minas Gerais State. It is included in a long aluminum belt, extending from São João do Nepomuceno up to the Northeast of Cataguazes.

This deposit, presenting a total of more than 100 million tons, constitutes Brazil's major reserve of aluminum ore. It was developed on Precambrian high grade metamorphic rocks (gneisses and granulites), which form the Juiz de Fora Complex.

The previous information about these deposits comes from the prospecting carried out in the region by the mining company (Curimbaba report, 1981) and lately from a study carried out in the vicinity of Cataguazes by Roeser et al. (1984).

Since then, the genetic aspects of this bauxite belt have been studied systematically within the Brazilian-Germany cooperation program, a joint project of the Universities of São Paulo and Hamburg, resulting in a serie of master's and doctor's thesis (Lemke, 1986; Kehlenbeck, 1986; Lopes, 1984; Beissner, 1989) and publications (Lopes & Carvalho, 1989; Valeton & Melfi, 1988; Valeton et al., 1991). Most of this paper is based on the results of the mentioned authors.

I. Regional Aspects

The area under investigation is situated west and north of Cataguazes, its most important town. The region is characterized by the presence of various "half-oranges" hills, systematically capped by bauxite.

The geology of the area is characterized by the Precambrian Juiz de Fora Complex of the Mantiqueira Province. It presents NNE-SSW strike and is mainly constituted by a great variety of medium to high grade metamorphic rocks associated with gneissic rocks (Fig. VI.1) (Brandalise et al., 1976; Oliveira, 1981, 1982; Barbosa & Grossi Sad, 1983).

This lithology is not regularly distributed, but it is possible to distinguish longitudinal bands, nearly continuous and parallel. The most inner band shows light gray fine granulites alternating with charnockites,

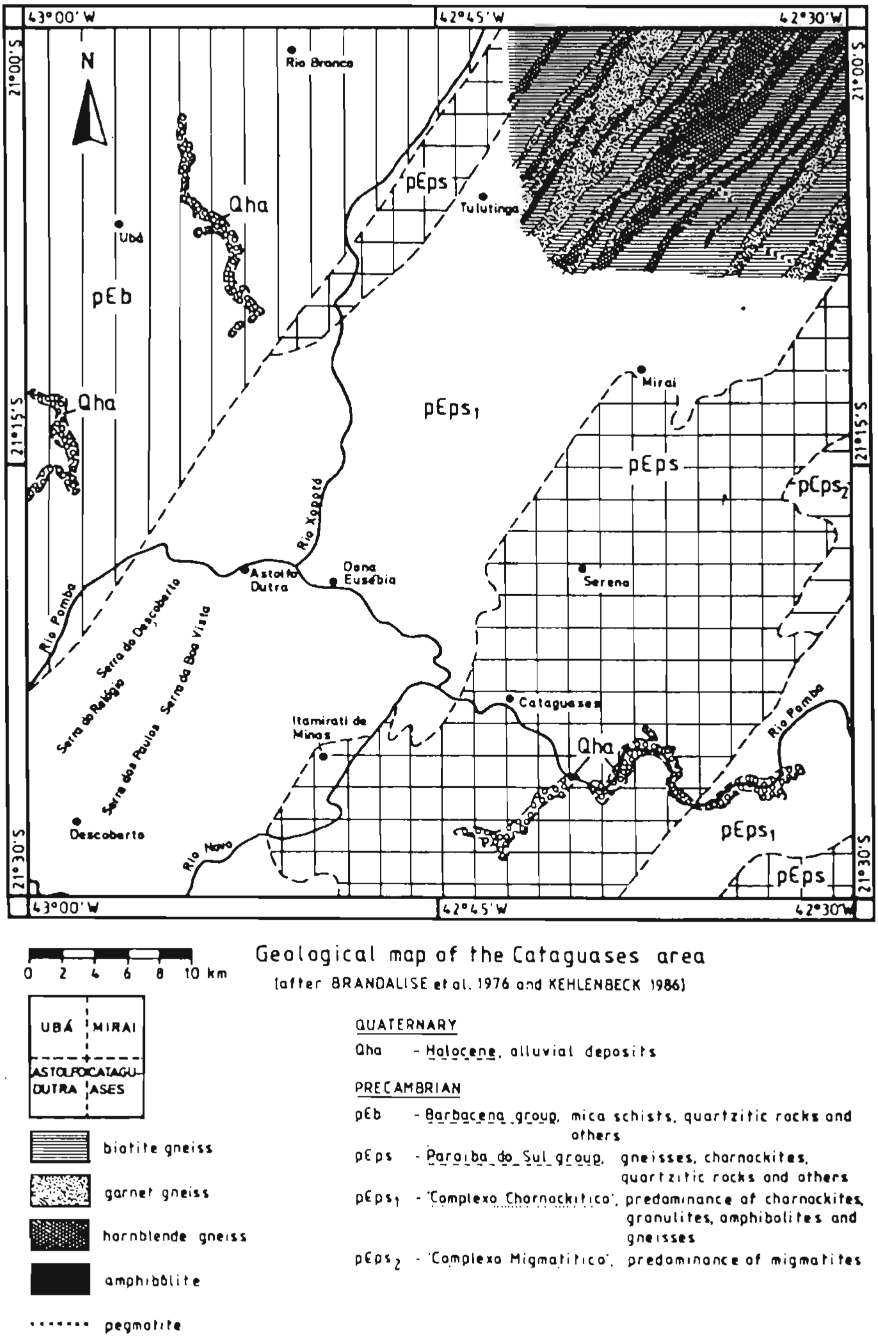

Figure VI.1 - Geological map of the Cataguazes area (after Brandalise et al., 1976 and Kehlenbeck, 1986).

enderbites and more basic phases. The following band shows varied migmatites with lentils and small bodies (boudins) of marble, amphibolites and quartz. In the region of Paraíba do Sul river, it shows banded gneisses and granulites.

The great variety of parent rocks is characterized by a mean range in SiO_2 of 47-66 wt.%, which is followed by an equivalent variation of all the accompanying elements. The Al_2O_3 values range is between 14-17 wt.%, essentially independent of the silica contents of the parent rocks.

On the basis of its geochemistry, Valeton et al. (1991) proposed to divide the parent rocks into four groups:

1. basic rocks (amphibolites, amphibole-pyroxene rocks) of probable magmatic origin;
2. intermediate rocks of predominantly magmatic character (amphibole-gneiss, amphibole-biotite-gneiss);
3. intermediate to acid rocks, comprising various metasediments;
4. acid rocks, mainly of metasedimentary origin (biotite-garnet-gneiss, biotite-gneiss with small contents of amphibole).

The folding and metamorphism of the banded gneisses led to a NE-SW directed foliation and a general SE dip. Cataclastic zones parallel to the foliation show a strong mylonitization.

The region presents two different morphologic structural domains, being the first one the crest alignment of Paraíba do Sul (alinhamentos das cristas do Paraíba do Sul) and the other one the stepped depression of Pombas-Muriaé rivers (depressões escalonadas dos rios Pomba-Muriaé) (Radam, 1983).

The first unit reflects the high geological control of the topography and it is constituted by oriented and flat hills facing convex concave ones. The other unit shows a topography dissected by the hydrographic basins of Pomba and Muriaé rivers, characterizing a stepped relief with altimetric levels between 100 and 700 m.

The climate of the area is characterized by an annual mean temperature of about 24°C, except for the regions with higher altitudes, where it is lower than 22°C. During the warmest month (January), the average temperature reaches 30-32°C in most of the region and is slightly lower (<29°C) in the higher altitudes. During the winter, the temperatures are milder (14°C), attaining 6-8°C in the higher zones.

The annual rainfall average is around 1,500 - 1,900 mm, with a maximum during the summer and minimum during the winter. It is a typical seasonal regime of the tropical zones.

The original vegetation of the region is the Tropical Semi-deciduous Forest (Radam, 1983), also known as Tropical Broadleaf Forest (Azevedo, 1960). It is characterized by high trees, with more than 25 m and a second stratum with 12 - 25 m. It is very little known, since most of it was totally destroyed.

II. Profile Characteristics

The bauxite deposits of Cataguazes occur on the summit regions (between 700-900 m) of more or less flat-topped hills of a so-called "half-orange" topography. The rest of the topography, corresponding to lower surfaces, is covered by a more clayey material (red sialitic saprolite) (Fig. VI.2). Some profiles are affected by younger dissolution and erosion or recovered by scree material.

In the region of Cataguases, it can be found mainly two types of profiles: in-situ and allochthonous profiles.

The complete in-situ profiles show the same sequence of horizons in the whole region (Fig. VI.3). They are formed by the basal saprolite, that comprises the isalteritic gibbsitic layer and isalteritic kaolinitic layer, and by the overlying bauxitic zones, constituted mainly by an isalteritic bauxite layer. An alloteritic bauxite layer is frequently intercalated in the isalteritic layer.

1. Alloteritic bauxite layer

It is constituted by resistant reddish and reddish-violet colored fragments, presenting essentially gibbsite and hematite, with whitish spots of gibbsite. It presents an important macro-porosity (cavities and voids), some of which filled in by allochtonous ferruginous clay material (ferrans and ferri-argilans). Some of these crystals have evolved to zoned ferri-gibbsitans. As a consequence of this absolute accumulation, the structure is completely destroyed.

2. Isalteritic bauxite layer

It shows a thickness varying from 5 to 20 m and is presented as resistant fragments with preserved gneissic structure and yellowish-white, rose and reddish color and a composition of gibbsite and hematite. It shows also a gibbsitic matrix, with various goethite pseudomorphs filled in by gibbsite as a result of absolute accumulation (gibbsitans). The quartz presents diffuse outlines and dissolution golfs, enveloped by gibbsite.

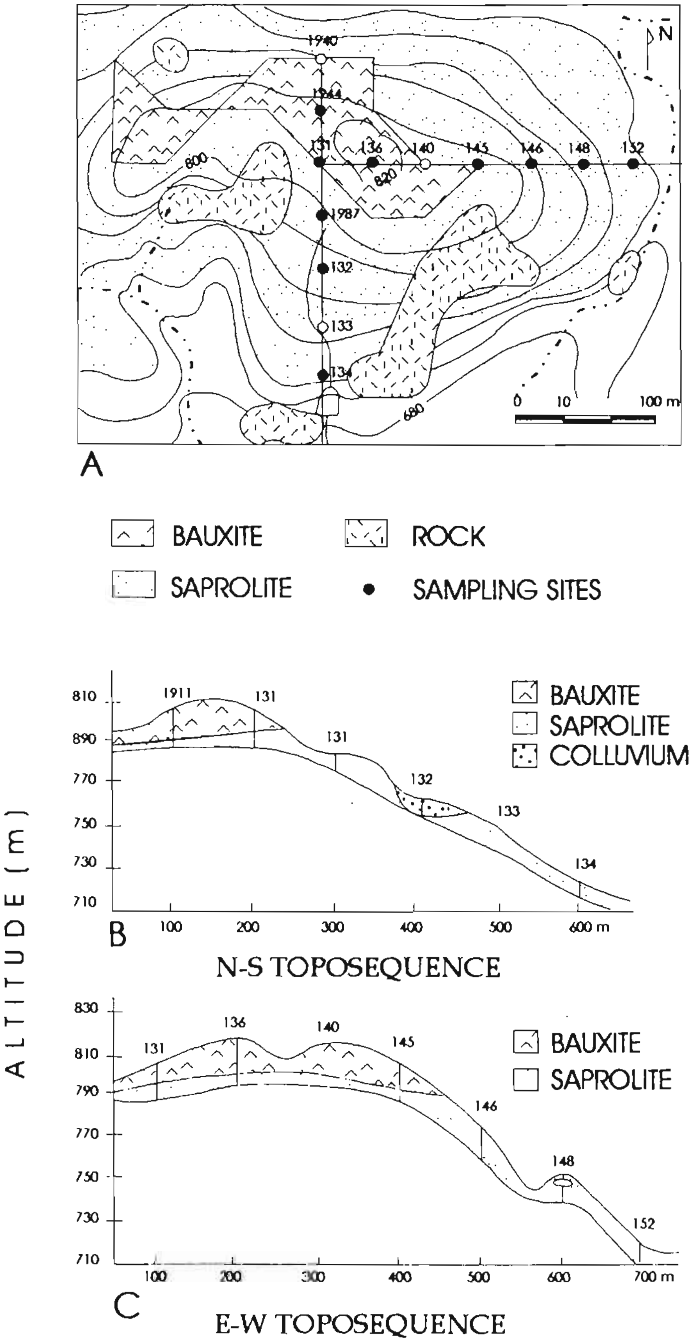

Figure VI.2 - Map showing toposequences N-S and N-E and correspondent profiles.

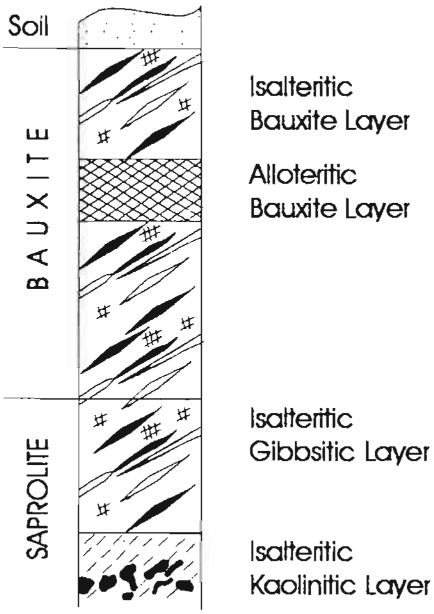

Figure VI.3 - Schematic hilltop alteration proflie showing the different horizons.

The upper part changes into an horizon formed by bauxite pebbles that correspond to an in-situ collapsed residual breccia. Locally, it is enriched in residual root system.

3. Isalteritic gibbsitic layer

It is constituted by fragments characterized by the presence of discontinuous bands with white, yellowish white and rose colors (essentially gibbsitic). These bands alternates with ferruginized mafic ones. The porosity is of fissure type. This layer is formed by a matrix showing pseudomorphose of gibbsite crystals on feldspar porphiroclasts and of goethite crystals on hiperstene and/or hornblende and also kaolinite either derived from biotite or from recrystallization process. It was also observed the presence of quartz with fractures, sometimes filled by gibbsite or by ferruginous material.

4. Isalteritic kaolinitic layer

It is formed by weathered rock fragments, with tabular shape and constituted by whitish sandy clay material. It presents a fissure porosity accordingly with the original foliation. These fragments are embedded in a friable clay matrix, of gibbsitic and kaolinitic composition. The fractures and fissures are filled by a whitish material (Halloysite $4H_20$) and a black material (Lithiophorite). Fractured quartz grains also occur, sparsely distributed or sometimes forming discontinuous layers or monomineralic layers.

The isalteritic bauxite layer is often covered by reworked material constituted by bauxite and/or clay horizon. The exactly boundary between in-situ and reworked material, especially along the slopes, is difficult to define. The contact between compact in-situ bauxite, residual breccia and reworked material, is often irregular and resembles a "karst" topography.

An about 0.30 to 1.00 meter thick recent soil is formed at the present surface, containing reworked bauxite pebbles.

Both, gradation from parent rock to saprolite and directly to bauxite are possible. On top of the hills, the saprolite is missing or underdeveloped. On slopes with depressions or along joints, faults and mylonites, a rather thick saprolite may be well developed.

The allochthonous profiles occur normally in local depressions along the hill slopes and are mainly composed of reworked material. These materials are mostly the result of local displacement by downslope mass movement. Slopes in other places are covered by isolated bauxite fragments lying in a kaolinitic matrix, which contains finely disseminated gibbsite.

III. Chemical composition

The behavior of main and trace elements of saprolites and bauxites, in relation with the four types of their parent rocks, is presented in Table 1. It can be seen that the distribution of the single elements, as well as their ratios, clearly depend on the parent rock parameters.

1. Major Elements

Silica, besides the alkalis and alkali-earth metals, is the most mobile and dissolved element in the profiles, during the alteration. The mean values in the bauxites range from 2 (in those derived from basic rocks) to 10% with a maximum value of 24% (in the profiles derived from more acid rocks). It has been preserved as relict quartz or combined with alumina (kaolinite and halloysite).

Table VI.1 - Chemical composition of main and trace elements of ferralitic weathering profiles on various parent rocks, Cataguases area (BREISSNER, 1989).

parent rock:	amphibolite (point 5 + 6)					amphibole-biotite-gneisses (point 7 + 8)							
	bauxite (n = 23)				saprolite (n = 1)	bauxite (n = 41)				saprolite (n = 12)			
main elements (wt.%)													
	$\bar{X}$	X_{min}	X_{max}	sdX		$\bar{X}$	X_{min}	X_{max}	sdX	$\bar{X}$	X_{min}	X_{max}	sdX
SiO_2	2.32	1.00	5.167	1.24	15.77	8.44	1.10	23.96	6.23	38.47	32.85	44.04	3.25
Al_2O_3	40.73	34.84	47.55	3.17	28.57	50.69	43.06	59.58	3.20	33.94	30.45	37.23	1.99
Fe_2O_3	27.19	20.30	35.53	3.88	33.53	11.09	3.42	17.47	3.76	9.45	4.91	15.66	2.79
MgO	0.11	0.00	0.29	0.08	0.11	0.02	0.00	0.14	0.04	0.01	0.00	0.13	0.04
MnO	0.03	0.01	0.08	0.02	0.06	0.01	0.00	0.03	0.01	0.03	0.00	0.17	0.05
CaO	0.04	0.01	0.06	0.02	0.04	0.01	0.00	0.05	0.02	0.03	0.00	0.03	0.01
Na_2O	0.02	0.00	0.04	0.02	0.15	0.04	0.00	0.016	0.03	0.05	0.00	0.34	0.10
K_2O	0.01	0.00	0.06	0.02	0.00	0.04	0.00	0.08	0.03	0.02	0.01	0.08	0.02
TiO_2	2.98	1.43	4.01	0.68	3.91	1.36	0.36	2.33	0.53	0.97	0.64	1.82	0.34
P_2O_5	0.32	0.19	0.68	0.10	0.31	0.22	0.08	0.44	0.10	0.13	0.08	0.21	0.04
H_2O^+	23.83	18.34	26.92	1.87	16.64	27.30	22.38	31.96	2.10	14.53	12.92	16.47	0.85

X: main value; X_{min}: minimum value; X_{max}: maximum value; sdX: standard desviation

parent rock:	garnet- gneisses (point 14)				biotite-gneisses (point 1)				
	bauxite (n = 5)				bauxite (n = 1)				saprolite (n = 1)
main elements (wt.%)									
	$\bar{X}$	X_{min}	X_{max}	sdX	$\bar{X}$	X_{min}	X_{max}	sdX	
SiO_2	10.37	4.74	15.53	5.40	9.11	1.02	23.02	7.12	32.29
Al_2O_3	49.50	42.44	53.93	3.31	45.44	32.16	54.54	5.57	27.36
Fe_2O_3	11.20	9.53	16.91	1.78	17.31	11.12	30.25	3.52	20.58
MgO	0.04	0.00	0.08	0.04	0.08	0.00	0.40	0.10	0.03
MnO	0.01	0.00	0.01	0.01	0.03	0.02	0.09	0.01	0.05
CaO	0.04	0.04	0.05	0.01	0.01	0.00	0.04	0.01	0.03
Na_2O	0.01	0.00	0.05	0.02	0.03	0.00	0.08	0.02	0.00
K_2O	0.03	0.00	0.10	0.04	0.05	0.00	0.08	0.02	0.01
TiO_2	1.29	0.52	2.60	0.44	2.45	1.53	4.39	0.55	3.06
P_2O_5	0.27	0.13	0.50	0.17	0.20	0.09	0.21	0.07	0.50
H_2O^+	26.61	23.56	29.12	3.12	24.67	17.34	29.83	3.339	12.12

X: main value; X_{min}: minimum value; X_{max}: maximum value; sdX: standard desviation

Table VI.1 - continuation

parent rock:	amphibolite (point 5 + 6)									amphibole-biotite-gneisses (point 7 + 8)			
	bauxite (n = 23)				saprolite (n = 1)	bauxite (n = 41)				saprolite (n = 12)			
trace elements (ppa)													
	$\bar{X}$	X_{min}	X_{max}	sdX		$\bar{X}$	X_{min}	X_{max}	sdX	$\bar{X}$	X_{min}	X_{max}	sdX
Ba	26	0	63	19	40	18	0	124	23	50	0	157	48
Ce	31	0	432	88	36	29	0	235	48	225	0	1255	405
Cr	401	143	1448	315	189	52	16	128	26	34	18	52	9
Cu	97	35	164	37	78	26	3	54	12	45	13	101	24
Ga	26	12	35	6	27	38	22	77	12	47	26	70	11
La	6	0	29	10	0	10	0	114	26	5	0	17	7
Nb	44	28	66	11	50	13	0	39	11	14	3	34	9
Nd	5	0	21	7	5	9	0	57	13	2	0	9	3
Ni	1	0	12	3	11	26	0	90	17	65	20	174	46
Sr	4	0	8	3	5	1	0	15	3	3	0	5	1
Vi	884	662	1208	179	1193	193	46	352	77	138	61	269	55
Y	2	0	9	2	0	6	0	19	5	3	0	10	4
Zn	2	0	17	4	2	20	0	71	19	65	38	99	21
Zr	168	108	272	37	144	180	47	660	128	118	58	216	536

X: main value; X_{min}: minimum value; X_{max}: maximum value; sdX: standard desviation

parent rock:	garnet- gneisses (point 14)				biotite-gneisses (point 1)				
	bauxite (n = 5)				bauxite (n = 1)				saprolite (n = 1)
trace elements (ppa)									
	$\bar{X}$	X_{min}	X_{max}	sdX	$\bar{X}$	X_{min}	X_{max}	sdX	
Ba	4	0	22	11	40	0	222	47	93
Ce	51	0	105	51	109	3	910	180	53
Cr	151	112	228	67	92	31	223	47	54
Cu	22	13	32	16	13	0	32	7	20
Ga	55	48	61	5	27	8	47	11	43
La	30	0	50	21	39	0	225	58	51
Nb	16	3	28	9	43	12	85	15	42
Nd	27	0	54	21	33	6	137	33	38
Ni	0	0	0	0	20	4	36	7	11
Sr	3	2	5	1	4	0	45	10	8
Vi	155	111	201	65	262	141	364	47	194
Y	4	1	8	3	9	0	26	6	15
Zn	30	18	35	17	9	0	48	14	105
Zr	13	165	490	122	666	241	1888	380	510

X: main value; X_{min}: minimum value; X_{max}: maximum value; sdX: standard desviation

Alumina, in the saprolites and in the bauxites as well, becomes enriched respectively in kaolinite or in gibbsite. But an essential part is also fixed in the iron minerals. The mean values lie between 40 (in those formed from basic rocks) and 51% with a maximum value of 60% (in the other types). The free alumina content depends on the contents of coarse quartz grains and kaolinite.

The iron contents in saprolites and bauxites reflect those of the parent rock. The lack of permanent hydromorphic and reducing conditions preserved the Fe:Al ratio and led to a relatively stable and high content of iron minerals (goethite and late formation of hematite) (Table VI.1). Bauxites overlying amphibolites contain nearly 30%, those on gneiss range between 15 to 21% iron mineral content. As iron becomes enriched together with aluminum, titanium and stable trace elements are also enriched.

Titanium in the more basic parent rock is incorporated in amphiboles and biotite (3-6% TiO_2), in addition to the primary Ti-minerals (ilmenite, rutile, sphene). In the saprolites and bauxites, finely disseminated anatase, up to 4%, is formed. Parts of the titanium content also occur in the secondary iron minerals.

2. *Trace Elements*

The trace elements distribution is related either to their previous concentration in the parent rocks and to the supergene concentration or depletion.

Therefore, Zr is mainly found as a proper mineral zircon in intermediate and acid rocks, or it occurs, like Ti, in amphiboles of the greenstone facies. It is, thus, correlated with Ti.

Zr mineral becomes relatively enriched in saprolite and in bauxites. Together with Zr, the elements Nb and REE La, Ce, Nd are found in considerable concentrations.

The isomorphous Zr in amphiboles of the greenstones increases considerably during the ferralitic alteration together with an increase of iron and titanium in the bauxites.

Analogous to iron, V and Cr present higher values due to the previous concentration in the parent rock.

Gallium, which appears in all primary rocks in relatively low concentration, increases via saprolite, in the bauxites. It is not found in the separate minerals and thus is presumed to replace Al isomorphicaly in gibbsite.

Ba and Sr, mainly originating from feldspars or from mineralization of veins, are dominantly depleted during the ferralitic alteration.

IV. Mineralogical evolution

The weathering profiles contain relict minerals (quartz, zircon, rutile, opaque minerals, etc.) and neoformed minerals.

The formation of neogenetic minerals in saprolites and bauxites depends on the primary minerals and on the intensity of drainage. The neogene minerals are kaolinite, gibbsite, goethite (with varying Al contents), hematite and traces of anatase and Mn minerals.

Table VI.2 shows the schematic evolution of the main minerals for the different profile horizons.

In the saprolites, feldspar is pseudomorphically replaced by kaolinite. In addition kaolinite also occurs as matrix. In these horizons, its content reaches 90%, while in the bauxite horizon it is less than 10-15%. The fine-grained matrix kaolinite in the saprolite possess a low crystallinity due to its inter growth with hematite. The crystallinity increases clearly in the bauxitic zone.

In the bauxite horizon, the transformation of the feldspar is isovolumetric concerning the space and results in the formation of gibbsite

Table VI.2 - Schematic evolution of the main minerals for the different profile horizons.

		ALTEROPLASMA			SKELETON
BAUXITE	Aloteritic	Gibbsite via Kaolinite	Gibbsite via Kaolinite	Goethite	Quartz, partialy dissolved
	Isalteritic	Gibbsite	Kaolinite Gibbsite ⇖ ⇗	Goethite	Quartz, partialy dissolved
SAPROLITE	Gibbsitic isalterite	Gibbsite	Kaolinite	Goethite	Quartz
	Kaolinitic isalterite	Isothropic material	Kaolinite	Goethite	Quartz
Alteration zone	Minerals	⇧ Feldspar	⇧ Biotite	⇧ Homblend Hiperstene	Quartz

SAPROLITE BAUXITE

septa along grain boundaries, cleavages and cracks. The way of alteration corresponds to the model of gibbsite-septa formation described by Nahon & Bocquier (1983).

The iron bearing minerals (garnet, biotite, amphibole and pyroxene), due to the good drainage, are replaced without leaving intermediate layer silicates, by oxides or hydroxides (goethite and hematite). The substitution of iron by aluminum is always greater in goethite than in hematite. The alteration step by step into goethite is described in detail in Bressner (1989).

As considering the alloteritic bauxite, the loss of the original structure, together with the presence of gibbsite and hematite, suggest a polyphasic evolution.

V. Genetic aspects

The genetic interpretation of the bauxite profiles of Cataguazes was rather difficult, particularly due to the heterogeneity of the parent rock.

On the other hand, it has to be considered that the chemical composition of the parent rocks was not very much favorable to the formation of bauxite. Thus, it was the morphological aspects together with the tectonic conditions, the predominant bauxitization factors. The tectonic activities, either acting as a structural control or uplifting the surfaces, has facilitated the chemical action and the erosion of the materials.

The bauxite formation was close related with the landscape evolution and particularly with the development of different planation plains. Valeton et al. (1991) suggested within Cataguazes area four different levels of elevation: above 1,000 m; 800-1,000 m; 500-800 m and 300-500 m.

The elevations above 1,000 m would represent erosional relicts of the so-called post-Gondwana surface. Between 500 and 1,000 m, the relicts of the hilly landscape of the "Sulamericano" surface form flat-topped summits bearing in-situ bauxites. The lower levels could be attached to Velhas cycle and Paraguassu cycle and are covered by fersialitic material.

According to Valeton et al. (1991), the morphological evolution of the area can be divided into three cycles, close related with the bauxitization process: pre-bauxitic, syn-bauxitic and post bauxitic cycles.

The pre-bauxitic history is characterized by the evolution of a continuous and extensive planation surface (Sulamericano surface).

This surface, cut deeply down by the weathering, would originate the "half-orange" topography, with differences in altitude of about 100 to

300 m. This topography would be the surface during the time of in-situ bauxite formation. The position of the weathering profile across the hills, showing a downsloping, would corroborate this hypothesis.

The post-bauxitic morphogenesis is characterized by the dissection of the existing surface, due to the tectonic uplift of the Sulamericano surface. The tectonic activities has risen up this surface to the present level (500-1,000 m). The bauxite was preserved and fossilized only on the "half orange" topography on top of Sulamericano surface. On the resulting lowered surfaces, a soft, red fersialitic (kaolinite-hematite) material was developed.

Taking into consideration the petrological characteristic of the studied profiles and the proposed morphological and tectonic aspects, it is possible to evidence some points about the evolution of the material.

The bauxite profiles were developed under good and permanent descending drainage, without continuous stagnation of the ground water and without reduction and separation of iron from aluminum. This is only possible in a kind of intersected land surfaces.

The contact between fresh rock and the bauxite, frequently very sharp and without intermediate zone (sialitic), seems to indicate that a strong pre-bauxitic erosion "cleaned" the Sulamericano surface and exposed fresh rocks.

The study of the different alteration layers showed that the bauxite profile of Cataguazes region was submitted to a rather complex process, resulting in a polyphasic evolution.

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THE BAUXITE OF NAZARÉ PAULISTA AND ASSOCIATED DEPOSITS

S.M.B. Oliveira & M.C. Toledo

Introduction

There are some small bauxite deposits along the southeastern Brazilian Atlantic coast, mainly in the states of São Paulo, Rio de Janeiro, and Espírito Santo. Among them, Nazaré Paulista, Curucutu and Mogi das Cruzes are the best known, with resources of about 6.10^6 ton of ore (Fig. VII.1).

Bauxite is derived from the lateritisation of Precambrian basement rocks of the Mantiqueira Province (Almeida et al., 1981). The lithological types comprise migmatites, gneisses, schists, amphibolites, and quartzites, cut by granitic and doleritic intrusions. These rocks have a general NE orientation and belong to different blocks separated by ancient and deep thrust faults.

The relief is mountainous with altitudes up to 1500 m. Paraíba do Sul and Tietê rivers are the principal drainage systems.

The climate is tropical humid with some few drier months during winter. Mean annual temperatures range between 16 and 26°C. Mean annual precipitation is around 1500 mm.

I. Nazaré Paulista

The Nazaré Paulista deposit is located 45 km northeast of the city of São Paulo, in a region known as Itaberaba Ridge, at altitudes of about 1300 m.

The area is built up by Precambrian basement belonging to the Itaberaba Group. It is a Proterozoic volcano-sedimentary sequence comprised of metabasic rocks (metaigneous and metatuffaceous rocks of basic to intermediate composition), calco-silicate rocks (metamarls and metadolomites), and metapelitic rocks (sericite schists). A granitic intrusion cutting the sequence transformed the nearby lithologies into hornfels.

The bauxite deposit was formed by lateritisation of metabasic rocks (amphibolites) in top and slope topographic positions.

According to Beljaviskis et al. (1984), resources total 5.6 10^6 tons of ore with 35% Al_2O_3, 7.7% SiO_2 and 29% Fe_2O_3.

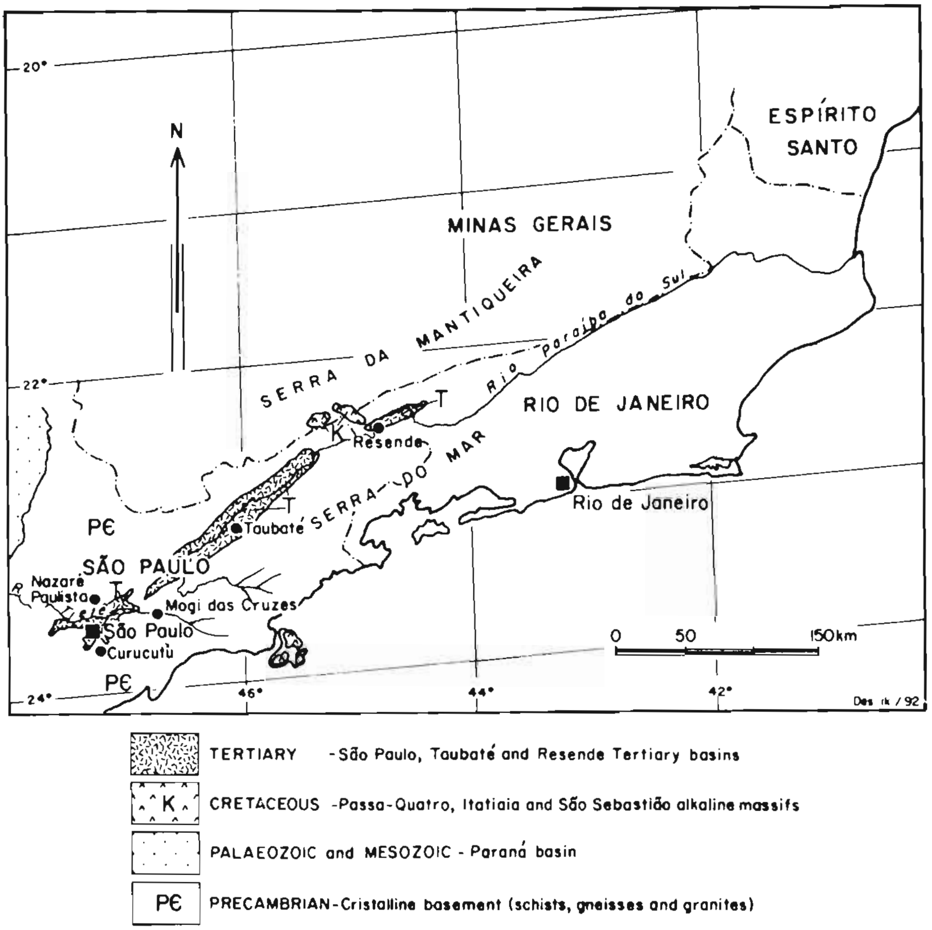

Figure VII.1 - Regional geological map of the southeastern Brazilian Atlantic coast.

1. *Profile-type*

At the Itaberaba Ridge the spatial distribution of bauxite is controlled by the topography. At altitudes higher than 1000 m, the weathering tendency is toward the formation of bauxite. Between 1000 and 930 m, the bauxitic horizons are thinner and mixed up with argillaceous material. At lower topographic levels, there is no more *in situ* bauxite, but only bauxite blocks in the colluvial horizons that cap the kaolinitic weathering profiles.

The bauxitic horizon is always in the upper parts of the weathering profiles, outcropping on the tops and being covered by a colluvial horizon on the slopes. Its thickness varies from less than 1 m on the slopes to 5 or 6 m on the tops (average 2.6 m). It is generally continuous, but can be intercalated with argillaceous levels. Such levels can also exist between the bauxitic horizon and the parent rock, but in general bauxite lies directly above the amphibolite.

Two main types of bauxite can be distinguished from a macroscopic point of view: a compact ore and a friable ore. The compact ore is a yellow reddish spongy material cut by very pure white bauxite veinlets, which preserves the original textures of the parent rock, being therefore of isalteritic type. The friable ore consists of centimetric to millimetric fragments of the compact ore in a yellow clayey matrix, and generally occurs near the surface. It seems to have been formed by disaggregation of the compact ore. Locally, pure gibbsite concretions of varied shapes and sizes can also be found.

2. Mineralogical composition

The fresh rock is formed by hornblende and plagioclase as main constituents and quartz, chlorite and titanite as accessory minerals.

Gibbsite and goethite are the most important minerals in bauxite. Quartz, kaolinite, lithiophorite and anatase can also be present. Gibbsite occurs as pseudomorphs after plagioclase and also filling voids formed by the hydrolysis of the hornblende. This mineral alters into goethite, leaving a very porous network. Quartz crystals, disseminated in the gibbsitic plasma, are generally fractured and corroded.

In the argillaceous level, kaolinite predominates, and lithiophorite is more abundant. The clay mineral is well crystallized and forms a cristalliplasma that, unlike gibbsite, does not replace pseudomorfically the plagioclase crystals. Kaolinite seems to have been formed from the dissolution of plagioclase through an amorphous phase.

3. Chemical evolution (Silva & Oliveira, 1989)

A. Behavior of major and trace elements.

The average composition for fresh rock and its weathering products is shown in Table VII.1. Lateritic products have much higher contents in Fe, Al, Ti, LOI, Cr, Pb, V and Zr, and lower contents in Si, Mn, Li, Y and Zn than fresh rock; they are totally depleted in Ca, Mg and Sr.

Isovolumetric calculations for major elements (Table VII.2) show that, in bauxites, Ca and Mg are totally leached, Si is almost totally leached, Fe is slightly leached and Al remains nearly constant. In clays,

Table VII.1 - Average contents in major and trace elements for 50 samples (Nazaré Paulista, São Paulo state).

	FRESH ROCK N = 3	BAUXITE N = 17	CLAY n = 30
	Major elements in %weight		
SiO_2	48.8	8.1	27.0
TiO_2	1.4	1.9	1.7
Al_2O_3	14.0	37.4	27.1
Fe_2O_3	16.4	29.3	25.6
CaO	9.52	0.03	0.03
K_2O	0.06	0.06	0.07
MgO	11.77	0.09	0.08
MnO_2	0.24	0.9	0.24
P_2O_5	0.14	0.20	0.12
LOI	-	22.8	18.0
	Trace elements in ppm		
B	5	7	17
Ba	30	19	54
Be	2	3	3
Co	60	72	88
Cr	74	558	255
Cu	164	295	182
Li	22	8	14
Mo	5	5	5
Pb	56	117	88
Sn	56	67	63
Sr	95	3	3
V	419	673	532
Y	28	4	10
Zn	121	58	101
Zr	70	126	96

the tendency is the same, the loss of Si being less intense. Such calculations demonstrate that the observed Fe enrichment in bauxites and clays is relative, that is, Fe is just less depleted than the other elements.

Pearson's correlation coefficients were calculated for 47 samples

Table VII.2 - Isovolumetric geochemical balance (% of gains and losses) (Nazaré Paulista, São Paulo state).

SAMPLE	Si	Al	Fe	Ca	Mg	DENSITY
Clay	-85	-9	-37	-100	-100	1.2
Bauxite	-94	0	-20	-100	-100	1.1
Bauxite	-94	+17	-28	-100	-99	1.3
Bauxite	-94	+7	-36	-100	-99	1.2
Fresh Rock g/100 cc	66.82	22.82	36.45	18.87	20.35	3.01

and 22 variables (Mo, K and Sr have been excluded because their contents do not vary). Table VII.3 shows the positive and negative correlation greater than 0.5. Three groups of elements can be distinguished: a) elements of the Fe-group: Fe, Be, P, Ti, V and Zr; b) elements of the Al-group: Al, LOI, Pb and Cr; c) elements of the Si-group: Si, Mn, Ba, Li, Co, Zn and Y. In each group, the elements have high positive correlation coefficients among them; elements of different groups are negatively correlated. The elements of the Fe and Al groups are in average more enriched in bauxites than in clays, revealing their marked residual behavior during weathering. The elements of the Si-group are in average depleted in lateritic products as a consequence of their higher solubility. However, except for Si, they can eventually be enriched in some samples of clays and bauxites, more often in the first than in the latter.

B. Behavior of the rare earth elements

REE contents in fresh rock were normalized to chondrite. Figure VII.2 shows a flat pattern with REE abundance about ten times over those of chondrites. It is typical of ocean floor basalts, from which the amphibolites seem to have been derived (Frascá et al., 1987).

In order to investigate the REE fractionation during weathering, the REE contents of weathered products have been normalized to average values in fresh rock. Figures VII.3, VII.4 and VII.5 represent the REE patterns for samples from 3 different profiles.

In profile A, the sum of REE contents in weathered products is less than in fresh rock (Table VII.4). Ce and La are less depleted than other REE. Some samples present Ce positive anomalies. All the heavy REE are depleted, but they normalized contents show a rising tendency according to the increasing atomic number (Fig. VII.3). In profile B, the

Table VII.3 - Pearson's correlation coefficients > 0,5 (47 samples, 22 variables) (Nazaré Paulista, São Paulo state).

	Pair of elements	Positive correlation coefficients
Cr	Al	0.554
Fe	Be	0.554
Mg	Ca	0.675
Mn	Ba	0.552
Mn	Co	0.714
Mn	Li	0.561
P	Be	0.602
P	Fe	0.606
Pb	Al	0.606
Si	Ba	0.723
Si	Mn	0.611
Ti	Be	0.757
Ti	Fe	0.744
Ti	P	0.538
V	Be	0.903
V	Fe	0.860
V	P	0.590
V	Ti	0.762
Zn	Mn	0.610
Zn	Si	0.573
Zn	Y	0.695
Zr	Be	0.676
Zr	Fe	0.716
Zr	P	0.805
Zr	Ti	0.738
Zr	V	0.640
LOI	Al	0.719

	Pairs of elements	Negative correlation coefficients
Ba	Al	0.528
Mn	Al	0.545
Si	Al	0.811
Si	Cu	0.640
Si	P	0.582
Si	Pb	0.584
Y	Al	0.547
Zn	Al	0.636
LOI	Ba	0.559
LOI	Mn	0.527
LOI	Si	0.782
LOI	Y	0.610

sum of REE in weathered products is greater than in fresh rock (Table VII.4), but the only elements that are actually enriched are La and Ce, the latter showing very strong positive anomalies (Fig. VII.4). In profile C, the sum of REE in weathered products is slightly less than in fresh rock (Table VII.4). In this profile, 3 samples are untypical, being strongly depleted in REE. In general, La is somewhat depleted and Ce is enriched, showing positive anomalies. Eu, although depleted, shows also positive anomalies. The heavy REE show the same tendency as in profile A: the heavier are less depleted (Fig. VII.5).

In all profiles, there are positive Ce anomalies, which are stronger in more REE enriched samples. REE have a general behavior during weathering, similar to the elements of intermediate solubility - Mn, Co and Y - being generally depleted in bauxite and clays, but occurring

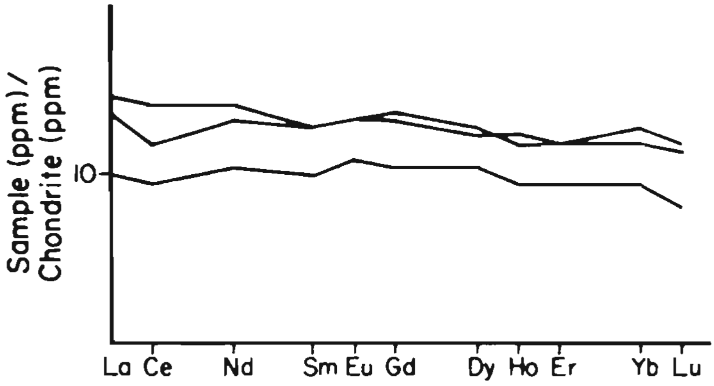

Figure VII.2 - REE pattern for the fresh rock (Nazaré Paulista, São Paulo state).

Table VII.4 - Average contents in Mn, Co, Y, Ce, and #REE (ppm) for weathered products and fresh rock in pits A, B, and C (Nazaré Paulista, São Paulo state).

	PITS	Mn	Co	Y	Ce	ΣREE
	A	400	16	3	7	21
	B	1300	195	10	91	115
	C	1000	56	7	24	36
Fresh rock		1700	60	28	11	43

locally in higher amounts (Table VII.4).

4. Concluding remarks

The lateritic weathering of the amphibolites of the Itaberaba Ridge led to the formation of an alteration blanket made up of iron bauxites on the tops and upper slopes, and clay at the lower topographic levels, where the leaching was less intense.

The elements of the Fe-group (Be, P, V, Ti Zr) and the Al-group (LOI, Pb, Cr) are more concentrated in clays and bauxites than in fresh rock. Ca, Mg and Sr are totally leached from the weathering profiles. Mn, Co, Y, Zn, Ba and Li have an intermediate behavior between the residual and the soluble elements during lateritisation. Although generally depleted in weathered products, they can be found concentrated in samples containing lithiophorite concretions.

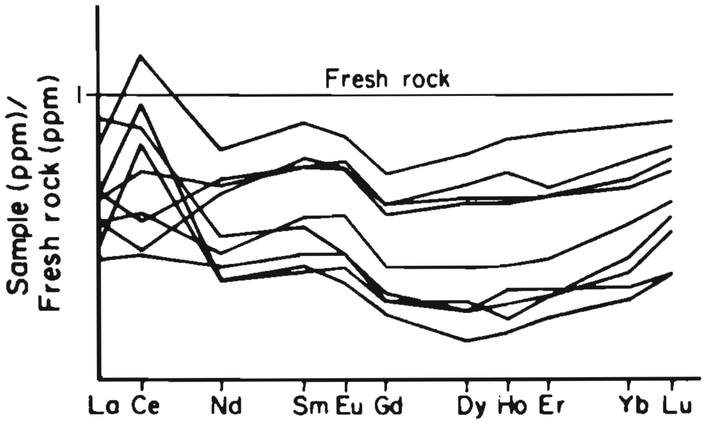

Figure VII.3 - REE pattern for the weathered products of profile A (Nazaré Paulista, São Paulo state).

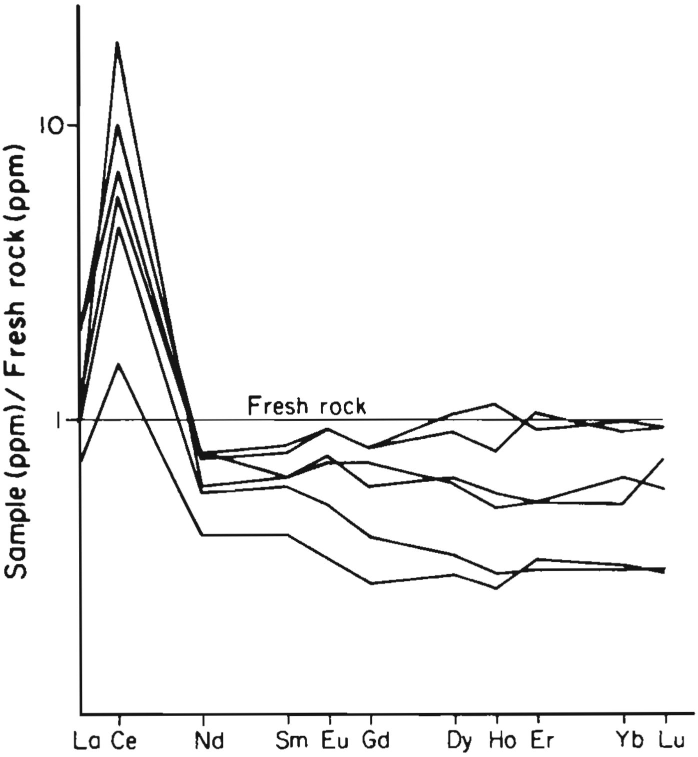

Figure VII.4 - REE pattern for the weathered products of profile B (Nazaré Paulista, São Paulo state).

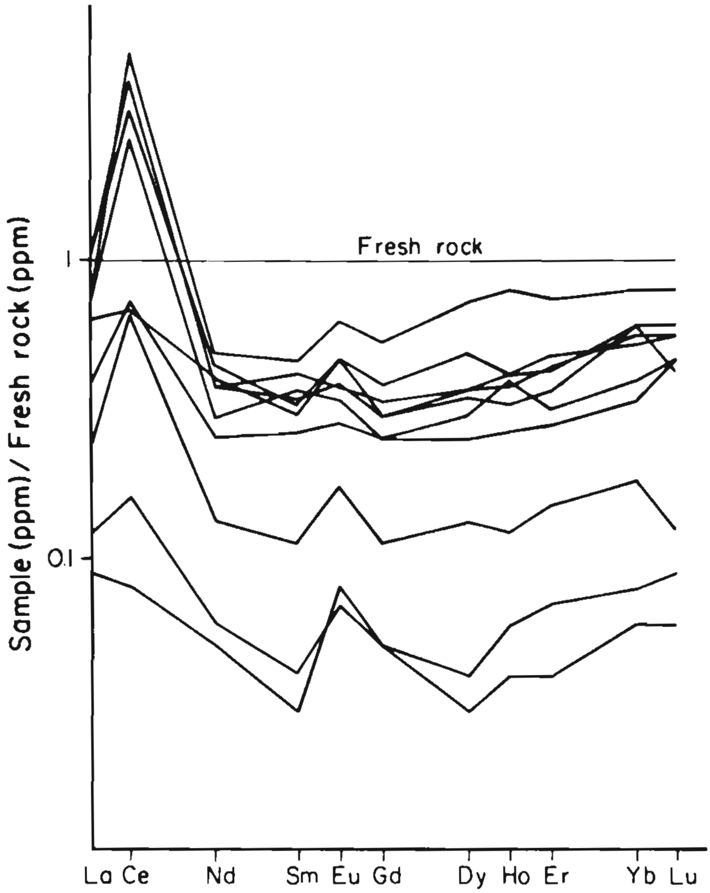

Figure VII.5 - REE pattern for the weathered products of profile C (Nazaré Paulista, São Paulo state).

REE present strong fractionation during lateritisation. Except for Ce, they are depleted in weathered products reaching higher values only in samples enriched in Mn. This correlation indicates that lithiophorite concretions concentrate REE. Positive anomalies have been found for Ce and Eu. As for Ce, they are generally interpreted as a consequence of the oxidation of Ce^{3+} to Ce^{4+} in lateritic environment. Regarding the heavy REE, the depletion is progressively less intense from Gd to Lu.

Fresh rock analysis suggests a primary association of Fe, Ti, V and REE, which was partially preserved during lateritisation. On the other hand, the association Mn-Co-Y-Zn-Ba-Li-REE was formed during weathering, corresponding to the lithiophorite neogenesis.

II. Curucutu

In the region of Curucutu, schists and gneisses of the Precambrian basement are cut by basic and ultrabasic rocks, most of which evolved into bauxitic material. The area is dotted by several small bauxitic occurrences always located at the upper parts of the landscape, summing up to 97500 ton of ore, rich in SiO_2 and Fe_2O_3, with 40% Al_2O_3 (Gomes, 1956).

A profile developed on metadiabase was studied in detail (Toledo-Groke, 1981). The parent rock is composed mainly by plagioclase, diopside and hornblende; olivine, showing a pyroxene reaction border, and magnetite are present in minor quantities.

1. Profile-type (Fig. VII.6)

A typical profile shows different weathering facies:

- Slightly Weathered Rock (SC-2). The transition from fresh rock to this facies is sharp; 1 or 2 cm from the fresh rock, the material is already almost completely altered, but the structure is still preserved.

The plagioclase is pseudomorphosed by gibbsite, and pyroxenes and amphibole by goethite, increasing the porosity and decreasing the bulk density, as compared to the fresh rock. The olivine alteration also forms goethite presenting a better crystallization than that originated from pyroxenes and amphiboles. Magnetite in the olivine fissures is preserved and the reaction cortex of the olivine, formed by pyroxene, is altered in the same way as the pyroxene crystals. Clay mineral of 2/1 type (ver-

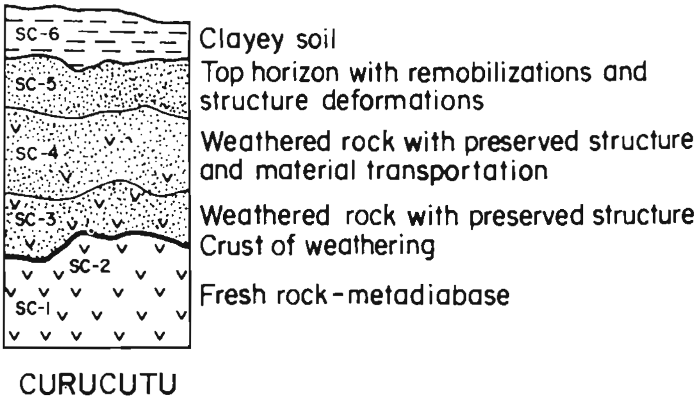

Figure VII.6 - Typical bauxitic profile of Curucutu (São Paulo state).

miculite) may be observed coating the pore walls, forming geodes and argilans.

- Weathered Rock with Preserved Structure (SC-3). The material corresponding to this weathering facies is similar to the "Slightly Weathered Rock", but more completely altered. A gibbsitic skeleton replaces the previous plagioclases, a ferruginous and more porous skeleton substitutes the pyroxenes and amphiboles, and a more massive goethite is derived from olivines. Vermiculite is not observed in this facies.

- Weathered Rock with Preserved Structure containing illuviation features (SC-4). The main difference between this facies and the "Weathered Rock with Preserved Structure" is the nearly complete destruction of opaque minerals and the significant importation of gibbsitic material. This material comes from the higher levels of the profile and fills the pores of both ferruginous and gibbsitic skeleton. In this case, an absolute accumulation occurs, decreasing the porosity and increasing the bulk density.

2. Chemical Evolution

Table VII.5 shows the chemical composition of selected samples. The evolution from the fresh rock to the more altered products is characterized by loss of alkalis and silica and concentration of aluminum and iron.

Isovolumetric calculations were made for the first stages of the weathering process (SC-2 and SC-3) and the results were compared with those of the fresh rock (Table VII.6), allowing the evaluation of gains and losses during the alteration. Those calculations show that there is not actually a gain of aluminum and iron in these levels, their concentration being only due to a relative accumulation process .

However, in the upper levels of the profile (SC-4),

Table VII.5 - Chemical composition (% weight) of fresh rock and its weathering products (Curucutu, São Paulo state).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O	TiO_2	H_2O^+
SC-1	50.94	11.90	9.81	12.96	1.65	9.62	0.15	1.00	1.04
SC-2	15.86	27.97	23.11	0.11	0.08	0.30	0	2.25	29.46
SC-3	12.84	31.90	22.25	0.23	0.03	0.14	0.01	1.64	29.81
SC-4	1.94	41.96	19.82	0.23	0.01	0.02	0	1.82	33.74

SC-1: metadiabase; SC-2: slightly weathered rock; SC-3: weatheread rock with preserved structure; SC-4: weathered rock with preserved structure containing illuviation features.

Table VII.6 - Geochemical balance (gains and losses in % relative to the fresh rock) (Curucutu, São Paulo state).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O	TiO_2	H_2O^+
SC-2	-86.5	+1.9	+2.0	-98.0	-98.0	98.6	-100	-3.2	+1125
SC-3	-90.4	+2.2	-13.6	-99.3	-99.2	-99.3	-100	-38.7	+990.6

micromorphological evidences indicate aluminum and iron absolute accumulation.

3. Concluding Remarks

The mineralogical, geochemical, and micromorphological studies brought out some interesting aspects regarding the bauxite formation.

Bauxitization occurred following two steps. The first one led to the relative Al and Fe accumulation through loss of other elements. In this case, prevailing mechanisms were desalkalinisation and partial desilication. Progressively, silica was totally leached and alumina was imported from the upper levels of the profile, leading to very low values for the molecular ratio SiO_2/Al_2O_3 (ki) of the final product (0.1 - 0.2).

The weathering products are generally isovolumetric. However, in the upper levels of the profile, the remobilization of Al and Fe together with pedogenetic processes gave way to the destruction of the original structures.

In Curucutu, the bauxite has a high iron content inherited from the parent rock. It was formed by a direct bauxitization process without kaolinite formation as an intermediate step. This is the result of a weathering process developed under an aggressive climate and favorable drainage conditions.

III. Mogi das Cruzes

Several small bauxitic occurrences in the region of Mogi das Cruzes, located 60 km northeast of São Paulo city, are the product of the weathering over quartz-rich rocks. They were the first bauxitic occurrences, noticed in Brazil, derived from that kind of rock.

The rocks at Mogi das Cruzes belong to the Precambrian basement forming the São Roque Group (micaschists, gneisses, migmatites, and quartzites, with granitic intrusions and diabase dykes).

Bauxite occurs mainly in the higher tops (820 - 830m).

According to Barbosa (1975), total resources are 120000 tons of bauxite with 50% Al_2O_3, associated to 2300000 tons of kaolin and 42000 tons of bauxitic clays.

The bauxitic material is formed by irregular layers of pebbles, either hard or friable, with thickness from some cm to 5 m.

A profile developed on rocks of granitic composition, with layered facies intercalated with homogeneous facies, was studied as to genetic aspects (Toledo-Groke, 1981).

The composition of fresh rock was deducted from the weathered levels. It should present quartz, plagioclase, muscovite, sericite, biotite and magnetite.

1 - Profile type (Fig. VII.7)

A profile type shows the following facies:

- Partially weathered rock: the material is still compact, but porous. Gibbsite forms pseudomorphs from feldspars and kaolinite from phyllosilicates partially altered (muscovite, biotite, and sericite). Among the phyllosilicates, biotite is the first to weather, with goethite deposition between the layers. Quartz grains show traces of dissolution, with goethite and gibbsite in the cavities.

- Totally weathered rock: it is a friable material, but preserving

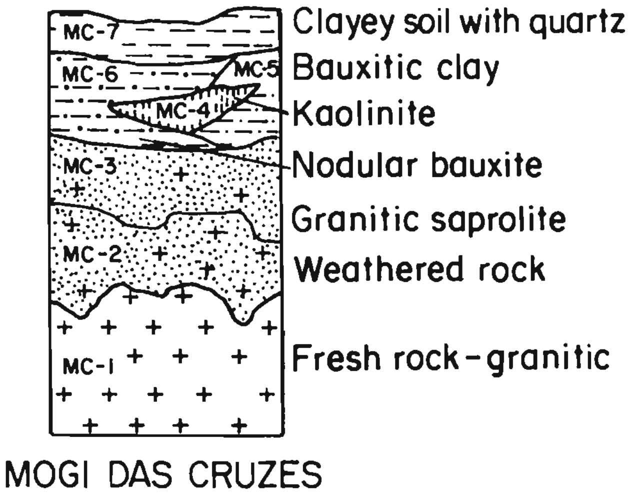

Figure VII.7 - Typical bauxitic profile of Mogi das Cruzes (São Paulo state).

partially the original structures. Gibbsite may occur from desilication of kaolinite. The quartz dissolution may be quite advanced.

- Surficial horizons (kaolin, bauxitic clay, and bauxite): present complex morphological characteristics, with friable and porous materials besides hard and massive ones. Both show no primary structures due to remobilization of iron and aluminum. Illuvial features are common, forming Al nodules with Si and Fe. Quartz grains are fractured and dissolved. Pseudomorphs of micaceous minerals are less frequent.

2. *Geochemical evolution*

There are no chemical data from fresh rock and typical isalteritic material. Remobilized levels analyzed show high contents of SiO_2 (Table VII.7).

Both relative and absolute Al accumulations account for the formation of bauxite. The first by leaching of other elements, and the second, by successive remobilization of Al. Iron and Si are also remobilized forming illuvial structures.

3. *Concluding remarks*

The occurrence of direct or indirect bauxitization in Mogi das Cruzes depends on the primary mineralogy. Feldspatic levels of the fresh rock are directly gibbsitized; micaceous facies are less susceptible to form bauxite and when they do, it is through a clayey stage.

Relative accumulation occurs early in these materials, mainly when feldspars lose alkaline elements. Absolute accumulation occurs since the beginning, but is more effective in the upper levels, destroying almost all pseudomorphs and other primary features.

Table VII.7 - Average chemical composition of bauxite and related products (% weight) (Mogi das Cruzes, São Paulo state) - MC-4: kaolinite; MC-5: bauxitic clay; MC-6: nodular bauxite.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O	TiO_2	H_2O^+
MC-4	63.5	24.3	1.9	0	0.1	0.3	1.0	0.6	8.5
MC-5	52.1	31.4	2.4	0	0	0.3	0.4	1.8	11.5
MC-6	19.2	52.1	3.0	-	-	-	-	0.6	-

IV. Genesis of the ore deposits

The bauxite deposits of the Southeastern Coastal Province are derived from the weathering alteration of igneous and metamorphic rocks under conditions of high temperatures and pluviosity. The distribution of the bauxite in the landscape is controlled by drainage conditions: well-drained tops and upper slopes are the most favorable sites. The ore quality depends strictly on the parent rock: basic rocks provide highly ferruginous bauxite, and low Al_2O_3/SiO_2 bauxites are derived from quartz-bearing rocks.

Bauxitization is generally a direct process resulting in an isalteritic product, where primary mineral change pseudomorphically into gibbsite without an intermediate phase. But besides this process of relative Al_2O_3 enrichment, absolute Al_2O_3 accumulation in certain levels also occurs, as demonstrated by the filling of biogenic voids and pores left by the weathering of primary minerals by massive gibbsite.

Economically, these deposits are of minor importance due to the quite small reserves and the poor quality of the ore.

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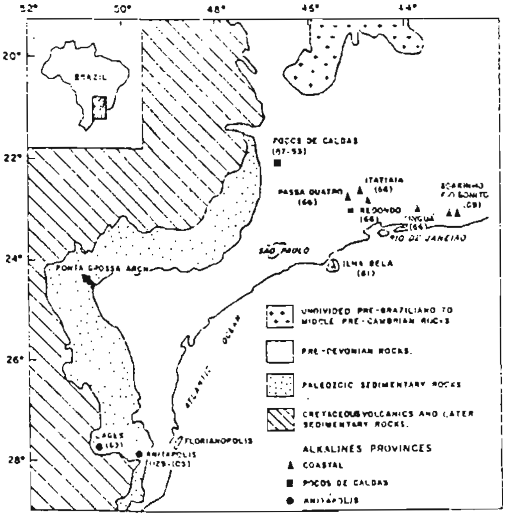
BAUXITE OF THE SOUTHEASTERN REGION

BAUXITE OF THE SOUTHEASTERN REGION

Several small deposits of bauxite related with alkaline rocks are found in the Brazilian Southeast region. This deposits, in total, represent less than 100x10^6 ton, but their economic importance is very great, due their excepcionally location, near of the more important consumer center of the country.

Alkaline rocks are widspread in Brazil, mainly in South and Southeast regions. Despite the adverse climate conditions prevailing in these regions (subtropical and temperate climate) these rocks, with a particular chemical composition (low silica and iron and high alumina) give rise bauxitic deposits rather than to kaolinitic material as might be expected.

The alkaline massifs of meridional part of Brazil is grouped by Ulbrich & Gomes (1981) in several provinces, which three of them shows important bauxitization phenomena: The Anitápolis, Poços de Caldas and Coastal Provinces (Figure).



The Anitápolis Province is situated in Santa Catarina State and consists of the Lages and Anitápolis massifs, only the first of which has associated bauxite deposits. Lages deposit represents the more meridional bauxite deposit of Brazil.

The Poços de Caldas Province in the State of Minas Gerais is formed by a only big nearly circular massif. It is the more important bauxitic deposit associated to the alkaline rock.

The Coastal Province, covering the States of São Paulo and Rio de Janeiro, exhibits a large number of alkaline massifs occurrences, most of them associated with bauxitic deposits. Passa Quatro is the most important deposit, and the only studied in this volume, follow to Tinguá, Redondo, Itatiaia etc..

These provinces consist mainly of unsaturated syenitic sequences made up essentially of syenites, phonolites, trachytes, foyaites, tinguaites and other less important alkaline rocks. These rocks present nearly the same mineralogical composition includes K-feldspar, napheline, aegirine-augite, sodalite, cancrinite and other feldspatoids.

Chapter VIII

BAUXITE OF POÇOS DE CALDAS

A. Schulmann, A. Carvalho, I. Valeton

Introduction

The bauxite deposits of Poços de Caldas are located within an alkaline massif, roughly circular in shape, with a diameter of 30 to 33 km and an approximate area of 800 sq.km (Fig. VIII.1). These intrusive alkaline rocks cut the pre Cambrian basement during the Upper Mesozoic and Lower Tertiary and are genetically related with the volcanic rocks of the Paraná Basin and with the opening of the South Atlantic.

The alkaline rocks correspond to silica-under saturated rocks, rich in sodium and potassium, belonging to the foyaite-tinguaite-phonolite series. They have similar composition and the difference among them is based on grain size. They are composed essentially of potassic-feldspar (orthoclase and sanidine), sodium-rich pyroxene (aegirine) and feldspathoïd (nepheline). Other feldspathoïds and zeolites may be locally abundant and wall-rock alteration (sericitization) is important at some places.

The bauxite forms a discontinuous cover within the massif and two different morphological facies characterize the ore deposit.

I. Regional Aspects

1. Geology and Geomorphology

In Poços de Caldas, an alkaline complex intrusion cut the pre Cambrian basement, formed by granitic and gneissic rocks, as well as its Mesozoic detritic-sedimentary cover. The basement rocks were locally affected by an intensive metasomatism, due to the alkaline intrusion, giving origin to a phenitization process.

The alkaline massif, studied by Ellert (1959) and Bushee (1971), is constituted mainly by nepheline-microsyenites (tinguaites), phonolites, together with foyaites, lujauries, chibinites, breccia and lavas of ankeritic type.

Hydrothermal solutions have altered the rocks of the southern and south-western part of the massif, originating clay products (kaolin-

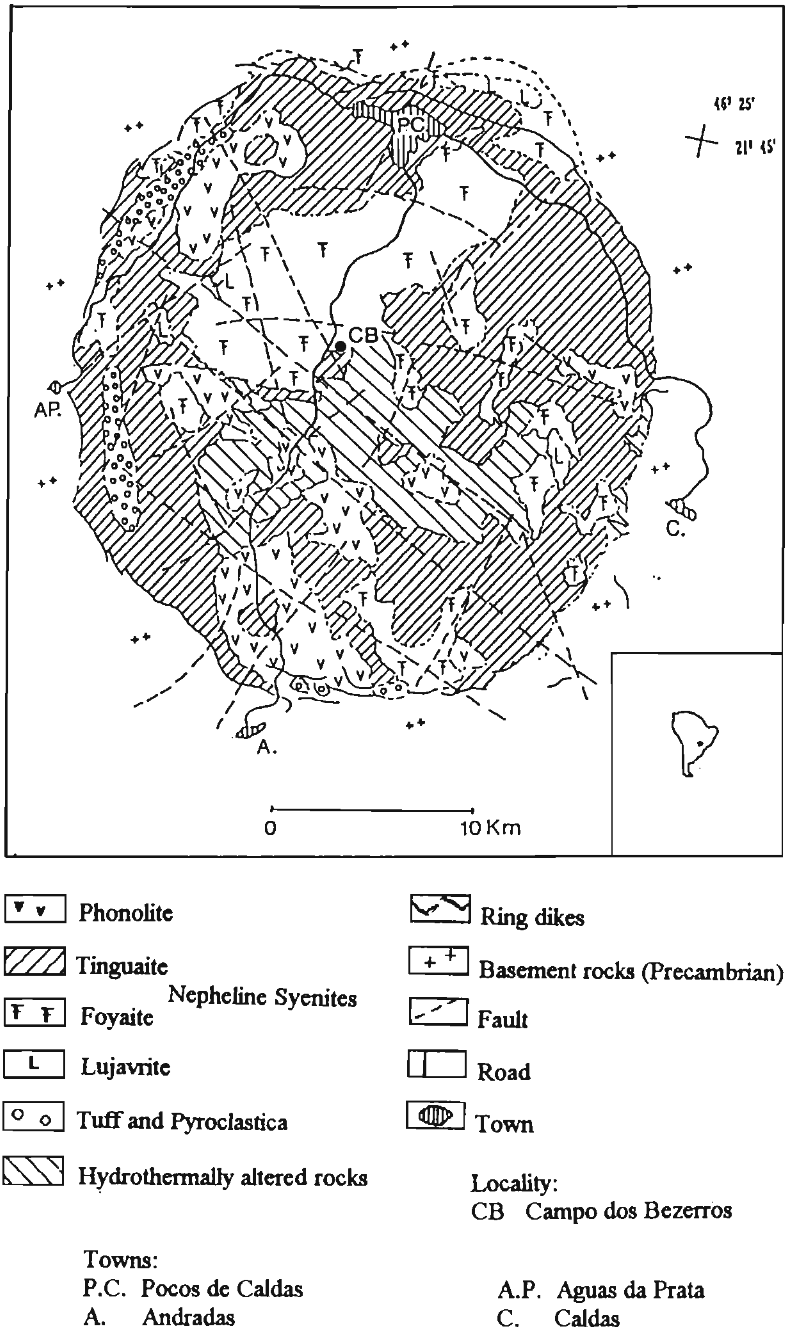


Figure VIII.1 - Geological map of the Poços de Caldas caldera (modified after ELLERT, 1959 and SANTOS, 1981).

ite, mica, halloysite) and sulphide minerals and fluorite. A clear association is observed between the hydrothermally altered rocks and zirconium, uranium, rare earth elements and magnetite deposits.

The morphological, mineralogical and chemical studies of these facies have shown the importance of the topography in the genesis and evolution of the ore deposit.

Two main geomorphological compartments can be distinguished in the massif: (a) the ridge topography, (b) the undulated topography of high plateau (Fig. VIII.2). In the eastern part of the massif, a secondary circular structure can be observed.

The ridge topography, as suggested by its name, follows approximately the massif border and sometimes the steepest slopes of the hills occurring in the central plateau (Fig. VIII.3). It corresponds to the highest areas of the complex, being about 650 m higher than the country rocks and 300 m higher than the internal plateau. It is 850 m wide and its slopes are normally steep, with maximum measured values of 28° on the southern border.

The undulated topography of the high plateau, the dominant geomorphologic unit, is characterized by a rolling topography with smooth slopes (around 5°). Drainage on the plateau is controlled by two basins, Rio das Antas and Rio Verde, both being tributaries of Rio Pardo and draining to the north and east. This area seems to have been stable for a long time and has undergone deep weathering.

2. Climate and Vegetation

The climate of Poços de Caldas may be classified as tropical climate of altitude. Poços de Caldas has an annual rainfall ranging from

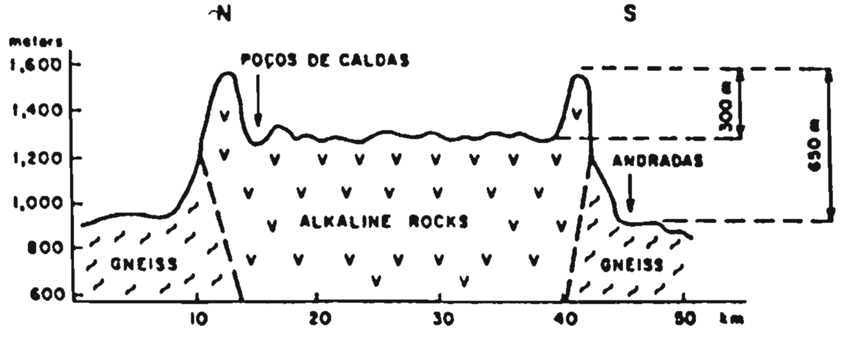


Figure VIII.2 - Schematic cross-section of the Poços de Caldas alkaline massif (after ALMEIDA, 1977).

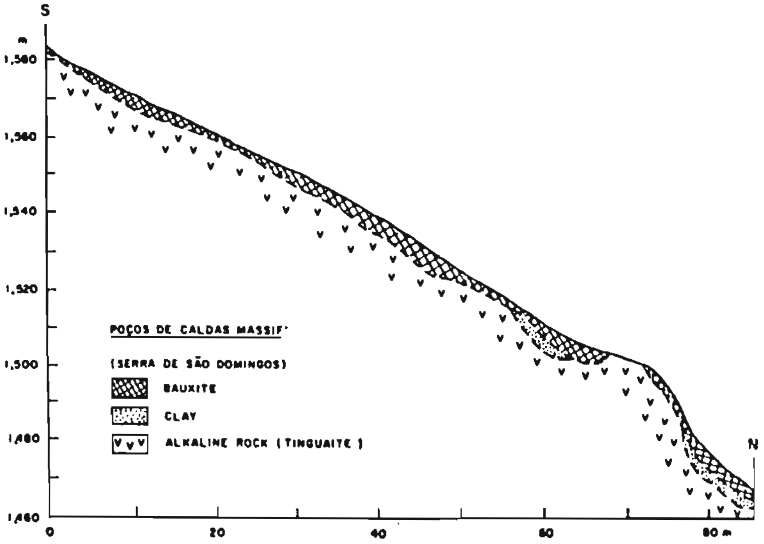


Figure VIII.3 - Ridge topography of the Poços de Caldas alkaline massif.

1,000 to 2,000 mm, with marked wet and dry seasons. The average annual temperature is about 17C which is lower than that for a typical tropical climate (19 to 20°C). The wet season occurs during the summer months, from December to February, while the dry season corresponds to the coldest months of the year, May, June and July.

The natural vegetation, mostly eliminated by human activities, seems to reflect the climatic changing probably occurred in the region during the Quaternary: Semi-deciduous Tropical Forest mixed with species from more temperate region (e.g. Araucaria Augustifolia), changing towards the summit area into a grassland.

II. Ore Deposits

The bauxite deposits of Poços de Caldas were previously studied by Almeida (1977) and lately by Melfi & Carvalho (1983).

The bauxite of Poços de Caldas forms a non continuous and rather thick cover, capping the alkaline rocks, and it is distributed in the morphological units described previously. The bauxite occurs extensively in the central-northern part of the massif, associated with tinguaites and phonolites. In the southern part, it occurs more scarcely, where the hydrothermally rocks are dominant.

The bauxite deposits of Poços de Caldas are classified by Almeida (1977) in two main types: (a) the rim deposits, and (b) the plateau deposits. The two types are distinguished by their difference in grades of Al_2O_3 and impurities, by the shape (surface area and thickness), by the homogeneity, slope of the terrain where they occur, and by the presence or absence of a clay layer between the ore and the fresh rock.

III. Profile Characteristics

1. Ridge Bauxites

The ridge bauxites (Rim deposits of Almeida, 1977) are the most important deposits. They are related to a more rugged topography of higher regions with flat top. They are dominant in the northern part of Poços de Caldas massif, associated with the external topographic high ring.

The profiles are well drained but the alteration layer is normally thin, due to erosion action. These profiles are homogeneous, with high alumina content and small amount of clay and/or ferruginous contamination. They are characterized by a direct contact of the bauxitic layer with the parent rock and present, practically, the same sequence of horizons, which are the following, from the top to the bottom:

Nodular horizon. This horizon, when present, is rather thin, rarely attaining 1m. The structure is nodular, fragmentary and concretionary, with the structural elements embedded in a reddish brown clay matrix or reddish yellow friable bauxitic matrix. The bauxitic blocks are irregular in size, varying from few millimeters up to several decimeters. Concentric structures, developed around roots or rock fragments are common.

Compact bauxite horizon. The horizon occurs normally above a friable ore or, sometimes, directly over fresh rock. It is a massive ore, rather coherent, hard and with high density (1.2 to 2.0 g/cm3). It has a yellow reddish color and present high porosity (up to 50%). Despite of being compacted, they present sometimes well-preserved relict structure.

Friable horizon with preserved structure. The alteration of the alkaline rock is rather complete within a few millimeters and gives origin, by intense leaching, to a homogeneous bauxitic horizon of pale yellow color, with high porosity (up to 60%), friable (Friable ore of Almeida, 1977). The thickness varies from 2 to 6 m with an average of 3 m and the density values are around 1 g/cm3. Joints, fractures or concentric structures of spheroidal alteration may persist in this horizon as relict structures.

The mineralogical composition of the profiles is shown in Figure VIII.4. It can be observed that the limits between fresh rock and the alteration horizon is quite sharp, with no transitional zone (saprolite). The primary minerals are rapidly altered, undergoing a nearly complete loss of silica and alkalis, forming gibbsite, goethite, halloysite and kaolinite, associated with small amounts of lithiophorite and aluminous gel.

Gibbsite is the predominant mineral, accounting for more than 80% of the bauxitic material bulk composition. Halloysite and kaolinite are frequent but not very abundant, except in clay veins zones which cut the bauxitic ore. Goethite, the main iron compound, is associated with minor amounts of magnetite and lithiophorite.

As concerning the chemical composition, this material corresponds to the high grade bauxite (Bárdossy, 1982) with high alumina content (55%) and low silica and iron.

2. Plateau bauxite

This type of bauxite is related to the smoother topography and more gentle slope of the internal plateau of Poços de Caldas massif (Plateau deposit of Almeida, 1977). It is also referred as grassland bauxite (bauxita de campo of Weber, 1959 and Parisi, 1988).

The profiles present a rather poor internal drainage, leading to an inhibition of leaching phenomena, originating a more heterogeneous material, with contamination, particularly, of clay. Nevertheless, these profiles are quite thick since they are protected against erosion. They

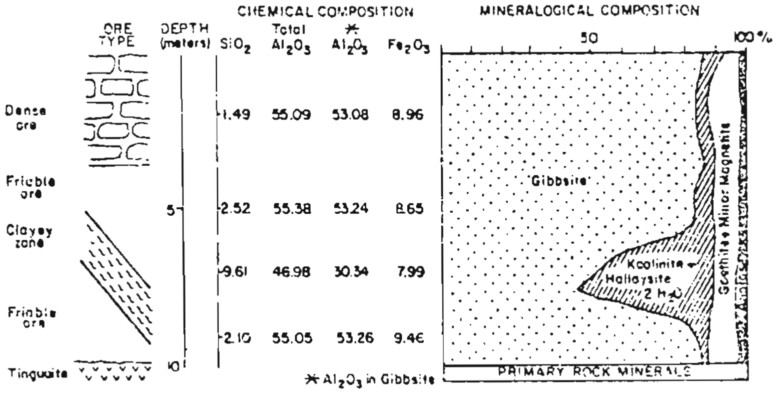


Figure VIII.4 - Chemical and mineralogical composition along the ridge alteration profiles, Poços de Caldas (after ALMEIDA, 1977).

are characterized by to different materials, the first one being rather thick, of clay nature and lying directly over the fresh rock. The other one covers the first material and is of bauxitic nature.

The bauxitic material, associated with the plateau topography, is quite thin and of lower quality, as compared to the ridge deposits.

The profiles show three main horizons, which are the following, from the top to the bottom:

Nodular horizon. This horizon, very rare in the ridge profiles, is common in the plateau deposits, where it can reach up to 2 m. The characteristics are essentially the same as the one in the Ridge profiles, but here the nodular elements can attain over 25 cm diameter.

Bauxitic material with preserved structure. This horizon, with thickness varying from 2 to 7 m, is rather coherent and dense, showing normally a spongy or compact structure. It presents light yellow or reddish yellow color, densities ranging from 1.6 to 2.0 g/cm^3 and porosity from 16 to 55%. In the lower part of the topography, the bauxitic horizon can be absent. The friable horizon with preserved structure, which is dominant in the ridge deposits, appears scarcely in the plateau deposits.

Clayey horizon. This horizon, with no preserved structure and thickness ranging from a few centimeters to 4 meters, lies directly over fresh rock. It presents a reddish color, clay textures and massive structure. The horizon is thicker in the lower parts of the topography, where it may be the only existing material.

The mineralogical composition of the described profile is shown in Figure VIII.5. The composition here is quite similar to that of Ridge profiles, the only difference being in the clay horizon that presents a micaceous illitic mineral. This horizon is made up predominantly of ka-

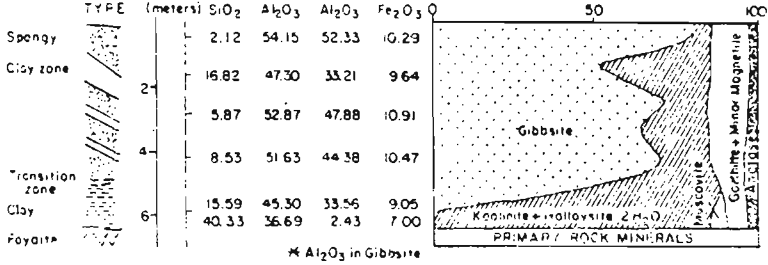


Figure VIII.5 - Chemical and mineralogical composition along the high plateau alteration profiles, Poços de Caldas (after ALMEIDA, 1977).

olinite with subordinated halloysite-$2H_2O$, illite (sericite) and traces of gibbsite.

In the bauxitic horizon, gibbsite is predominant (50 - 70%) but less abundant as compared to the Ridge profiles. The kaolinite and halloysite contents are rather important and can reach 30%. Boehmite, goethite, magnetite, cliakite and anatase are also present.

These deposits are less homogeneous than the Ridge profiles and clay intercalations are frequent. The average content of Al_2O_3 is around 50%, SiO_2 6% and Fe_2O_3 10%.

IV. Chemical Composition

The mineralogical and chemical composition of a representative profile of bauxite of Poços de Caldas was studied in detail within a Brazilian/ German joint project (Schumann, 1992).

The results of the mineralogical composition is shown in Table VIII.1 and the chemical composition in Table VIII.2.

1. Major elements

The behavior of the major elements during the bauxitization was rather normal and within the expected trend.

Thus, potassium together with silica are characterized by a successive loss with increasing bauxitization (Fig. VIII.6). The silica alter-

Table VIII.1 - Modal composition of the nepheline syenite and the bauxite.

Nepheline Syenite Mineral	Vol (%)	Bauxite Mineral Vol (%)	
Orthoclase	50.0	**Gibbsite**	32.0
Nepheline	34.0	**Goethite**	6.0
Clinopyroxene	11.0		
Others (Amphibole Analcime, Natrolite, Albite, Muscovite, *opaque material, Sodalite, Giannettite, Loparite, Anacylite, Olgite)*		**Others (Relic Minerals,** *REE-bearing minerals,* **Veintels, coating of pores)**	

Mineral identified with polarization microscope
Minerals detected with EDAX

Table VIII.2 - Whole rock analyses (XRF) of the nepheline syenite and its bauxitic weathering products (nepheline syenite samples: 20, 50a, 51; samples of the transition zone: 50b, 50d, 50e, 50f; bauxite samples: 50g, 50h, 50i). For sample location see Figure VIII.3b. Total Fe expressed as Fe_2O_3; oxides in wt%, elements in ppm.

Sample	20	50a	51	50b	50c	50d	50e	50f	50g	50h	50i
SiO_2	51.18	49.17	51.11	48.41	43.93	43.62	40.91	34.48	10.71	2.75	1.04
TiO_2	0.24	0.28	0.23	0.28	0.30	0.30	0.31	0.43	0.63	0.75	0.68
Al_2O_3	22.35	23.77	22.01	23.78	26.25	27.33	28.65	35.65	51.37	56.63	58.27
$Fe_2O_3^*$	2.93	3.30	3.08	3.39	3.87	2.87	3.28	4.50	6.57	7.91	7.36
MnO	0.21	0.19	0.22	0.21	0.20	0.18	0.15	0.30	0.23	0.20	0.12
MgO	0.13	-	0.03	0.13	0.07	-	-	-	0.03	-	-
CaO	0.88	0.41	0.98	0.32	0.17	0.07	0.07	-	0.09	0.09	0.09
Na_2O	10.09	3.87	9.11	2.99	1.79	0.36	0.12	-	-	-	-
K_2O	8.50	8.84	8.52	8.98	8.48	8.70	8.14	7.66	2.05	0.33	-
P_2O_5	-	-	-	-	-	0.04	0.04	0.04	-	-	0.03
Total	96.61	89.83	95.29	88.49	85.06	83.47	82.67	83.06	71.68	68.66	67.59
H_2O	3.11	5.54	2.50	5.76	8.18	8.32	9.59	14.33	26.41	30.22	31.23
LOI	3.76	10.20	2.76	11.67	15.47	14.63	16.25	15.39	27.51	30.83	31.70
Cr	16	20	13	28	21	13	21	14	20	14	10
Ni	3	2	-	1	1	1	2	9	30	-	-
Co	15	10	13	6	-	9	13	27	11	21	34
V	33	28	50	57	64	54	48	82	137	148	149
Cu	10	4	-	2	13	9	10	7	15	-	-
Pb	35	45	35	46	43	45	51	55	82	93	98
Zn	167	133	150	135	112	72	59	109	94	24	27
K	71391	73383	70727	74546	70395	72221	67573	63588	17018	2739	-
Rb	172	195	183	201	193	192	187	181	41	3	-
Ba	48	66	54	20	113	119	43	138	113	64	23
Sr	478	129	532	102	45	38	27	28	20	17	-
Ga	43	49	43	52	53	48	58	81	135	153	159
Nb	207.0	242.0	202.0	245.0	259.0	264.0	283.0	408.0	597.0	673.0	623.0
Zr	739	916	754	1031	958	957	1035	1516	2483	2937	2737
Ti	1439	1679	1379	1679	1799	1799	1858	2578	3777	4496	4077
Y	56	33	41	42	19	1	--	6	1		
Th	1.00	21.00	24.00	21.00	42.00	32.00	12.00	48.00	95.00	90.00	97.00
U	-	15.00	11.00	15.00	2.00	11.00	23.00	27.00	25.00	13.00	10.00
La	276.00	254.00	285.00	191.00	57.00	63.00	59.00	62.00	76.00	71.00	-
Ce	385.00	394.00	403.00	438.00	423.00	448.00	450.00	842.00	959.00	811.00	588.00
Nd	61.00	73.00	83.00	58.00	-	19.00	15.00	18.00	2.00	22.00	6.00

ation curve mainly depends on feldspar weathering, and on the fact that Si still remains in relict minerals whereas other elements are washed out rapidly. Calcium, included in the pyroxenes, and sodium, present in the nephelines, are also leached easily (Fig. VIII.7), the same way as magnesium, normally found in the pyroxenes and some amphiboles.

Fe, Ti and Al show a relative enrichment with increase bauxitization, presenting roughly a continuous trend (Fig. VIII.8). Pro-

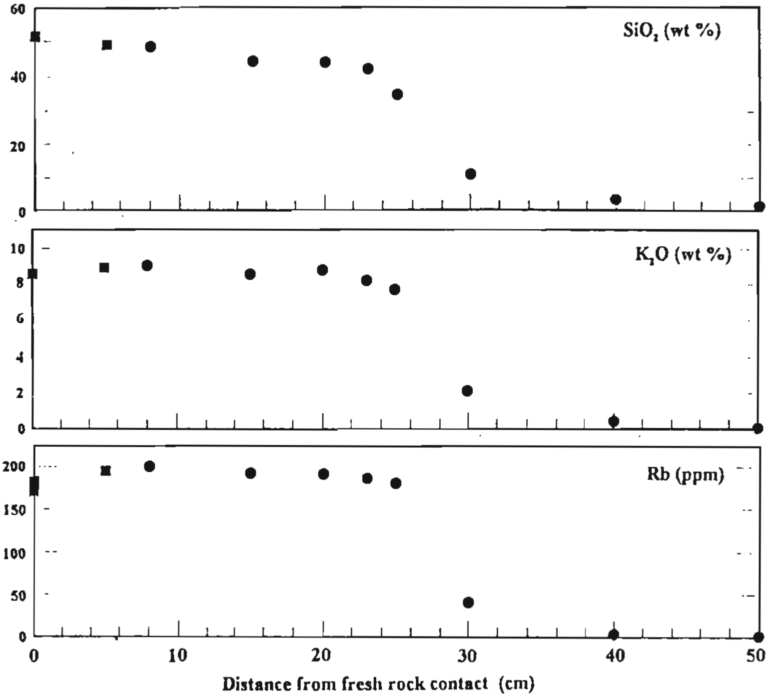


Figure VIII.6 - Variation diagram for selected elements vs. increasing distance from the fresh rock (squares: nepheline syenite; circle: weathered parent rock).

gressive goethitization of pyroxene and amphibole is reflected by direct accumulation of these elements. Amorphous plasma occurs as small veins rich in Al, Fe and Ti (Table VIII.3), cutting the preserved relict texture of the bauxite (Fig. VIII.9d, VIII.9e). Feldspar and nepheline are the source of Al in the parent rock, and Al-goethite and gibbsite are the main Al-bearing mineral of the alteration product (Table VIII.4).

2. *Trace elements and Rare Earth Elements*

These elements show a chemical behavior that is close related with the different major elements.

Rb, preferentially fixed in the feldspars, shows a behavior similar to K, while Sr, Y and La, are like Ca and Na. Sr and La are constituent of REE-bearing minerals. Sr occurs also in carbonates (Table 4) and it probably replaces Ca in the lattice of pyroxene and giannettite. Y may also occur in giannettite (Soubiés et al., 1992; Schorscher et al., 1992). Ni,

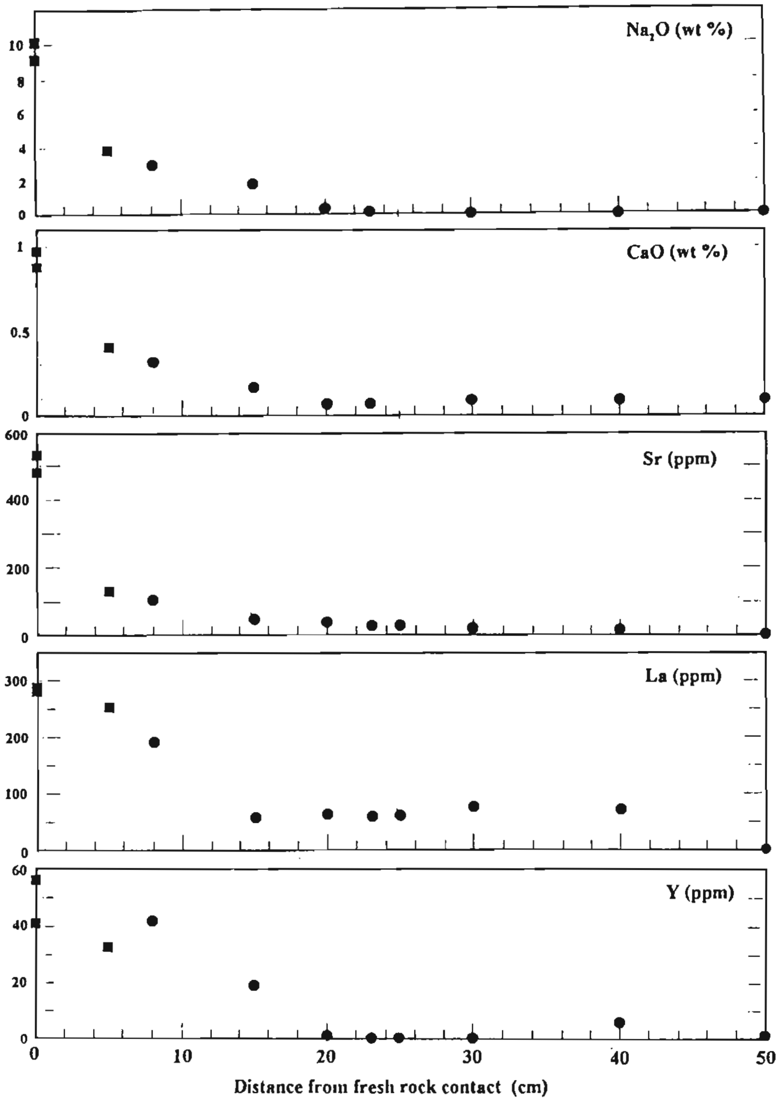


Figure VIII.7 - Variation diagram for selected elements vs. increasing distance from the fresh rock (squares: nepheline syenite; circle: weathered parent rock).

Cr, Nd and Co, like the Mg are generally mobilized and washed out.

Mn, Ce, Ba, Zn and U form a group of elements with a specific trend. At the beginning of the alteration process they show an ambigu-

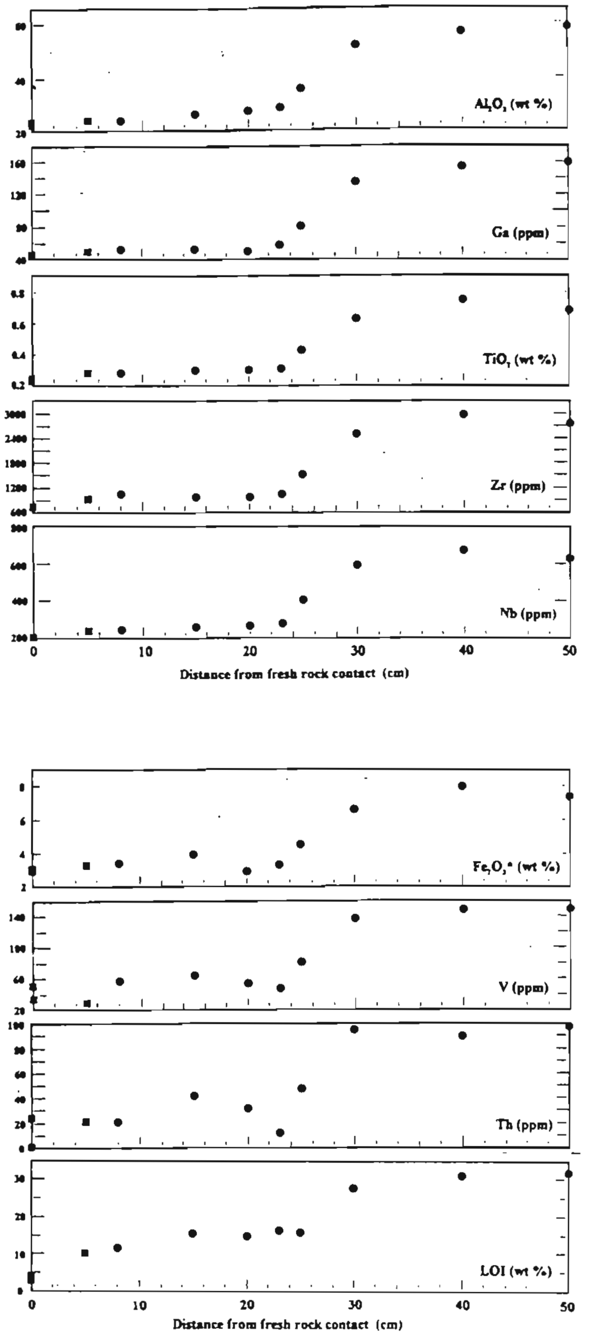


Figure VIII.8 - Variation diagram for selected elements vs. increasing distance from the fresh rock (squares: nepheline syenite; circle: weathered parent rock).

Table VIII.3 - Analyses (EDX) of veinlets and coating of pores in the bauxite (sample 50i).

Mineral Element (At%)	a1	a2	b1	b2	b3	c	d
Si	11.5	1.8	0.4	0.7	2.3	5.0	-
Al	69.0	25.4	5.0	12.4	3.2	19.7	37.9
Fe	1.9	4.0	7.1	6.3	7.0	69.3	-
Ti	3.5	9.2	2.9	-	-	5.3	-
Mn	-	-	-	-	-	-	58.7
Zr	4.0	6.9	0.8	1.2	1.2	0.7	-
Ce	20.1	52.8	83.8	79.5	88.3	-	-
Co	-	-	-	-	-	-	3.3

Minerals/ ( ) Number of analyzed specimen - a1, a2: Zoned Veinlet (2), rim/core; b1, b2, b3: Zoned Veinlet (3), from the rim to the core; c: Veinlet (1); d: Coating of a pore (1).

EDAX analysis pointes: a1: 50i/6; b1: 50i/10; b2: 50i/9; b3: 50i/8; c: 50i/14; d: 50i/18.

ous behavior. In the bauxite zone, the elements present a trend firstly characterized by relative enrichment which reverses afterwards. Small veins, coatings of pores and REE mineral relicts are holder of these elements in the bauxite (Table VIII.3, VIII.4). Mn is a constituent of pyroxene and amphibole (Table VIII.5). High amount of Mn and Ce are found in some REE bearing minerals (Table VIII.6). Sphalerite seems to be the main holder of Zn, that can also occurs replacing Mg or Fe in amphiboles (Wedepohl, 1992).

The elements Zr and Nb correlate extremely well with Fe and Ti and show the same behavior during the goethitization of pyroxene and amphiboles. The same occurs with Ce in the amorphous plasma of the small veins (Table VIII.3). Th was only found in one REE-bearing mineral (Olgite, Table VIII.6). The weathering behavior of Ga follows that of Al and Fe, suggesting substitution in gibbsite and substitution and/or sorption in aluminous goethite.

Relative depletion and relative enrichment factors, as considering the normalization basis the parent rock, of selected elements with bauxitization are shown in Figure VIII.10.

The transformation of pyroxene and alkali feldspar into its weathering products is illustrated in Figure VIII.11. The dominant neoformed minerals in the bauxite are Al-goethite and gibbsite. Goethitization of pyroxene seems to be an initial process, and gibbsite formation seems to require more time.

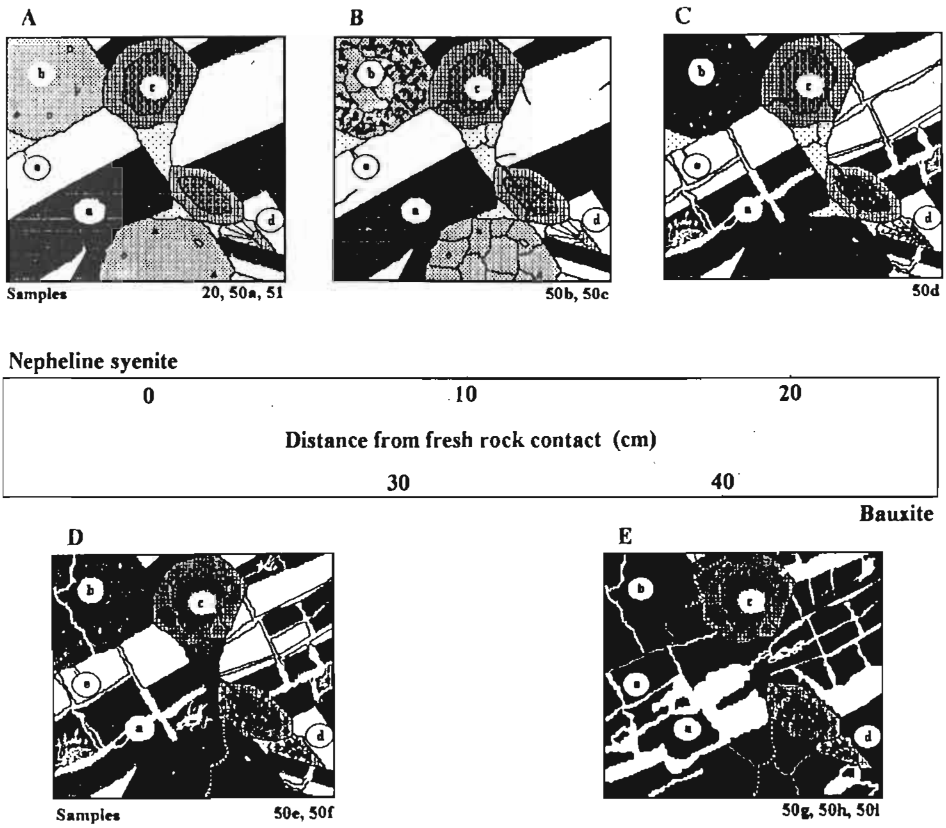


Figure VIII.9 - Illustrated differences visibile in thin section with progressive bauxitization (A: a: orthoclase; b: nepheline; c: zoned clinopyroxene; d: felty amphibole; e: others; B: initial stage of weathering, appearance of cracks; C: a: gibbsite nucleation along cracks; simultaneous gibbsite growth and orthoclase dissolution; b: breakdown of nepheline and dissolution of the mineral; c: goethitization of the inner part of the zoned clinopyroxenes; d: goethitization of felty amphibole; e: others; D: a: progressive gibbsite nucleation and dissolution of orthoclase; b: nephelines are dissolved;c: goethitization of the residual rim of the clinopyroxenes; d: goethitization of felty amphiboles; e: others are partly dissolved: occurrence of neoformed veinlets (pointed line); E: a: gibbsite boxwork pseudomorphs after feldspar, b: dissolved nepheline; c: goethite pseudomorphs after clinopyroxene; d: goethite pseudomorphs after felty amphibole; e: others are partly dissolved; occurrence of neoformed veinlets).

V. Origin of the Bauxite Deposits

The aluminum accumulation as a general, is the result of the

Table VIII.4 - Analyses (EDX) of gibbsite pseudomorphs after feldspar and goethite pseudomorphs after zoned clinopyroxene and felty amphibole in the bauxite (sample 50i).

Mineral Element (At%)	a	b1	b2	c
Si	0.2	2.9	4.0	5.0
Al	99.5	35.5	24.8	32.7
Fe	0.4	56.3	64.1	52.8
Ti	-	4.7	6.0	8.1
Zr	-	0.7	1.	1.4
Nb	-	-	0.3	-

Minerals/ ( ) Number of analyzed specimen - a: Gibbsite (3); b1, b2: Goethite (2), rim/core; c: Goethite (1).
EDAX analysis points: a: 50i/2, 50i/5, 50i/31; b1: 50i/27, 50i/33; b2: 50i/28, 50i/34; e: 50i/16.

Table VIII.5 - Mineral analyses (EDX) of orthoclase, nepheline, clinopyroxene, amphibole and analcime in the fresh rock (sample 20).

Mineral Element (At%)	a	b	c1	c2	d	e
Si	58.7	37.4	63.1	51.2	51.3	53.6
Al	18.8	37.7	1.6	1.5	6.5	34.2
K	22.5	11.7	0.1	-	-	-
Na	-	13.2	8.3	3.8	7.2	12.3
Ca	-	-	3.7	24.8	0.8	-
Fe	-	-	20.6	14.7	27.4	-
Ti	-	-	1.8	0.6	4.8	-
Mn	-	-	0.9	1.1	2.1	-
Mg	-	-	-	2.3	-	-
Zr	-	-	-	0.1	-	-

Minerals/ ( ) Number of analyzed specimen - a: Orthoclase (3); b: Nepheline (3); C1, c2: Clinopyroxene (4), rim/core; d: Felty Amphibole (1); e: Analcime (3).
EDAX analysis points: a1: 50i/6; b1: 50i/10; b2: 50i/9; b3: 50i/8; c: 50i/14; d: 50i/18.

interaction of various factors, of morphological, bioclimatic and lithological nature.

In the case of Poços de Caldas alkaline massif, the morphological and bioclimatic conditions are characterized by a strongly undulated topography with steep slopes and marked erosion, a high plateau vegetation and a mesothermic subtropical to temperate climate with well distributed rainfall. These conditions are far from being favorable to baux-

Table VIII.6 - Analyses (EDX) of REE-bearing minerals in the nepheline syenite (sample 20). Because of the extreme small grain size and the exotic geochemical composition the identification of the minerals loparite, olgite and ancylite is problematic.
(Giannettite*1: $X_{16}(Si_2)_7)_4(O,OH,F)$; X:Na, Ca, REE, Ti, Nb, Zr, Mn^{2+}, Fe^{2+}, Mg; Loparitestrontian*2: $(Sr,Ce,Na)(Ti,Nb)_3$; Olgite*2: $Na(Sr,Ba)PO_4$; Ancylite*2: $(Sr,Ca)(La,Ce)(CO_3)2xH_2O$).
References: *1Melfi et al. (1992) suggested structural formula for giannettite similar to that of "hiortdahlite" minerals group
*2Bayliss, P.; Erd, D.C.: Mrose, E.M.; Sabina, A.P.; Smith, D.K. (1986). Mineral Powder Diffraction File, Data Book. International Center for Diffraction Data. Park Lane, SW arthmore, USA.

Mineral Element (At%)	f	g	h	i
Si	46.0	-	-	-
Al	0.8	-	-	-
K	1.7	-	-	-
Na	2.8	8.8	0.8	-
Ca	34.0	4.7	0.8	5.2
Fe	1.2	-	-	-
Ti	0.6	54.8	-	-
Mn	4.8	-	-	-
Zr	5.3	-	-	-
Sr	2.4	3.2	52.5	29.8
Ce	0.5	10.7	8.5	35.8
La	-	-	7.2	29.3
Nb	-	19.0	-	-
P	-	-	30.0	-
Th	-	-	0.3	-

Minerals/ ( ) Number of analyzed specimen - f: Giannettite (1); g: Loparite (2); h: Olgite (1); i: Ancylite (2).
EDAX analysis points: f: 20/10; g: 20/17, 20/18; h: 20/51; i: 20/1, 20/6.

ite formation. Consequently, only the rock composition, i.e., high feldspar and feldspathoïds content, with no quartz and very few ferro-magnesian minerals, can account for the aluminum accumulation. A clear evidence favoring this interpretation is the fact that other rock types do not form bauxite deposits. That is the case, for example, of kaolinitic sediments and hydrothermally altered alkaline rocks in the southeastern part of Poços de Caldas massif or the surrounding gneissic-granitic rock. On the other hand, the deposits that are formed, are not very thick, since the topographic conditions favors quick erosion.

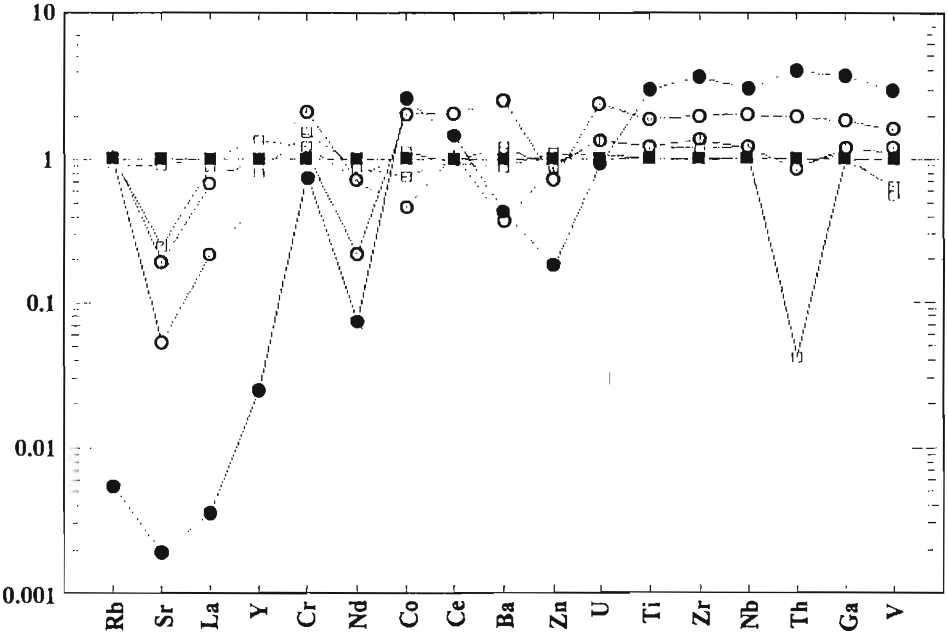


Figure VIII.10 - Relative depletion and relative enrichment factors of selected elements for weathered parent rock samples and bauxite, normalized to the nepheline syenite (filled squares: nepheline syenite, sample 51; open squares: nepheline syenite, samples 20, 50a; filled circle: bauxite, sample 50i; circles: weathered parent rock, samples 50b, 50f).

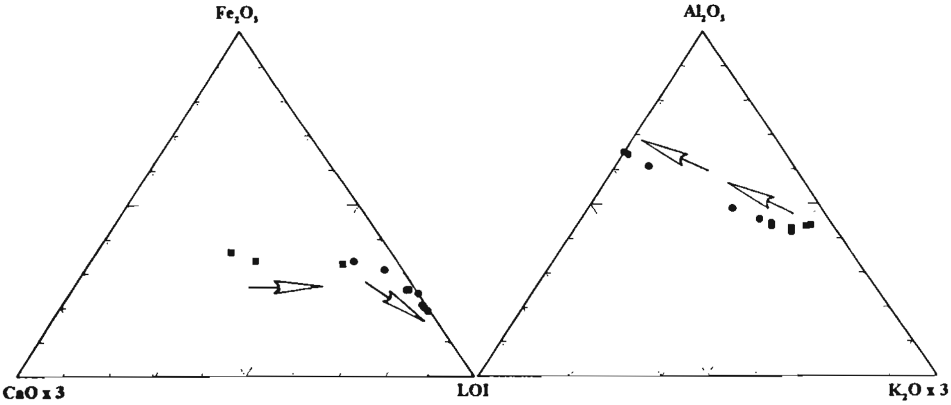


Figure VIII.11 - Diagram showing goethitization and gibbsitization trends (squares: fresh rock; circles: weathered rock).

The direct contact ore/tinguaite in rim deposits without any intermediate zone is an evidence that bauxite is the most recent weathering product. This direct bauxitization is also supported by the preservation of the original rock structure.

The mineralogical evolution, under this particular conditions, can be followed by microscopic analysis.

It can be observed that the feldspathoïds are the first minerals to be affected by weathering, and change very early, their optical properties. The process starts at the border and discontinuities of the crystals, giving origin to a gibbsitic network, preserving the original rock structure (Fig. VIII.9b, VIII.9c) (Plates VIII.1c, VIII.2b).

The alkali feldspar reacts less sensitive as compared to the feldspathoïds, but follows the same pattern of alteration. It seems that dissolution of alkali feldspar occurs simultaneously with gibbsite nucleation (Fig. VIII.9b, VIII.9c) (Plate VIII.1c). Dissolution proceeds forming amorphous compounds (cliakite type), which can evolve into gibbsite or can be eliminated leaving empty cavities. Continuous weathering results into an extremely porous material, with preserved structure, of box work type. This material, initially friable, can change into a hard and spongy one as a result of partial gibbsite recrystallization.

The pyroxenes, altered almost simultaneously with the feldspar, are completely dissolved and replaced by aluminous goethite. Hematite can also occur associated with the goethite, Normally, in the pyroxene, the alteration start at cracks and the inner part is completely altered, without affecting the outer rim. (Fig. VIII.9b). The alteration of amphiboles follow the same path, but with no zonation like the pyroxene.

The REE-bearing minerals were difficult to detect and only one intertitially occurring specimen of giannettite was found in nepheline syenite. (Plate VIII.2a, Table VIII.6). It seems that this mineral is completely dissolved in the process, since no sign of its structure is found in the alteration product.

Phosphates and carbonates occur frequently (Table VIII.6) as very small inclusions in host minerals, mainly pyroxene. The weathering products include secondary phosphate an Al, Fe or Ti rich phase with high amounts of selected REE elements (Table VIII.7).

In the upper part of the bauxitic profile, the physico-chemical conditions promote the partial dissolution and migration of gibbsite and precipitation of a secondary gibbsite in the cavities, forming a compact and dense bauxite.

As a consequence, three generations of gibbsite can be recognized in the bauxitic horizon, two of which are associated with relative

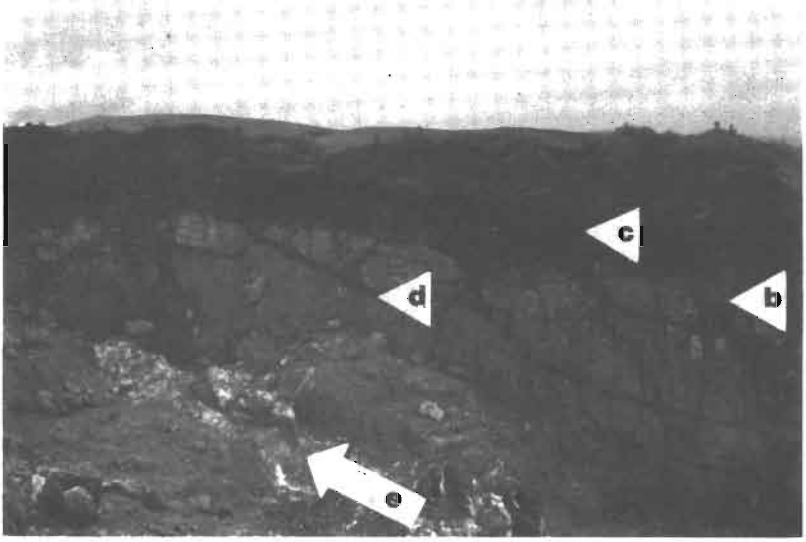


Plate VIII.1a.: Campo dos Bezerros bauxite deposit. Weathering profile showring the different horizons (scale: hight fo the profile: 8m). a: compact bauxite horizon with core stones of nepheline syenite; b: in situ residual breccia of the bauxite; c: reworked bauxite horizon and partly removed recent soil on top of it; d: fissures; e: cleyey dikes.

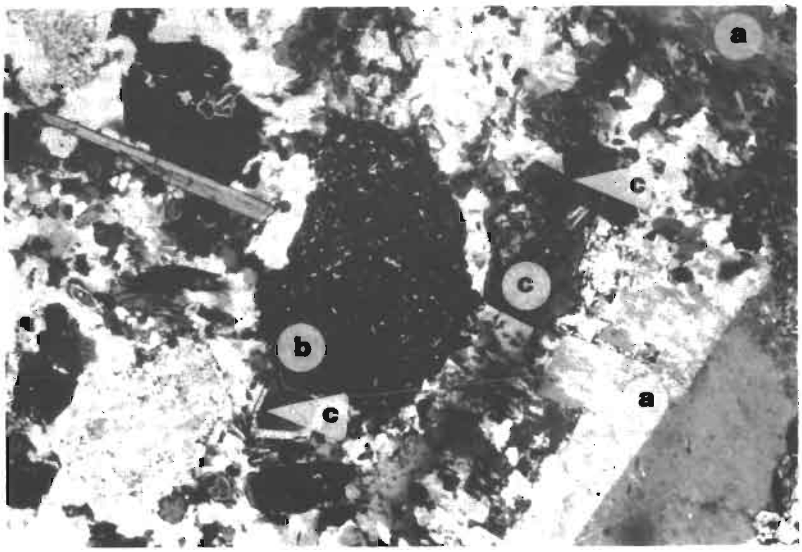


Plate VIII.1b.: Thin section of the nepheline syenite (sample 51, x- nicols, scale: 1 cm = 0,3 mm). a: orthoclase; b: nepheline with small inclusions of guest minerals; c: zoned clinopyroxene.

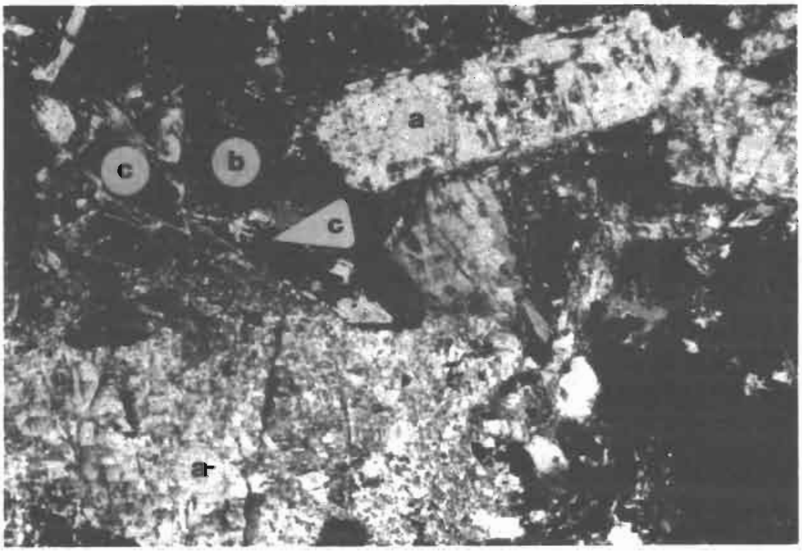


Plate VIII.1c.: Thin section of the slightly weathered syenite (sample 50d, x - nicols, scale: 1cm = 0,3 mm). a: orthoclase; gibbsite nucleation starts at cracks.; b: nepheline becomes isotropic; c: the inner part of the clinopyroxene breakes down and turns to goethite; the rim is not affected.

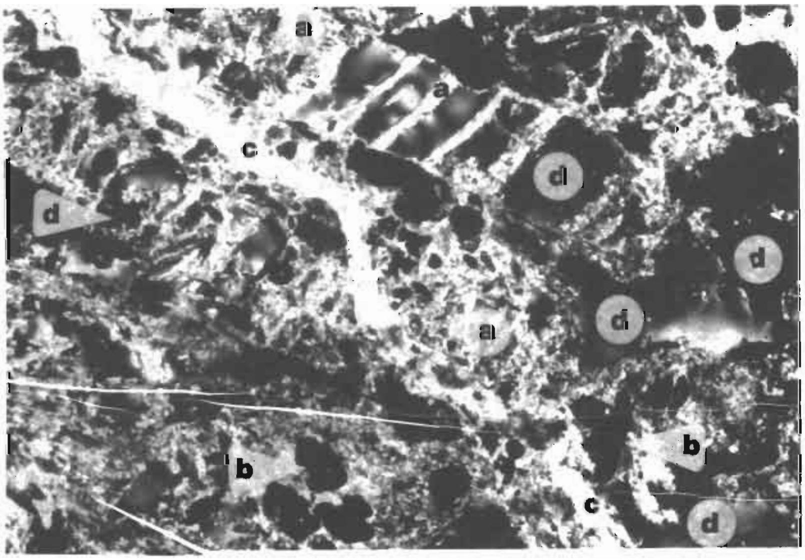


Plate VIII.1d.: Thim section of the bauxite (sample 50i, x - nicols, scale: 1 cm = 0,3 mm). a: gibbsite boxwork pseudomorphs after orthoclase; b: goethite pseudomorphs after clinopyroxene; c: fissure filled with gibbsite crystals; d: open pores.

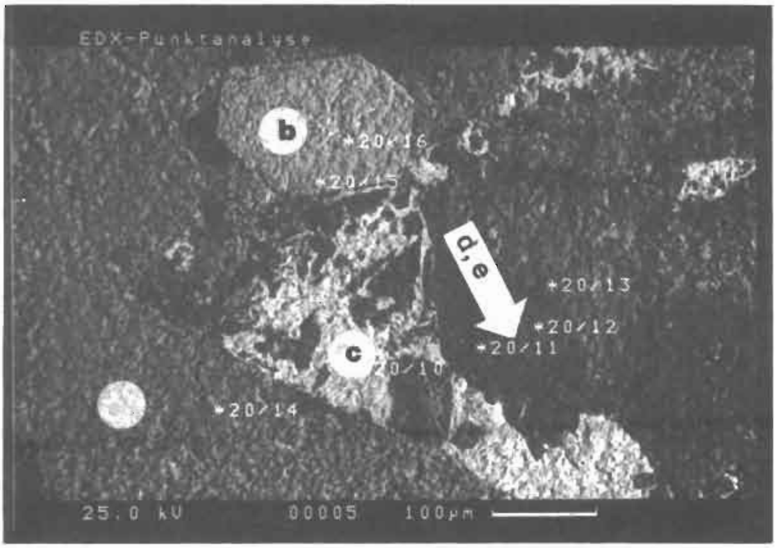


Plate VIII.2a.: REM of the surface of a nepheline syenite (sample 20, *20/10 = analysis point). a: orthoclase; b: zoned clinopyroxene; c: giannettite; d: transition zone of a hydrothermally altered orthoclase; e: ? natrolite.

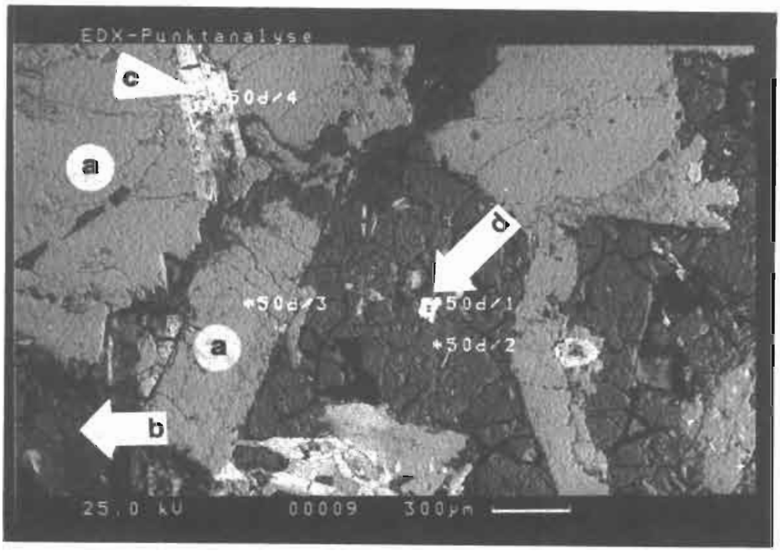


Plate VIII.2b.: REM of the surface of a slightly weathered nepheline syenite (sample 50d, *50d/l = analysis point). a: unweathered orthoclase; b: nepheline crystals are weathered, relics of the crystals form a mosaic of fragments; c: cores of the clinopyroxene crystals are slightly weathered. The core is transformed into goethite; d: REE-bearing mineral.

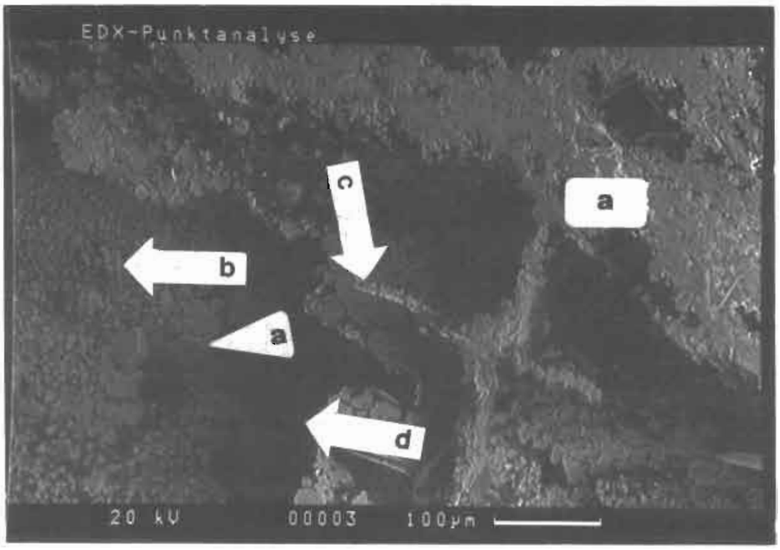


Plate VIII.2c.: REM showring a boxwork structure in the bauxite (sample 50i). a: gibbsite crystals; b: lawn like areas of small gibbsite crystals; c: thin veinlet; d: open pores.

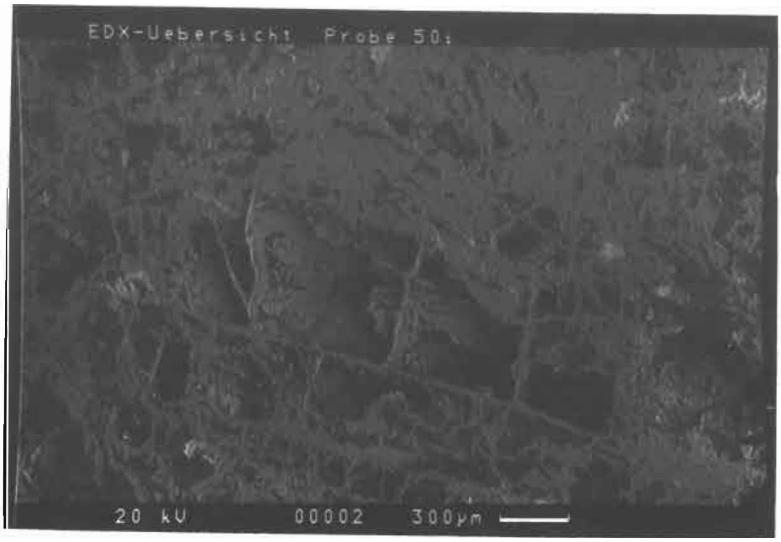


Plate VIII.2d.: REM of a gibbsite boxwork pseudomorph after orthoclase (sample 50i).

Table VIII.7 - Analyses (EDX) of REE-bearing relic minerals in the bauxite (sample 50i).

Mineral Element (At%)	a1	a2	a3	a4	a5
Si	3.1	3.5	4.1	2.6	1.4
Al	0.8	-	9.9	17.	8.3
K	-	-	-	-	1.5
Ca	-	-	-	-	1.7
Fe	5.3	4.4	5.9	48.8	2.1
Ti	12.0	10.8	9.9	4.8	2.1
Mn	-	-	5.0	-	61.6
Zr	11.7	-	12.6	7.4	1.1
P	-	9.4	-	-	-
Ce	67.3	72.0	52.0	18.8	4.7
Pb	-	-	-	-	0.6
Th	-	-	0.7	0.6	-

Minerals/ ( ) Number of analyzed specimen - a1: RRE-bearing Mineral (2); a2: RRE-bearing Mineral (1); a3: RRE-bearing Mineral (1); a4: RRE-bearing Mineral (1); a5: RRE-bearing Mineral (1);
EDAX analysis points: a1: 50i/4, 50i/11; a2: 50i/1; a3: 50i/23; a4: 50i/36; a5: 50i/41.

accumulation process. The first one is formed at the beginning of the weathering process and is related to alteration microsystem. The second one is associated with the evolution of amorphous gels of aluminous and siliceous aluminous composition. Finally, the last generation is formed by aluminum absolute accumulation through ionic or gel migration and precipitation.

In most of the profiles, specially in the plateau deposits, the occurrence of a clay layer between fresh rock and the bauxitic material may suggest an indirect origin for the bauxite. Nevertheless, even in this case, the analytical data and field observation seem to favor a direct origin. The preservation of the original rock structure in the bauxitic layer, though not in the clay layer, seems to be a clear evidence for a direct process. On the other hand, micaceous clay-minerals are present in the clay layer, but not in the overlying bauxitic material. These micaceous minerals are stable and resist to the weathering process. Consequently they are expected to be present also in the bauxitic zone, if it was formed, from the clay horizon through indirect process.

The relationship between the two profile types can be studied in various profiles occurring in a topographic sequence, leading to a better understanding of their genesis.

In the situation where the slope is very steep the erosion is dominant over chemical weathering and fresh rocks remain exposed at the surface. In situation of gentle slope the chemical weathering prevails and drainage is intense enough to wash out most of the silica of parent material and only bauxite is being formed. In the situation when, drainage is intense close to the surface, but becomes impeded with depth, bauxite is forming at the top, while clay develops at the bottom of the profile. Most of the plateau has being peneplanized, probably because the Antas River has found a local base level in the sandstone which occurs in its valley, near the northern border of the massif. As the surface is lowered the ore/fresh rock interface may reach a level where the drainage intensity is not enough to form bauxite, and then, clay would start to appear as the main weathering product. This scheme is a very common case in the plateau deposits.

In the upper and steepest part of the topography, the excellent internal drainage lead to the formation of a bauxitic layer with no clay intermediate horizon. In the lower part of the topography, where the internal drainage is not as good and where silica lateral migration is active, a clay layer is formed, with predominant kaolinite. This material, being impervious, slows down the solution movement, blocking the lateral migration. As the process goes on, the kaolinitic/gibbsitic limit migrates towards the top, leaving behind profiles with kaolinitic material at the base and gibbsitic material at the top. It is evident, in this case, that kaolinization is the active evolution process. Consenquently, in the plateau situation, it is the kaolinite material which is in equilibrium with the environmental conditions, moving bauxitization back, so that it is found only on the steepest zone of the topography.

Conclusions

As considering the present study and the results of Melfi & Carvalho (1983), it is possible to put forward some general considerations about the bauxitization process in the region of Poços de Caldas, that can be extended to the southern Brazil.

1. The bauxitic formation from alkaline rocks is a direct process. Initially, gibbsite is formed directly by alteration of the primary silicate minerals, with no intermediate clay material. In the upper part of the profile, under particular conditions (higher acidity, presence of organic matter, etc.), this gibbsite becomes unstable, is dissolved and reprecipitates further down as a new generation of gibbsite (secondary

gibbsite).

2. In the region of Poços de Caldas, the most important factor controlling bauxitization is rock composition, followed by topography and in particular internal drainage.

3. Kaolinization is the general active process, which means that it is the one in equilibrium with the environmental conditions. Bauxitization corresponds to a past evolution and, at present, bauxites are being destroyed. Exceptionally, bauxitization is still an active process on the steep slopes.

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THE BAUXITES OF THE PASSA QUATRO ALKALINE MASSIF

J.B. Sigolo, B.Boulangé

Introduction

The Passa Quatro massif, as well as the Itatiaia massif, is located in the limits of Minas Gerais and São Paulo States. It is a part of the Mantiqueira Mountains and corresponds to alkaline intrusions (nepheline syenites, microsyenites, tinguaites and phonolites) in a Precambrian basement constituted mainly of gneisses, migmatites, schists and quartzites (Fig. IX.1). The minimum age for the alkaline rocks is 70 million years (Ulbrich & Gomes, 1981). The up throwing of the massif is

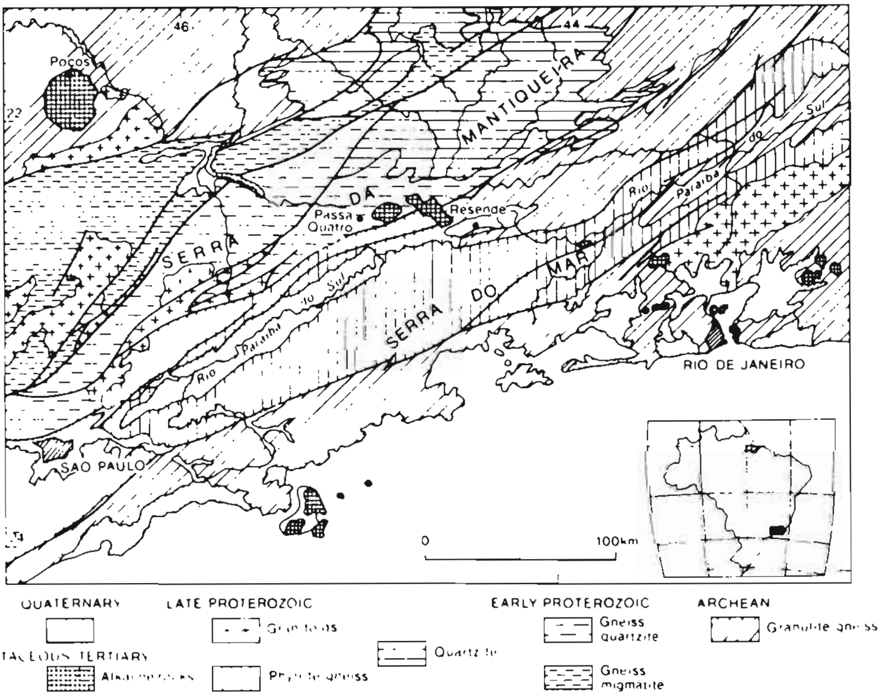

Figure IX.1 - Geological map of the East São Paulo and the South Minas Gerais states (after Fonseca et al., 1979 and Almeida et al., 1984) and localization of Passa Quatro alkaline massif.

contemporaneous to the opening of the Paraíba Rift (Upper Cretaceous to Miocene) (Almeida, 1976, 1980).

Following this tectonic phase, three main geomorphologic units werw developed in the region: a mountainous zone, with altitudes ranging from 2,770 to 1,300 m; a zone of slopes and hills with altitudes comprised between 1,300 and 600 m, and a zone of low valley extending till the sedimentary continental basins, distributed within the rift bottom (Volta Redonda, Resende and Taubaté basins).

The rocks of the Passa Quatro massif werw submitted to an important bauxitization, originating two types of bauxite deposits, related to the upper geomorphologic units. The summit bauxites, in the mountainous zone, is characterized by an "in situ" preservation of the weathering profiles. The piedmont bauxites, within the slope zone, are colluvial accumulations related to pediments. The global reserves of these deposits have been estimated at about 15 million tons of which 5.5 million tons correspond to the piedmont deposits.

The mountainous zone is submitted to a humid tropical climate of altitude, with an annual average rainfall of 2,400 mm, a mean temperature of 11°C, the minimum attaining -6°C (Nimer, 1979).

The slope zone presents a humid tropical climate with contrasting seasons, having an annual rainfall of 1,500 mm and mean temperature of 18°C. The winter months (May to August), with a precipitation lower than 50 mm, are the driest months.

I. The Summital Bauxites

The summital bauxite deposits of the Passa Quatro massif were prospected in 1974 (CBA) and 1981 (CORIMBABA). One of these deposits, Alto das Posses, was selected for a detailed study. The deposit is constituted of a group of hills, with 2,200 m of altitude, surrounding a central depression with 2,000 m of altitude. The external slopes form a large rocky escarpment. The bauxite outcrops on the internal convex steep slopes (40°).

In one of these slopes, a serie of shafts were established (Fig. IX.2). In the upper and the middle part of the slope, the bauxite lies directly on the parent rock, while in the lower part, a clayey horizon is intercalated between the bauxite and the parent rock (Melfi & Carvalho, 1983).

Only one of the summital shaft (PQA) was studied in detail. This profile, 9 m deep, presents, from the fresh rock up to the surface, four main facies: a friable saprolite, a massive saprolitic bauxite, a fragmented

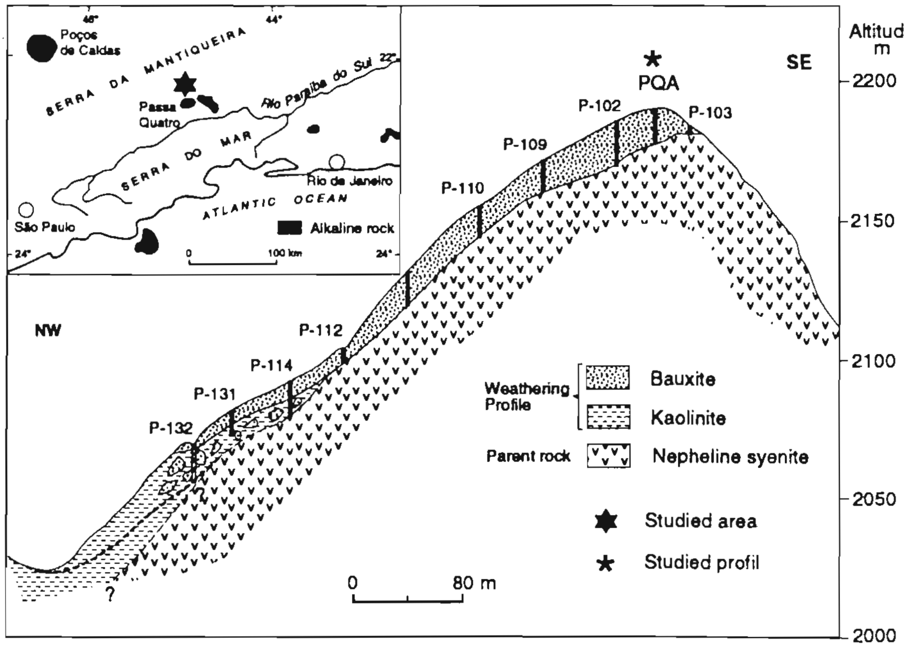

Figure IX.2 - Geographic setting of the Passa Quatro alkaline massif and cross-section of the studied ridge (Sigolo, 1988).

saprolitic bauxite and a surface nodular bauxite (Fig. IX.3) (Sigolo, 1988). The density and porosity values, as well as the volumetric changes, based on the iso-zirconium reasoning (Brimhall & Dietrich, 1987; Colin et al., 1988) are given in Table IX.1. As a matter of fact, the high and constant zirconium content throughout the alteration profile are related with the presence of unaltered euhedral zircons of small size. (<50 μm) (Boulangé & Colin, 1994).

The chemical analysis for the profile PQA, as well as the alteration balance calculated on the basis of constant zirconium are given for major elements and rare earth elements in Table IX.2.

II. Profile Description

1. The parent rock, as spherical blocks of metric size, was found between 8 and 9 m of depth (sample 17c). It is a nepheline syenite with granular structure. The normative mineralogical composition, calculated from 5 analysis, shows 58% potassic feldspar (microperthitic orthose, sanidine), 31% nepheline, 8% ferrous-magnesian minerals (biotite 1.9%,

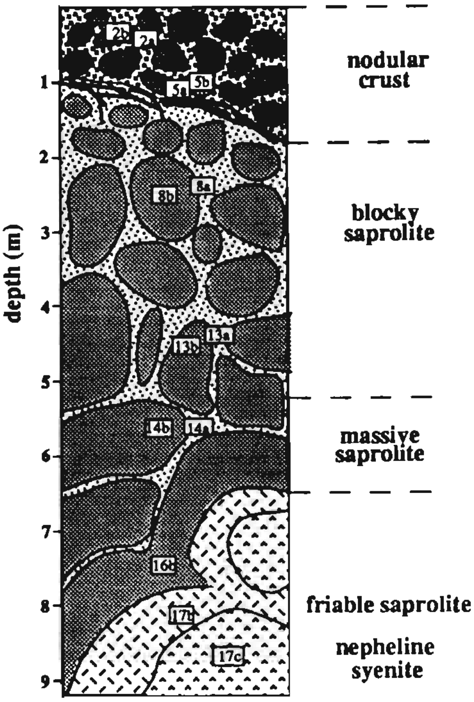

Figure IX.3 - Sketch of the PQA pit and sample location. The member indicates the sample, the index indicate the matrix (a), the bauxite fragments (b) and the syenite (c).

hornblende 0.9%, ægerine-augite 5.1%) and zircon (0.085), sphene (0.74%), magnetite (1%), apatite (0.56%) and pirochlore as accessory minerals. The bulk density (2.57), lower than the real density (2.70), shows a weak porosity (<5%) for the rock, due probably to a slight alteration.

2. *The friable saprolite (sample 17b)* forms a thick white cortex (15 to 20 cm), with granular texture, around the parent rock. The transition from fresh syenite to friable saprolite is quite sharp. The mineral transformation is observed at the rock contact within few millimeters. The nepheline and feldspar crystals are replaced by gibbsite, while the pyroxene and the amphiboles have been dissolved and partially replaced by goethite, crystallized in the cleavage plans and grains border. The X ray diffraction analysis shows that gibbsite and goethite, forming a porous network, are well crystallized. The bulk density is week (1,46) and its relation with the real density (2,58) (Table IX.1) shows the development of a strong porosity (42%), associated to the dissolution of primary

Table IX.1 - Physical properties of the PQA samples for the matrices (a), the bauxitic fragments (b) and the nepheline syenite (c): bulk density ($_{\rho w}$), grain densit ($_{\rho g}$), porosity ($_{\phi}$) and volumetric change (ε_{Zr}).

Sample *	**Depth** (m)	ρ_w g/cm^3	ρ_g g/cm^3	Φ %	**Zr** (ppm)	ε_{Zr}
2 b	-0.50	1.77	2.45	28	2083.26	-0.52
2 a	-0.60	2.10	2.58	19	2816.36	-0.70
5 b	-1.10	1.62	2.44	34	2288.92	-0.53
5 a	-1.20	2.13	2.57	17	2509.10	-0.67
8 b	-2.50	1.64	2.53	35	2463.41	-0.52
8 a	-2.60	2.02	2.52	21	2241.48	-0.65
13 b	-4.50	1.93	2.55	24	2777.92	-0.57
13 a	-4.60	2.05	2.58	21	2102.54	-0.69
14 b	-5.50	1.49	2.57	42	2344.99	-0.43
14 a	-5.60	2.00	2.59	23	2056.55	-0.53
16 b	-7.50	1.43	2.52	43	2539.69	-0.52
17 b	-8.20	1.46	2.58	43	2641.26	-0.54
17 c	-9.00	2.57	2.70	1	684.31	0.00

(*)sample numbers are keyed to numbers in Fig. IX.2.

minerals. In the saprolite, the volume change attain 54%, a nearly constant value up to the surface.

3. *The massive saprolite or massive bauxite* (sample 16b) presents a thickness varying from 1 to 3 meters. It is formed by large rounded blocks, separated by fissures of 1 to 5 cm width. As a continuation of the alteration cortex, it preserves the granular texture and the friability. The blocks are constituted essentially by gibbsite (90%), associated with small amount of goethite, hematite and anatase. The bulk density (1,43) and the real density (2,52) reflects a strong porosity (43%). Except for the zircon, all the minerals of the parent rock are altered, with a pseudomorphic texture. The fissures are the preferential way of water circulation and they are partially filled by a matrix constituted by cryptocrystalline gibbsite, goethite and small amounts of kaolinite.

4. *The fragmented saprolite or fragmented bauxite,* 4 meter thick, is formed by bauxite blocks (samples 8b, 13b and 14b) with 40 to 80 cm of diameter, enveloped by a fine matrix (samples 8a, 13a and 14a). The blocks present a friable nucleus with hard borders and the structures are preserved. The bulk density varies from 1,49 to 1,90, the real density is

Table IX.2 - Major elements (wt%) and rare earth elements (ppm) of the samples from PQA profile. The gains ($\tau > 0$) and the losses ($\tau < 0$) based on the Zr constant in relation to the syenite.

	nodular crust				blocky saprolite						massive saprolite	friable saprolite	syenite
Sample	2b	2a	5b	5a	8b	8a	13b	13a	14b	14a	16 b	17b	17c
SiO_2	1.78	1.76	1.67	3.02	1.96	4.76	1.12	1.78	0.51	0.53	0.52	0.64	54.20
Al_2O_3	59.86	59.00	57.50	56.10	59.13	55.65	60.00	57.00	59.00	58.20	59.00	58.00	21.00
Fe_2O_3	4.80	5.90	5.60	8.22	5.59	6.69	5.67	7.51	8.14	7.84	7.60	5.85	2.06
MgO	0	0	0	0	0	0	0	0	0	0	0	0	0
CaO	0.03	0.05	0.35	0.14	0.06	0.01	0.37	0.21	0.17	0.09	0.04	0.01	1.61
Na_2O	0	0	0	0	0	0	0	0	0	0	0	0	7.30
K_2O	0.18	0.20	0.14	0.36	0.39	0.73	0.16	0.31	0	0	0.22	0.05	7.90
TiO_2	0.83	1.18	1.07	1.49	1.21	1.29	0.97	1.66	1.30	1.87	2.09	1.37	0.62
MnO	0.19	0.24	0.20	0.30	0.10	0.20	0.13	0.22	0.22	0.20	0.22	2.79	0.13
H_2O	31.50	31.42	31.40	29.25	31.20	29.12	31.65	30.61	31.05	30.57	31.02	30.88	1.87
Total	99.17	99.75	97.93	98.88	99.64	98.45	100.07	99.30	100.39	99.30	100.71	99.59	97.03
La	125.57	113.32	105.68	88.28	96.46	75.29	121.27	104.41	78.63	60.22	52.96	68.40	176.23
Ce	1033.32	1152.84	1051.00	1127.68	870.9	1146.59	843.12	1114	694.32	2048.21	461.90	310.92	368.30
Nd	50.71	65.60	63.58	46.25	43.83	33.62	55.03	43.28	41.06	35.72	23.96	37.08	134.03
Sm	6.90	9.61	9.21	6.65	6.11	4.90	7.82	6.07	5.96	5.14	3.45	5.36	18.51
Eu	0.94	1.23	1.19	1.02	0.87	0.77	0.95	0.91	0.78	1.02	0.58	0.64	1.77
Gd	6.93	9.93	9.71	7.20	5.22	5.22	6.31	6.31	6.04	6.04	3.73	5.25	16.48
Dy	5.82	8.78	8.90	6.89	5.53	4.87	6.33	5.65	5.89	6.5	3.57	4.18	10.35
Er	3.60	5.97	5.79	4.69	3.83	3.26	4.52	3.79	3.98	3.73	2.66	3.55	5.40
Yb	4.41	8.01	7.13	5.71	4.75	3.85	5.42	4.73	4.50	4.22	3.54	4.23	4.27
Lu	0.84	1.34	1.19	1.02	0.86	0.66	0.99	0.83	0.79	0.74	0.60	0.77	0.72
ΣREE	1239.04	1376.63	1263.38	1295.39	1038.36	1279.03	1051.76	1289.98	841.95	2171.54	556.95	440.38	736.06
τSi	-0.99	-0.99	-0.99	-0.98	-0.99	-0.97	-0.99	-0.99	-1.00	-1.00	-1.00	-1.00	0
τAl	-0.06	-0.31	-0.18	-0.27	-0.21	-0.19	-0.29	-0.11	-0.18	-0.07	-0.24	-0.28	0
τFe	-0.23	-0.30	-0.19	0.09	-0.24	-0.01	-0.32	0.19	0.16	0.27	0.00	-0.26	0
τTi	-0.56	-0.54	-0.48	-0.34	-0.45	-0.36	-0.61	-0.12	-0.38	0.04	-0.09	-0.42	0
τLa	-0.77	-0.84	-0.82	-0.86	-0.85	-0.87	-0.83	-0.81	-0.87	-0.89	-0.92	-0.90	0
τCe	-0.08	-0.24	-0.15	-0.16	-0.34	-0.05	-0.44	-0.02	-0.45	0.85	-0.66	-0.78	0
τNd	-0.88	-0.88	-0.86	-0.91	-0.91	-0.92	-0.90	-0.89	-0.91	-0.91	-0.95	-0.93	0
τSm	-0.88	-0.87	-0.85	-0.90	-0.91	-0.92	-0.90	-0.89	-0.91	-0.91	-0.95	-0.92	0
τEu	-0.83	-0.83	-0.80	-0.84	-0.86	-0.87	-0.87	-0.83	-0.87	-0.81	-0.91	-0.91	0
τGd	-0.86	-0.85	-0.82	-0.88	-0.89	-0.90	-0.88	-0.88	-0.89	-0.88	-0.94	-0.92	0
τDy	-0.82	-0.79	-0.74	-0.82	-0.85	-0.86	-0.85	-0.82	-0.83	-0.79	-0.91	-0.90	0
τEr	-0.78	-0.73	-0.68	-0.76	-0.80	-0.82	-0.79	-0.77	-0.78	-0.77	-0.87	-0.83	0
τYb	-0.66	-0.54	-0.50	-0.64	-0.69	-0.72	-0.69	-0.64	-0.69	-0.67	-0.78	-0.74	0
τLu	-0.62	-0.55	-0.51	-0.61	-0.67	-0.72	-0.66	-0.62	-0.68	-0.66	-0.78	-0.72	0
τZr	0	0	0	0	0	0	0	0	0	0	0	0	0

around 2,55 and the porosity decreases from 42% to 25% (Table IX.1). The porosity decrease corresponds to the formation of gibbsitic and/or goethitic cutans in the dissolution voids. The mineralogical constituents are gibbsite (90%), hematite (6%), goethite (1%), kaolinite (2%) and anatase (1%). The matrix is light red to rose, with argillomorphic textures with small bauxite grains. The bulk density goes up to 2 and the porosity is 20%. This matrix is constituted of gibbsite (86%, kaolinite (6%), goethite (6%) and anatase (2%).

5. The nodular crust or nodular bauxite, 1 to 2 m thick, forms the surface horizon. It is constituted of bauxite blocks with 10 to 15 cm diameter, enveloped in a humic matrix with gray color in the surface and brown yellow in depth. Blocks and matrix are formed mainly by gibbsite (90%). But the initial gibbsite, pseudomorphic on primary minerals, is partially replaced by a second generation gibbsite that mask the inherited textures. The lower part of this surface horizon is marked in the presence of sub-horizontal small veins rich in magnesium (lithiophorite). These veins, together with the decreases of bauxite blocks size, mark a clear structural discontinuity between this crust and the underlying fragmented bauxite.

On the slope of this hill (Fig. IX.3), the bauxitic facies are similar to those described in the higher shaft (PQA). Nevertheless, under the massive bauxite, the contact with the fresh rock is not direct, but through a clay horizon having fragments of bauxite with preserved structure. The clay matrix is constituted essentially by kaolinite (>70%). The bauxite fragments (30% of the material) present variable sizes from centimeters to some decimeters. On the larger fragments one can observe, from the exterior towards the center, all the terms of the gradation from the pure kaolinite, with no preserved structure, to a bauxite with granular and preserved texture, like the one observed in the higher shafts. The observation with the SEM and the analysis with the electronic microprobe showed that the internal gibbsite of the blocks is submitted to a resilication process (Sigolo, 1988).

III. The Geochemical Variations

The main geochemical changes occur during the transformation of the nepheline syenite into friable saprolite. It is noteworthy the extreme thinness (2 to 3 mm) of this transformation zone. All the parent minerals are altered during this step. The alkaline and earth alkaline elements are totally leached. The aluminum, iron and titanium are partially leached and the rest precipitates in situ, forming mainly gibbsite associated with a small amount of goethite, hematite and anatase.

Globally the chemical composition keeps constant toward the top of the profile. The volume reduction varies from 50 to 70%, with higher values for the matrix as compared to the bauxite blocks. On the other hand, the transformation of massive saprolite into fragmentary saprolite is followed by a slight iron increase (Fe between 16 and 27%) and a relatively low aluminum loss (Al between 7 and 18%). This differentiation occurs together with the deposition of gibbsitic and goethitic cutans, that are observed at this level in the minerals dissolution voids, and underlines an absolute accumulation of these elements (Boulangé et al., 1975; Bocquier et al., 1985). The structural discontinuity observed at a microscopic scale, between the fragmentary saprolite and the nodular crust is expressed chemically as well as mineralogically.

The alteration conditions, leading to the direct bauxitization of a parent rock, gives origin to a fractionation and an important leaching of the REE, that is lower for Ce and HREE (Fig. IX.4)(Sigolo et al., 1987). In the parent rock, the REE are mainly concentrated in the apatite and sphene. Cerium and HREE are also present in the zircon (Gromet & Silver, 1983). As for the transition from the friable saprolite into the massive saprolite, one observes that the REE leaching, as compared to the major elements, shows a slight delay, which is manifested by an increase of all REE losses. This delay is associated with the differential alteration of the parent minerals. As a matter of fact, the apatite is altered at the same time as the nepheline and feldspar, while for the sphene, more resistant, the alteration goes up to the massive saprolite. The cerium has a peculiar behavior. One observes (Fig. IX. 4B), from the friable saprolite to the massive saprolite, a strong positive Ce anomaly. Cerium can precipitate as Ce^{3+} and form locally florencite $(La,Ce)Al_3(PO_4)_2(OH)_6$ (Sigolo, 1988).

However, this Ce anomaly is not only due to its liberation from the alteration of apatite and sphene, but also to the stability of the zircons. As a matter of fact, the zircons, with size lower than 50 μm, are frequently associated with the sphene in the parent rock and liberated during the alteration. The zircons preserve their euhedral shape and present no traces of alteration. The REE distribution in the zircon shows a strong HREE concentration, and a positive Ce anomaly (Murali et al., 1983;

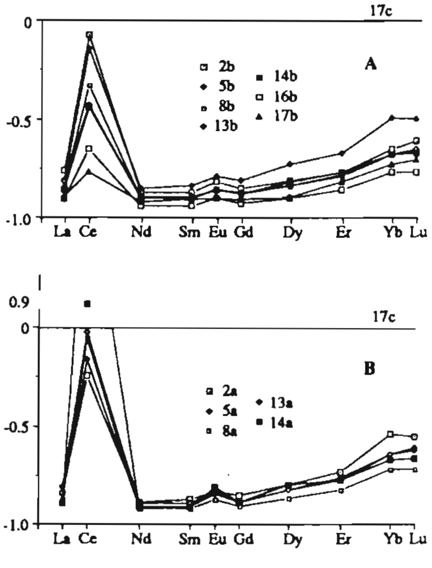

Figure IX.4 - REE net mass transport fonction patterns (τ). A is related to bauxite fragments, B is related to matrices.

Hinton & Upton, 1991). The ratio (Ce/ HREE)ch ,relatively constant (around 8) in the bauxite fragments (16b to 8b), show clearly that the positive Ce anomaly is partially associated with the zircon stability and its concentration in the saprolite. On the other hand, the strong variation of this ratio (10 to 24) in the matrix (14a to 8a) shows a mobilization of Ce in the circulation zone. The utilization of iso-zirconium reasoning allows to make evident an intensive leaching of all REE and a relation between Ce and residual HREE in the zircons (Boulangé & Colin, 1994).

As considering the low REE content, the results for fragmentary and nodular bauxites has to be taken carefully and only the global variation has some signification. The values obtained for $(\tau_{j,w})$ (Table IX.2) are always lower in this upper facies. It means that the mass balance, as referred to the underlying saprolite, shows a gain in REE. In the nodular crust in the surface, only Ce is leached (-79 g/m^3 as referred to the massive saprolite). Consequently, as except for CE, it seems that no particular chemical variation marks the existing discontinuity between the two upper facies.

IV. Genesis of the Bauxitic Profile

This summit profile results from a direct bauxitization (Millot, 1964; Boulangé & Millot, 1988) of the nepheline syenite. The alteration is rather intensive and the individualization of aluminum and iron oxihydroxides as gibbsite and goethite, occurs even in the contact of the parent minerals. All the petrologic and geochemical characteristics confirm the direct evolution from the parent rock. The large amount of dissolved elements gives origin to an important porosity. This porosity represents about 70% of the feldspars volume and 40% of the nephelines volume. Considering the dominance of these minerals in the parent syenite, it is observed that, despite the structure being preserved, a volume reduction of approximately 50% occurs. Under the microscopy, considering a bidimensional scale, this reduction is about 20%, which is not easily observed.

Apart of some small variation between the bauxite fragments and the matrix, the chemical composition keeps rather constant within the profile. Nevertheless, a discontinuity under the upper horizon of nodular crust is observed. However, the mass balance shows that there is no particular variation of the elements and that the nodular crust is originated from the same parent rock as the underlying facies. Consequently, the discontinuity, only structural, could be considered as a limit between an ancient alteration profile and the recent one, represented by the saprolite underlying facies. Thus, the geologic history of this profile would involve two bauxitization period, which duration is not possible to stablish.

In the slopes, the presence of a kaolinitic horizon with residual bauxite balls would be an evidence of the succession of the two episodes. The first episode would be an intense bauxitization and the second one a partial resilication. This resilication could correspond to an accumulation of silica coming from the alteration of the summit profile, during the second bauxitization period.

V. The Piedmont Bauxites

The piedmont bauxites are slope colluvial accumulations. They are constituted of numerous blocks of syenite and bauxite embedded in a clay matrix. They are observed in all the surrounding of the alkaline massifs of Passa Quatro and Itatiaia and it is particularly abundant in the regions of Lavrinhas and Queluz, in the southern part of Passa Quatro (Pinto, 1937; Ribeiro Filho, 1967; Penalva, 1967). These deposits extend from 500 m up to 1,330 m altitudes on large accumulation surfaces (glacis), developed on the basement gneiss (Fig. IX.5) (Sigolo, 1988). These bauxite ores (5.5 million tons) are destined to direct commercialization or treated in place for corindon production (calcination) or aluminum sulfate production.

1. Characteristic of the colluvium deposits

A geomorphological study of the piedmont zone, has shown the presence of three great units named upper surface, middle surface and lower surface (Fig. IX.6). The pediment colluvium deposits are constituted of boulders and blocks of bauxite and alkaline rocks embedded in a clay matrix overlying weathered rocks of the Pre-Cambrian basement. The deposits of each surface present different characteristic.

The upper surface is the most important of Lavrinhas and Queluz sector and its extension can reach 8 km. It presents an altitude of 1,300 m, in the contact of the alkaline massif and the basement gneisses, and 800 m, in its lower part, towards Paraíba do Sul river, forming a 10 to 15° slope. The colluvial deposit , according to the metamorphic basement undulations, can reach 20 m of thickness. The studied profile (Jazida da Sede), with a thickness of 12 m (Fig. IX.6), is constituted, from the top to the bottom, of i) a soil developed on ii) a colluvial deposit, having in its

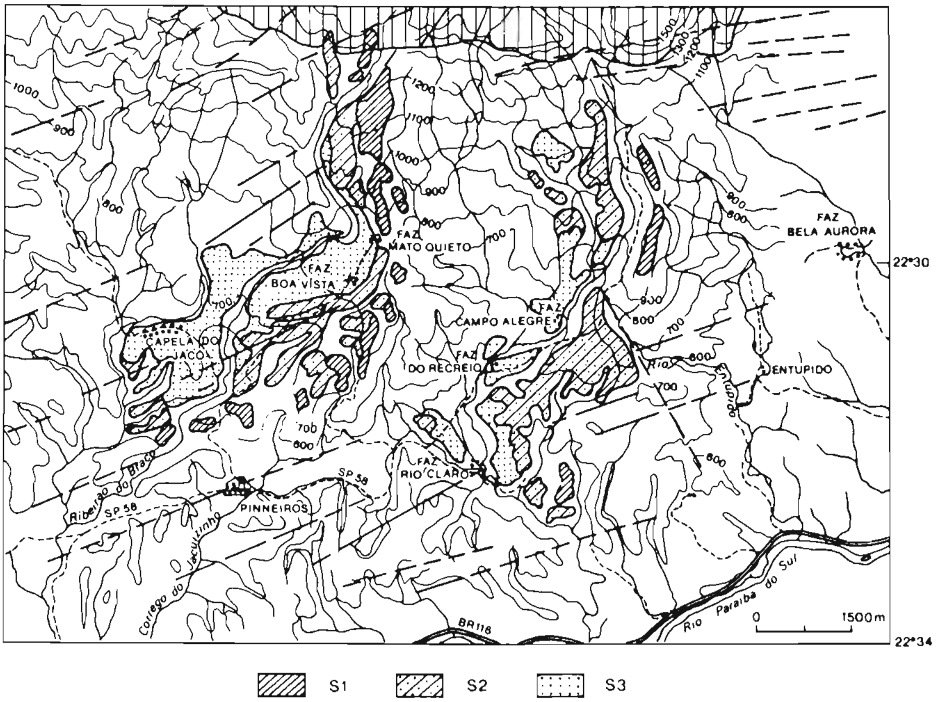

Figure IX.5 - Geomorphological and structural map of the south piedmont of the Passa Quatro alkaline massif (Lavrinhas and Queluz areas).

base iii) a transitional zone in the contact with the basement metamorphic rocks.

The soil or upper barren layer, developed from the colluvial deposits, has a thickness of 2 to 3 m. It is formed of two horizons:

- the upper horizon (1 m), under a thin humic layer, is constituted of gibbsitic nodules, with 2 to 5 cm of diameter, embedded in a matrix formed by kaolinite and quartz. The nodules, normally rounded and sometimes as a tube, are formed by a cryptocrystalline gibbsite and contain always an important amount of silica (20 %),

- the lower horizon with yellow colour is a clay quartzous material, constituted mainly of kaolinite, quartz and gibbsite, concentrated in small whit tubes surrounding roots.

The colluvial middle layer with a thickness of 6 to 7 m, the deposit of economic interest, is constituted of:

- blocks of various rock types (nepheline syenite, microsyenite, hornblende syenite), that can attain 10 m diameter and having or not an alteration cortex;

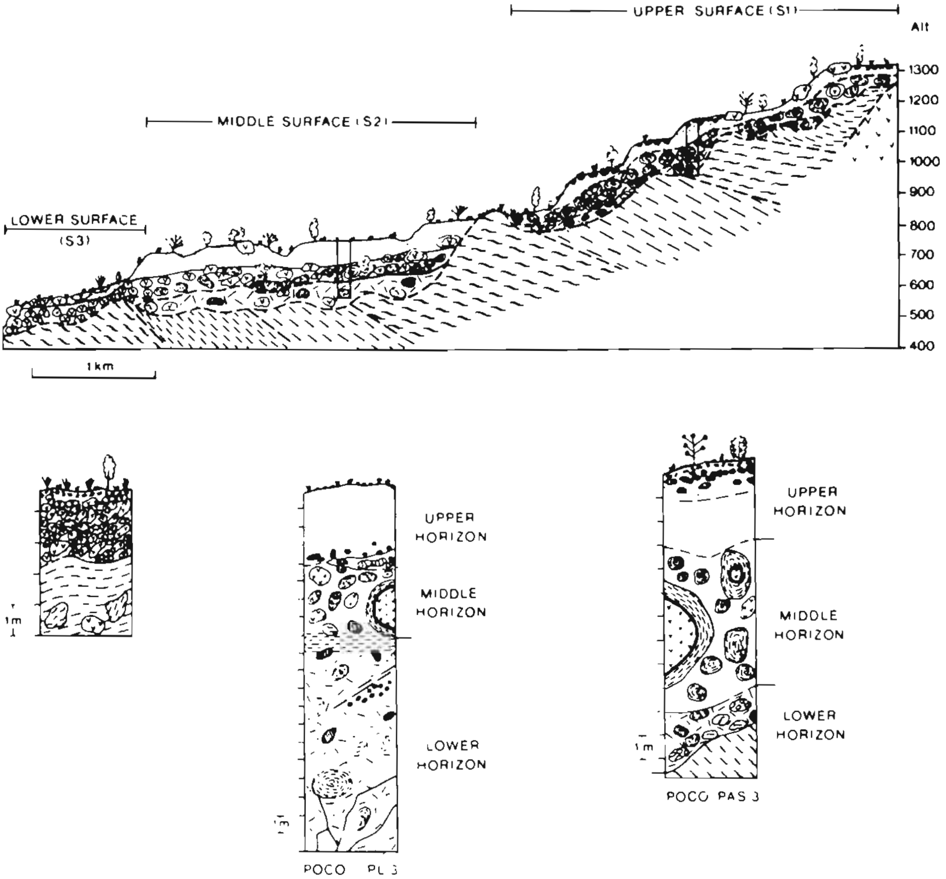

Figure IX.6 - Sketch of the piedmont formation.

- bauxite balls, of decimetric to metric size, with texture and composition close similar to the summit bauxite. These bauxite balls, that could present a rocky core, are affected particularly in its base by a resilication process and its transformation into the kaolinitic matrix is gradual.
- the matrix, of yellow colour, is constituted of kaolinite, gibbsite and quartz.

The lower layer (1 to 2 m), preferentially located in the lower zones of the substratum paleotopography, contains numerous fragments of basement metamorphic rocks (gneiss, quartzites). Certain gneiss fragments are totally altered, some of them into kaolinite and others into gibbsite. The matrix is kaolinitic.

The middle surface extends alongside the recent valleys, down the upper surface. Its altitude ranges from 700 to 800 m, with a gentle slope (lower than 10°). The described profile (Jazida da Sede) presents a thickness of 20 m. The colluvial material of the middle surface presents the same vertical distribution, but the characteristics of each horizon are slightly different as compared with the upper surface horizons.

The soil, with a thickness of 3 to 4 m, is homogeneous and presents only one clay-quartzous horizon. It shows yellow colour, and is overlaid by a very thin humiferous horizon, associated with the herbaceous vegetation presence. Gibbsitic tubular nodules related to a superficial pedogenesis are observed at its base.

The middle layer, with a thickness of about 4m, which also forms the ore deposit presents a lower amount of bauxite boulders, a greater quantity of fresh rock boulders of smaller size. In this case, all the steps of the transition from the bauxite boulders into kaolinite matrix can be observed.

The lower layer can attain here a thickness greater than 10 m. The bauxite blocks are less abundant and sometimes totally resilicated. The fragments of metamorphic rocks, specially those of quartzite, are little abundant. Fissures, coated with manganese appear in the lower part of the profile.

The lower surface presents a small extension with regard to the previous one. It is developed at the foot of the middle surface, some 50 m lower, between 520 and 700 m of altitude, to which is connected through a concave slope. It is in this surface that the last geomorphologic feature, constituted by the present cutting, is impressed

The colluvial material of this surface, with thickness of 4 to 5 m, is constituted of blocks, boulders and pebbles of alkaline rocks and some rare pebbles of bauxite embedded in a little abundant clayey sand matrix. The boulders and pebbles have an average size smaller than those of the upper and middle surface. The recent stream beds have cut in the material of this surface, leaving behind only a pavement of blocks, boulders and pebbles of alkaline rocks.

2. *The evolution of the colluvium deposits*

This piedmont colluvial deposits were submitted, after their placement, to an evolution associated with the new morphoclimatic conditions of the ore deposit.

The upper horizon of sandy clay texture results from a pedogenetic evolution of the upper fine-grained part of the colluvium, locally at the surface. Some gibbsitic nodules indicate an alumina remobilization by roots activity.

In the middle layer, the boulders of alkaline rocks often present a gibbsitic weathering rind, at their upper part. They present as well a kaolinitic fringe, at their base, resulting from a recent differential weathering process, associated with the drainage conditions at the boulder's contact. The bauxitic boulders present resilication features, linked to the present evolution within the profile.

In the lower part of the colluvial material, it occurs bauxite boulders originated from the alteration of syenite or the basement gneiss. This could be an evidence that, before the pediments formation, rocks of the alkaline massif and the Pre-Cambrian basement were submitted to the same bauxitization process. Most of the rock fragments are altered into kaolinite and the bauxite boulders themselves were completely or partially resilicated and now appear in continuity with the kaolinitic matrix.

Thus, the evolution of the piedmont bauxitic colluvium seems to have been toward the kaolinization, either by weathering of the alkaline rock fragments or by resilication of bauxite fragments. In any case, except locally in the cortex of the syenite blocks at the upper part of the profiles, the transformations indicate a post-deposition "in situ" bauxitization.

VI. Relation between the summital bauxite and the piedmont bauxite

In this area of Passa Quatro massif, two types of bauxite occur. The first one, on the summit, results from an in situ bauxitization of the syenite. The second one is formed of boulders and blocks, with the same structure and the same mineralogical and geochemical compositions that the summital saprolitic bauxite. They are embedded in a kaolinitic matrix, deposited on the basement, at the foot of the alkaline massif. A genetic relation between them seems to be obvious.

There are many arguments showing that the bauxitization has occurred on the syenite before the deposition of the colluvium. As a matter of fact, in this colluvium material one can observe: a mixture of blocks and boulders of fresh alkaline rock and of bauxite; the presence in the lower horizon of bauxite boulders formed from the weathering of gneisses; the resilication of the bauxite boulders in the middle and lower layer of the profiles in this pediment.

These piedmont bauxites were associated with an eventual glaciation of Pleistocene age (de Martone, 1940; Rich, 1953; Odman, 1955). In fact, these deposits could be associated with an important *solifluxion* phenomena (mud-flow or mud stream) of weathered material, coming from the higher zones of the alkaline massif. The phenomena would be caused by the rupture of the equilibrium during the Paraíba rifting (Ebert, 1960; Sigolo, 1988).

It is difficult to accept that the three surfaces were developed at the same time. The topographic situation of the middle and lower surfaces, as compared to the upper surface, seems to indicate that they result from an evolution and redistribution of colluvial materials of the upper surface. A tectonic event, following the formation of the upper surface, is probably responsible for the differentiation of the middle surface. The convex slopes linking these two surfaces would indicate a slow movement during a humid period. The down thrown zones of the middle surface are submitted to a more intense hydromorphy as compared to the deposits of the up thrown surface. This leads to a weathering of the syenite boulders into kaolinite and resilication of the bauxite boulders.

The lateral extension of the colluvial upper surface was certainly more important than it is today and it should be covered the areas where the middle and low surfaces are now observed. Indeed, considering the gentle slopes, mechanical erosion is the only explanation for the presence of very big syenitic boulders within the deposits of the low surface and as far as in the stream beds. This erosion would draw out the fine grained material cleaning the colluvial deposits of the upper and middle surfaces. Thus, locally these fill-in fill pediments were superimposed one into the other.

Considering the age of the alkaline rocks (70 My), the bauxitization would affect simultaneously those rocks and the metamorphic basement rocks during the early Cretaceous and Eocene. The Paraíba rifting could have started at the end of this period, during the Oligocene (Almeida, 1976; Melfi et al., 1976), related to the age of the sediments of Resende and Taubaté basins (Amador, 1975; Lima & Amador, 1983; Melo et al., 1985a and 1985b). This would be also the period of formation of the upper surface. After the cold and dry period of the Oligocene, a new bauxitization period has taken place on the massif. This period would be responsible for the formation of the bauxite profile in the summits and also for the in situ pediment deposits evolution: weathering rind of the rock boulders, resilication of bauxite boulders, alumina remobilization. From the Pliocene up to now, the reworking of the pediment deposits by the rivers was responsible for the shaping of the low surface and its recent incision.

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THE BAUXITE OF LAGES DISTRICT

M. Formoso, N. Dani, I. Valeton

Introduction

The southernmost bauxite deposit described in Brazil is found in the Lages Alkaline District (Fig. X.1) located in the southeastern part of Santa Catarina state (27°33'S, 50°13'W). With an area of 12000 km, it comprises Paleozoic to Mesozoic sedimentary rocks and Upper Cretaceous rocks (Amaral et al. 1966; Scheibe et al., 1985) of volcanic and subvolcanic alkaline intrusions of the Parana Basin Sequence.

Among the alkaline rocks, phonolites are dominant and the bauxite deposits are related to this type of rock by virtue of its susceptibility to weathering and also high aluminium and low iron contents. Although the bauxite is a weathering product restricted to alkaline rocks, recent papers (Szubert & Vergara, 1975; Dani, 1988) have shown evidences

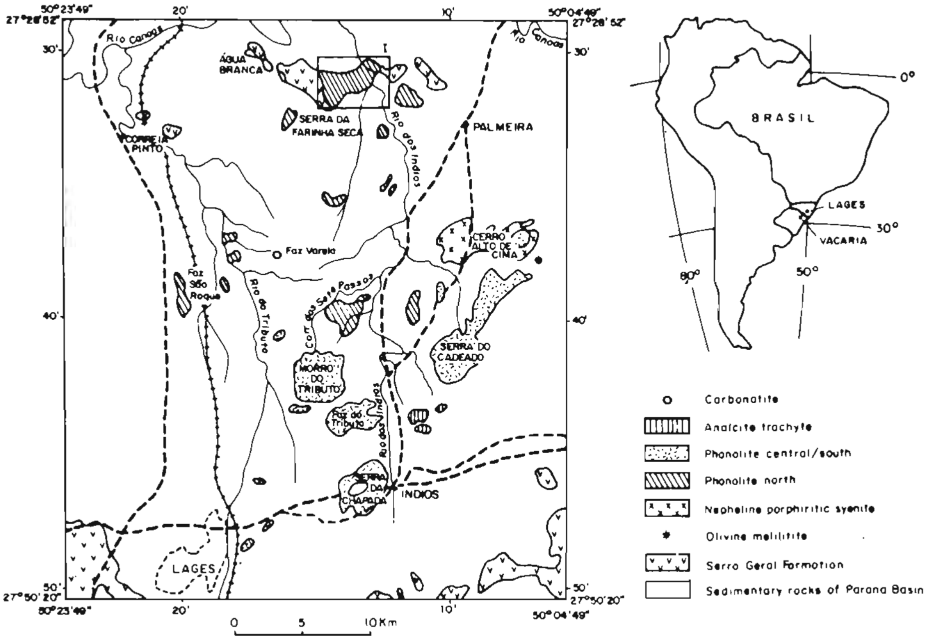


Figure X.1 - Geological map of Lages (modified of Scheibe et al.II, 1984) that the lateritization processes have extended to other rocks such as the diabases and basalts of the Parana Basin.

The Lages bauxite shows many evidences of being an occurrence disconnected with present environmental conditions and it is considered to be a paleoalterite. The presence of clay material surrounding blocks of bauxite identify late processes which might represent an equilibrium with the present environment which is favourable to siallitization processes (Pedro & Melfi, 1982).

Other aspect that dissociate this occurrence from the present time is the relation that was found between the alterite and the local relief preservation conditions.

I. Climate

In Lages, all seasons are well defined and the average temperature tends to be low, around 15°C being usual frost during the winter and, at least, there is snow precipitation three days a year. In general, two principal factors are responsible for the present climate of Lages: geographical position (latitude around 30°S) and altitude (average 900 m). Rainfall is evenly distributed during the year with values higher than 100 mm per month. There is no period of drought, which is common in the Brazilian climate. Thus, the climate is temperate and highly humid. Lages is geographically situated on the limit of the favourable zone (Lelong et al., 1976; Bardossy, 1982) for bauxite formation. At present time, factors like geographical position, climate conditions and field evidences make the processes of podzolization more favourable than lateritization.

II. Regional Aspects

The Lages Region is situated in the eastern border of the intracratonic Paraná Basin which is filled up mainly with detrital sediments and consists of rocks from the Upper Paleozoic to Mesozoic ages. In the geological evolution of the Paraná Basin, the final event consists of extensive basaltic lava flows of Serra Geral Formation with radiometric age of 130 to 135 Ma. (Cordani & Vandoros, 1967). In Lages, the post-basalt alkaline rocks, intrusive in the sedimentary rocks of the Paraná Basin, display a circular structure showed today by differential erosion. The older sedimentary rock extend over the central part of the circular structure whereas the young basaltic and sedimentary rocks extend over the borders (Fig X.1). Included in this sequence, the younger alkaline rocks occurs with average radiometric age around 70 Ma. (Amaral et al., 1966; Scheibe et al., 1985) at the limit between the Cretaceous and the Tertiary.

The subvolcanic alkaline rocks of Lages exhibit important textural and mineralogical variations. The alkaline association include rocks as phonolites, nepheline syenites, more acidic members as analcite trachyte and also ultrabasic-alkaline rocks as olivine melilitites, breccia and carbonatites.

The existence of products which denote deep weathering is widespread in Lages, but true bauxite deposits with economical importance are concentrated in a restricted area, in the northern part of the circular structure, named Serra da Farinha Seca (Fig. X.1 and X.2). The most important weathering profiles were developed over phonolites of the northern type.

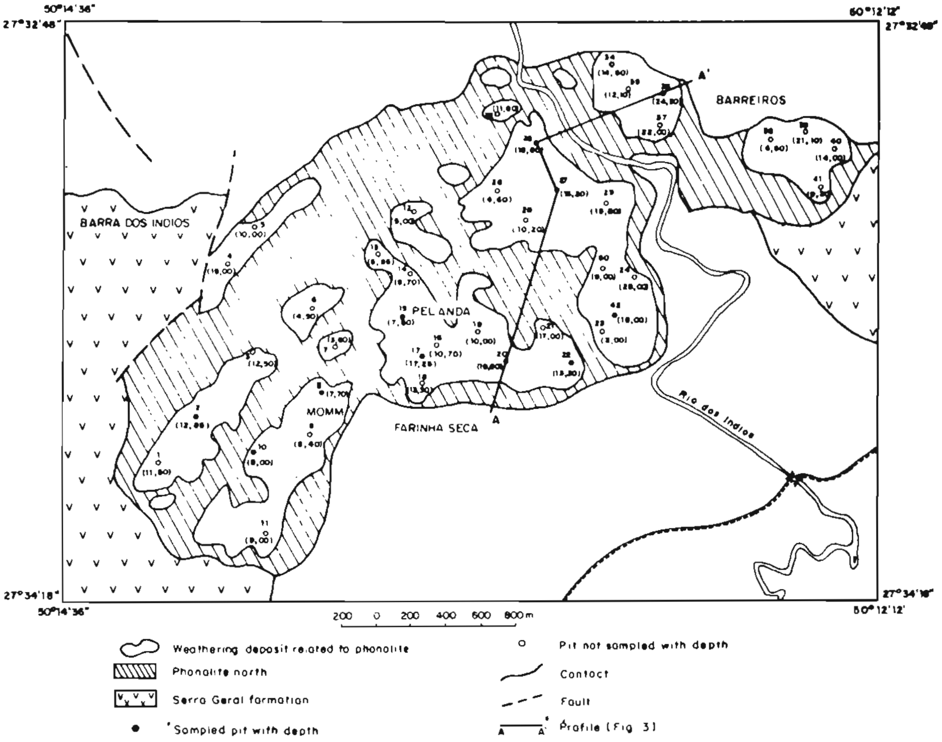


Figure X.2 - View of Farinha Seca hills (Site I, Fig. X.1) where is located the main bauxite deposits of lages region.

III. Geomorphology

The high plain of Lages is part of the large Brazilian Meridional Plateau. Lages and other areas, which are preserved from erosive action, as Vacaria (Fig. X.1), in the southern part, and São Joaquim and Bom Jesus, in the eastern part, indicate the existence of a high surface, which in the past constituted a wider plain. This plateau has been included in the South American Cycle (Melfi et al, 1984), in which the average altitude is 900 m, although higher altitudes are common, reaching up to 1,700 meters (São Joaquim).

In this high plain, there are many evidences of a thick lateritic profile, although deeply eroded principally in the drainage valleys of the present rivers. Normally, laterites are concentrated in places where the altitude is around 900 m, that represent a plain land probably established in the Tertiary in lower altitudes than today (Valeton, 1985). Afterwards, this region was submmited to uplift movements and to differential erosional events.

In the toposequence of the typical bauxite of Lages, is shown that alterites remain only in high places of occurrence of alkaline rocks (Fig. X.3). Towards the drainage and valleys, the weathering cover becomes gradually thinner and fresh rock occurs directly in the valleys, showing instability of alterite in present conditions. Although the

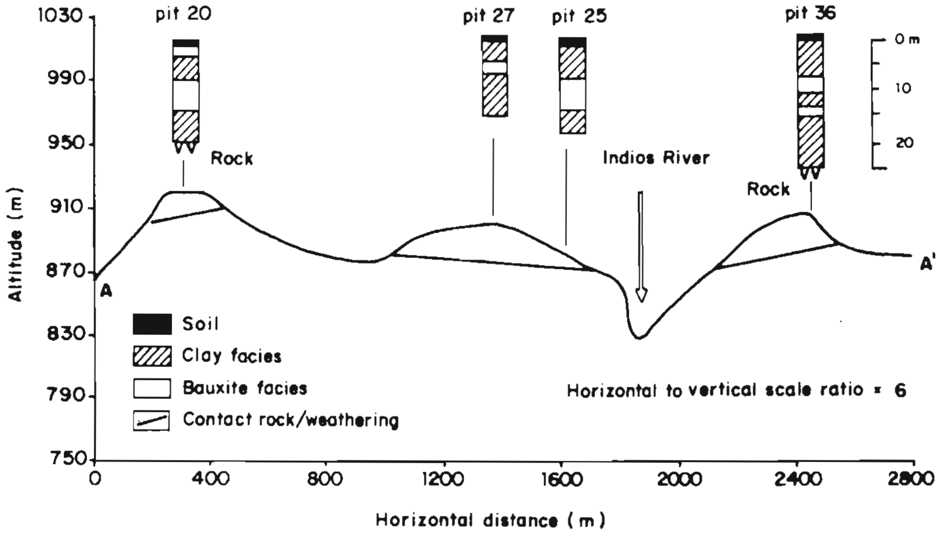


Figure X.3 - Schematic toposequence showing the different alteration profiles.

stratigraphical position of the laterites of Lages represents an unsolved problem, an indirect approach about the ages of this may be evaluated observing the development of the Indios River channel, which cuts deeply these alterites. It is reasonable to think that lateral erosion was intense, so that the averaged 10 m of thickness of the present profiles probably represents a part of the original.

Also, it is observed that the rock/alterite interfaces are found in different altitudes and are associated with different succession of facies which lead to the idea of polycyclic events of lateritization, probably related to variations of water table depth and consequent reativation of weathering process.

IV. Ore Deposits

Basalts and alkaline suite are the igneous rocks which occur in the Lages area. The composition of weathering products reflects the mineralogy and chemistry of rock. As the iron contents of basalts and diabases of Serra Geral Formation are higher than those of alkaline rocks, the former weather to iron bauxite, and the latter, poor in both iron and silica, form true bauxite.

The influence of factors as geomorphology and geology explain why bauxite deposits with economical importance are not widespread, but are found in some restricted areas (Fig. X.2). In these sites, the occurrences are covering small hills, forming blanket deposits with "in situ" weathering products. Evidences of reworking are found only in the top horizons of the profile and typical deposits of secondary origin are not known.

The alkaline district of Lages was prospected for bauxite (Szubert and Vergara, 1985), and a reserve of 75 million tons was estimated, including low (clay facies) and high grade ores (bauxite facies). This value has been overestimated and the reserves of this district are around 5 million tons. Although the reserves are low, the feasibility of mining this area must be considered, especially that the aim is the use of bauxite for the production of aluminum sulfate. The region has a favourable situation and with a sulfuric acid plant geographically close.

V. Profile Types

In Figure X.3, the profile of each pit was simplified taking into account four principal facies observed in a bauxite profile: fresh rock-weathered rock, clay facies, bauxitic facies and recent organic soil. As a result of field work, and chemical and mineralogical studies (Dani, 1988), it was possible to divide the profile in two general zones (Fig. X.4). A large isalterite basal zone, where the original textures and structures of subjacent rocks are preserved; and a small aloterite top zone, where collapsed structures and reworking process are identified in the upper part.

In general, the bulk weathering paragenesis consists of gibbsite and sometimes boehmite; clay minerals in which 10Å halloysite predominates and iron minerals, as aluminum goethite, providing a yellow colour to the weathering profile.

1. Isalterite Zone:

By definition, isalterite is a weathering material in which original textures and structures of parent rocks are still recognizable (Boulangé, 1984). The isalteritic zone is the widest portion of a bauxite profile in Lages and may be divided in facies that exhibit a significant vertical and horizontal variability. Normally, at the bottom, the sequence has a transi-

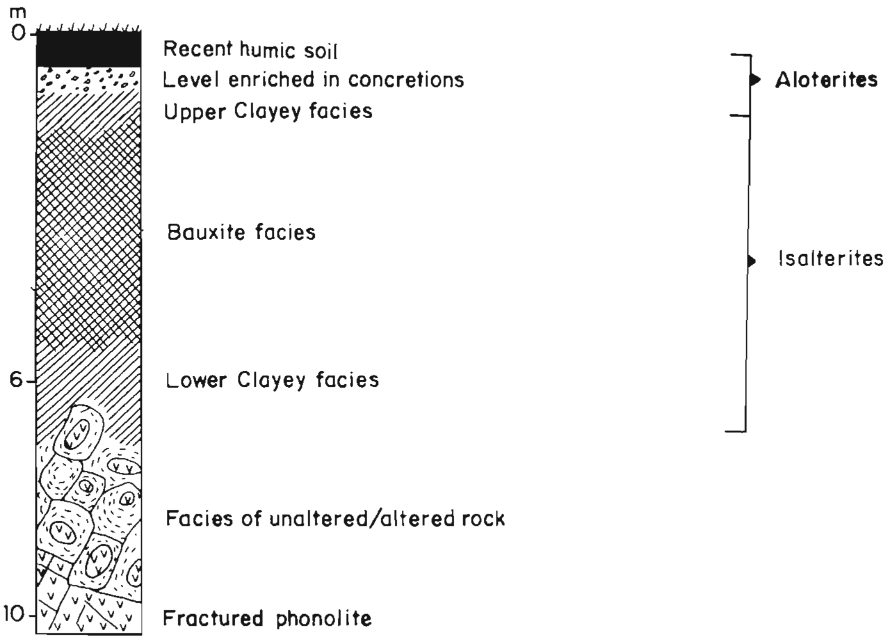


Figure X.4 - General weathering profile of type area (Serra da Farinha Seca).

tional zone formed by a weathered rock facies which is followed by clay facies and bauxite facies. In some places, the bottom weathered rock facies is under the clay facies and this under the bauxite facies. Also, it is not uncommon to find bauxite directly over the weathered rock facies without clay facies. In fact, the variability of facies in the isalteritic zone is an evidence of different evolutions. Locally, the succession of clay and bauxite facies may represent variations in porosity and permeability, which generate micro-environments with different drainage conditions, and then creating zones more favourable to bauxite or clay facies formation.

Hand samples of fresh phonolite have in average, densities between 2.3 and 2.5, and natural porosity between 2 or 4%. Considering the rock in situ, the porosity certainly is higher than was measured on hand sample. Accordingly, field observations show that the phonolite in Farinha Seca is more fracturated and the fracture system is tighter than that of the phonolites of the southern part of the area, and in part, mainly this fact explains also the higher alteration of the phonolite of Farinha Seca in comparision with other phonolite blocks. At the bottom of the profile, in the weathering rock facies, the alteration begins in fractures and moves towards the rock, that, in more advanced stages, form isolated blocks, with typical onion skin structure, in which the dissolution and transport of the elements increase towards the external portion. At the zone of loss of elements or cortex (Lacroix, 1913), it is possible to estimate the degree of transformation of the rock using parameters as change of colour and massiveness. The colours change from gray in the phonolite to fainting colours in weathered phonolite, and white-gray or yellowish gray, when the rock becomes a friable material. In the first steps of weathering, it is possible to identify cavities (sometimes euhedral), which were formed by dissolution of primary mineral phases, as nepheline, resulting in an increase of porosity which reaches values of 14%. In the wheathering rock facies, normally the density reaches values as low as 1.9 and 2.0.

The lower clay facies still displays the structures of the underlying rock. The colour is variegated and more often from red to yellow with dark dots related to primitive mafic minerals. There is a network of pores 2-12 mm wide, where normally gibbsite occurs. The texture is relict and the material is friable. The clay facies has a high porosity as 50%, at least, and a low density, with values of 1.5. The common minerals are 10Å halloysite and minor gibbsite, boehmite and goethite (Fig. X.5).

In the bauxite facies, the enrichment of alumina and the loss of silica are remarkable. The bauxite facies is residual and autochtonous, with relict texture and original rock structures visible in hand samples

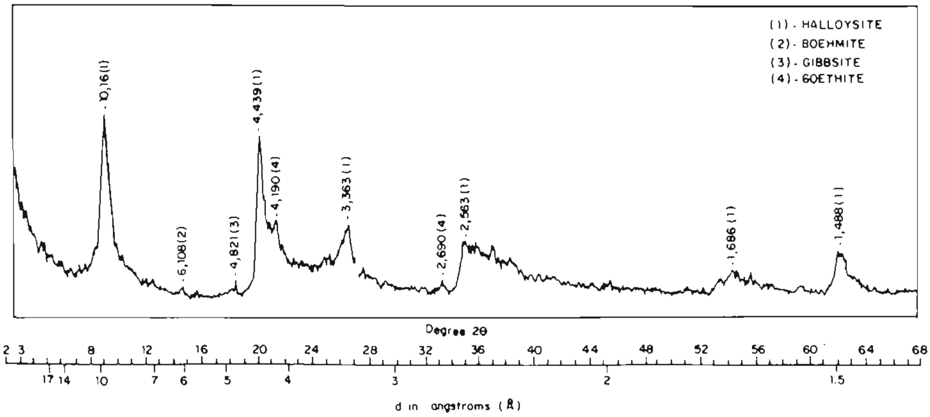


Figure X.5 - X-ray diffractometer patterns of clayey facies, (Cu Kα radiation)

and under the microscope. In the field, the bauxite facies shows prismatic blocks related to underlying rock. Their boundaries are evidenced by fractures of the original subjacent phonolite. The hand sample exhibits large number of pores which increase the porosity to values higher than 50%. The density is low, with an average of 1.5 but it is common values near 1.0. In this case, it is possible to observe that felsic minerals are more unstable than mafic ones. The nepheline is altered and forms dissolution cavities which are partially filled with gibbsite. Concerning the mafic minerals, which are more resistant to weathering, it is possible to see the forms of a normal pseudomorphose, with as goethite and gibbsite. The alveolar texture is typical, showing a network of pores with walls made of gibbsite (Photo X.1). The shape of these pores resemble that of the original mineral. The mineralogy of this horizon has mainly gibbsite with minor boehmite and goethite (Fig. X.6).

2.- *Upper alloteritic zone:*

In the upper part of this zone, there was a breakdown of the profile, with a mechanical enrichment of gibbsitic nodules. The late pedogenesis affects the upper clay facies so that the structure of the rock is not recognized anymore. In this process, the progressive leaching of gibbsite produces first a weak bauxitic framework with high porosity, which forms at the end a fine collapsed material named upper clay facies.

The thickness of the upper organic soil is less than 0.5 m. Normally, below the soil, the upper clay facies has a brown colour due to pedogenetic influence. The increase of kaolinite towards the top prob-

Photo X.1: Alveolar texture of Farinha Seca Bauxite (MEV-1200X).

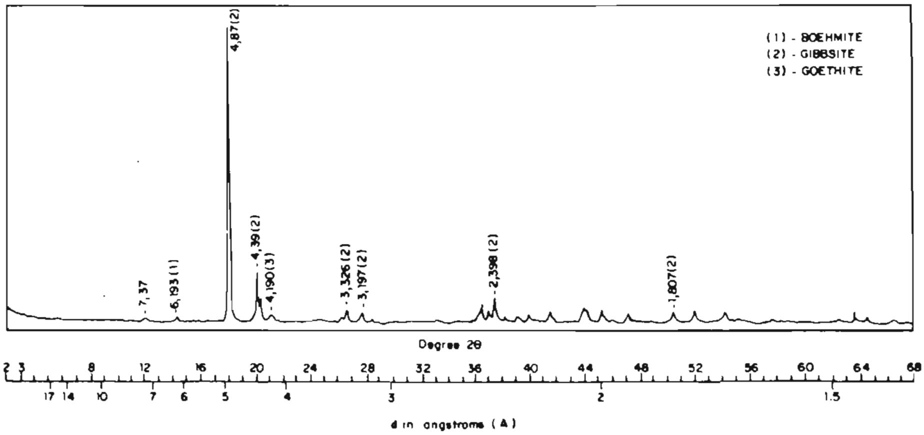


Figure X.6 - X-ray diffractometer patterns of bauxite facies (Cu Kα radiation).

ably is related to the instability of ferralitic material in the present climatic conditions favourable to ferrisialitization (Valeton & Melfi, 1986). In this region, the mobilization of aluminum and iron results in a relative increase of silica. Iron and aluminum are probably transported as organic complexes to lower horizons, where they precipitate as amorphous or crystalline phases in pores, fissures and joints. Some typical phases of those late processes are manganese minerals (as lithiophorite), gibbsite and halloysite, often as "cutans" (thin skins).

3. Veins and remobilization:

In the isalteritic zone, a network of veins occurs which normally are filled with porcelanic 10Å halloysite and manganese minerals, in which the crystalline phase is lithiophorite. Also, at the bottom of the profile, thin layers occur covering bauxite blocks or filling small fractures in the phonolite constituted of gibbsite with botryoidal habit, originated by local remobilization of aluminum (Photo X.2). The mechanism that may explain the aluminium mobilization is related to the present process of podzolization, in which the element is transported due to the interaction with organic matter, forming chelates and other complexes (Violante & Violante, 1980). In this way, veins and "cutans" in the isalteritic zone represent later precipitated material.

Among blocks in the bauxite facies and in open spaces in the weathering profile, a superimposed red brown clay material occurs, which was carried by later migration of clay particles from the upper part. Also, in the upper zone of the weathering profile, a horizon with red hard nodules of gibbsite and pedotubes occur originated by a mechanical enrichment. found in the bauxite facies. The distribution of nodules is not uniform and certainly is related to areas where their enrichment were favoured by mechanical processes.

VI. Behaviour of Common Minerals of the Phonolites in weathering processes

In general, the phonolites, which form isolated massifs in the area, show quite similar mineralogical and chemical composition, considering only the essential minerals. These are K-feldspar, nepheline and pyroxene. It is possible to divide phonolites in two groups, based on the percentage of phenocrystals and matrix, granulometry and acessory minerals. The phonolites of southern part of the area are more fine than those

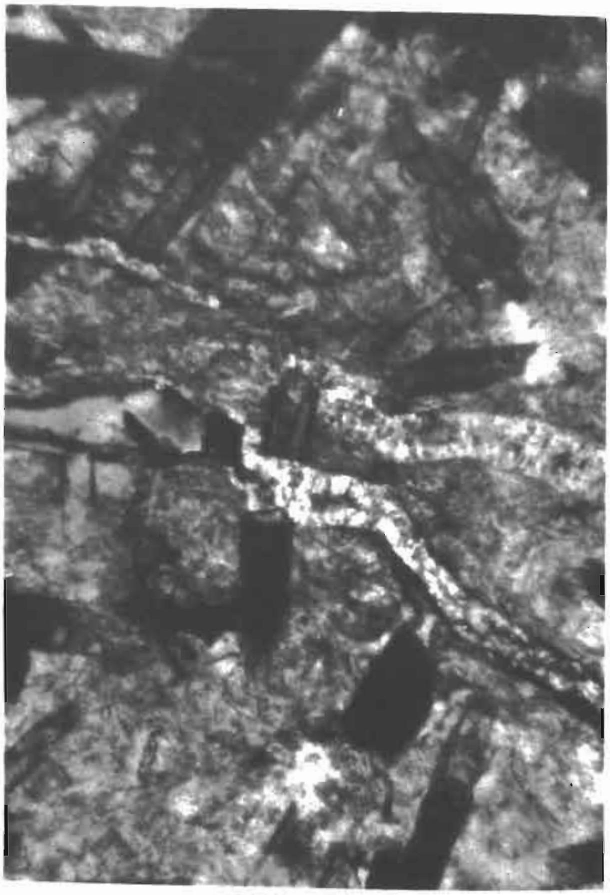


Photo X.2: Veinlets of gibbsite cutting the incipient weathered rock (LP-125X)

of the northern one and the proportion of matrix is also higher in the southern part, resulting in differences that alone are not conclusive to explain their behaviour in weathering alteration. Those phenocrystals are of variable size, in the porphyritic texture.

a - Nepheline.

In the alteration process, the nepheline is the phase more unstable to weathering (Formoso et al., 1990). This mineral is only found at the bottom of the profile, in the facies rock/weathered rock. Nepheline is almost dissolved, remaining only the borders, increasing rapidly the secondary porosity which accelerates the process of supergenic alteration.

In the first steps of mineral weathering, it is possible to observe that corrosion begins to develop on the boundaries and fissures of nepheline minerals. Afterwards, the dissolution increases towards the inner parts of the mineral forming dissolution cavities. Gibbsite is the principal weathering phase, growing preferentially along the boundaries and partition directions of original mineral, covering dissolution cavities. The typical alveolar texture characterize the end of this process. By analysing the composition of material originated by nepheline weathering, high aluminum phases (ratio Si/Al=0.7), probably amorphous, occur. In the zones of more advanced alteration, gibbsite, which is the final product of alteration, is associated with amorphous material (Fig. X.7).

b - Feldspar.

Feldspars are the most abundant minerals of phonolites. The first stages of weathering of feldspars are evidenced by their corrosion and appearance of loose particles on the surface of the mineral. Scanning eletronic microscope (Photo X.3) associated with EDS analysis (Fig. X.8) display globular structures with silicium and aluminum ratio equal 1.

Related to local conditions, feldspars show two ways of weathering evolution, one convergent to minerals of kaolinite group and other to gibbsite. The mineralogy of altered rock is dependent of chemical composition of solutions which circulate through the weathering profile (Velbel, 1982), and also of the composition of the dissolved minerals. In the case of feldspar, the nature of the secondary phases depend on the availabil-

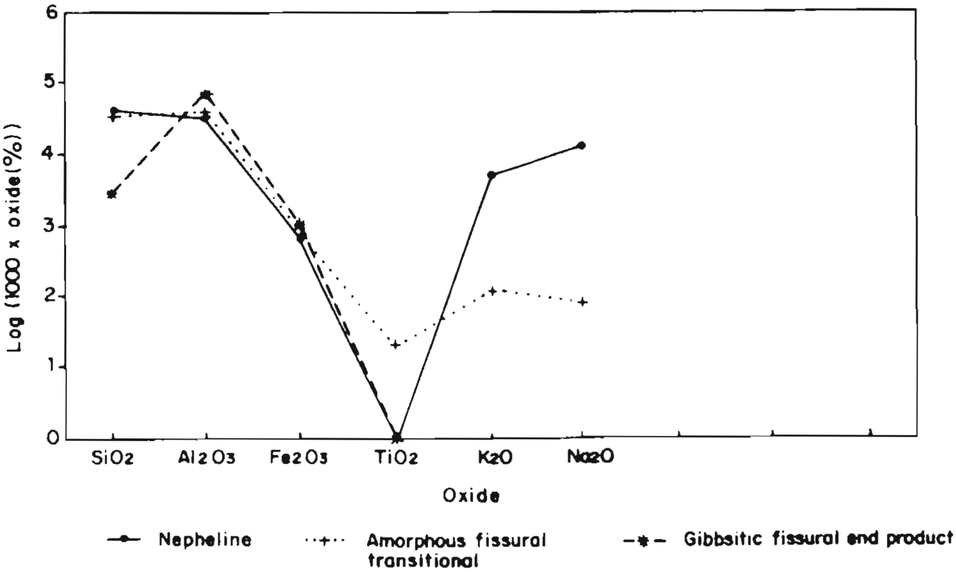


Figure X.7 - Chemical analyses of hepheline and associated alteration products.

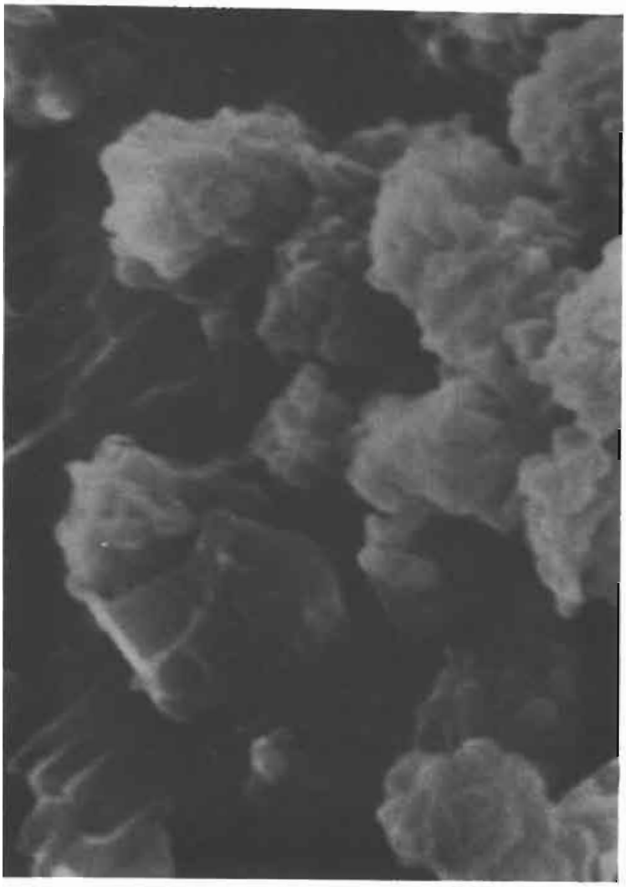


Photo X.3: Feldspar grain with gibbsite and globular silico-aluminous amorphous material (MEV-8700X)

ity of silica in the environment. With high silica activity, feldspar alters to clay minerals; with low silica, the product is gibbsite. Delvigne (1967) observes that, before the generation of secondary gibbsite or kaolinite, the formation of amorphous materials with aluminum and silicium occur in fractures, cleavage and twin planes. This amorphous material represents an intermediate phase in the supergenic evolution of feldspar alteration. This material may evolve to gibbsite if the drainage conditions are very good, or to halloysite if the solution has a composition with higher activity of *H\24\1SiO\24\1.*

c - Pyroxenes.

Concerning to pyroxene, in Farinha Seca area, the diopside-

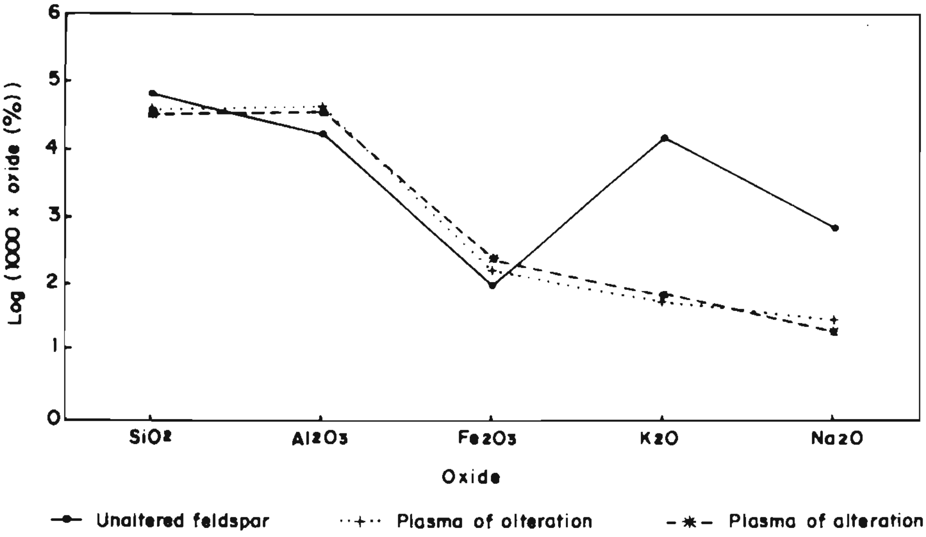


Figure X.8 - Chemical analyses of feldspar and primary alteration plasma.

hedenbergite phonolite predominate and in the southern part, aegerine-augite phonolites are more important (Scheibe, 1986). In general, pyroxenes, principally the latter, are more resistant phases to supergenic alteration than felsic minerals in this area. The concentration of iron is very low in leucocratic alkaline rocks and it is related mainly to pyroxenes.

The first stage of weathering of pyroxene can be detected when the mineral loses rapidly some original properties, acquiring brown colours, weaker birrefringence and corrosion aspects. The iron migrates to fracture and cleavage planes and precipitates as goethite.

Through the intramineral migration of iron, a network of globular goethite is formed with crystals of *5 \7m\1m* size. Associated phases are minerals of the kaolinite group, probably halloysite. In the more evolved facies, as in bauxite, the original pyroxene is entirely replaced by a primary plasma of goethite. In the dissolution cavities of pyroxenes, the gibbsite is formed, as a transference plasma related to an outer source of aluminium.

d - Weathering phases.

In the lateritic weathering, the main secondary phases are gibbsite and goethite. They have differences in habit as probably a consequence of their geneses. It is possible to observe two types of gibbsite: one microcrystalline, forming the primary plasma and occurring as a pseudomorphous replacement after felsic minerals. The other type occurs as a later product of aluminum remobilization through the profile consisting of a transference plasma. This second gibbsite is normally euedric and forms large crystals which may reach 0.2 mm size.

Goethite is the principal phase of the plasma alteration of ferromagnesian minerals. Goethites appear with microcrystalline habit, a pseudomorphous replacement product which grows oriented parallel to "c" axis of pyroxenes. In fractures of ferromagnesian minerals, goethites have a coarse different habit and grow perpendicularly to the fracture boundaries.

In the ferrisialitic facies, the dominant mineral is 10A halloysite. This phase occurs in different habits, as small well formed tubes (Photo X.4) or as small globules with tendency to be an amorphous material. In general, clay facies is soft and loose and with yellowish brown

Photo X.4 - Tubular halloysite (MEV-2700X).

colours. Interpreted as later events in the profile, veins of halloysite are common and cut the entire profile. Those veins are filled with 10Å halloysite, generally associated with manganese minerals (lithiophorite). They have a hard consistency and a milkylike appearance, typical of porcelaneous halloysite.

In the upper zone, normally the proportion of 7Å spacing clays increases (dehydrated halloysite) due to decrease of natural humidity of the environment.

VII. Geochemistry

The ferralitic alteration of alkaline rocks of Lages consists of a process of leaching of major and minor chemical elements (Dani et al., 1989, Formoso et al., 1989). Taking into consideration the mean chemical composition of each facies which forms the isalteritic zone and comparing with the chemical concentration in fresh rock (Fig. X.9), is notable the high mobility of some chemical elements as Si, Mg, Ca, Na an K and the weaker mobility of Al, Fe, Ti and P, resulting in a relative enrichment of these elements. In the rock, sodium is found mainly in the nepheline

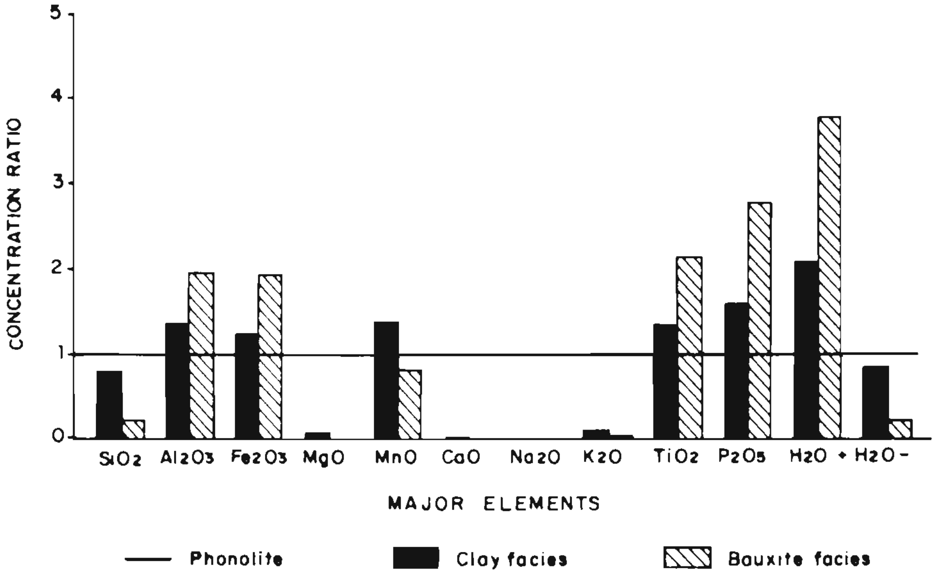


Figure X.9 - Relative gain and loss of some chemical elements in relation to unaltered phonolite.

phase, and the higher instability of this phase reflects the rapid decrease of Na in the profile. Potassium has a similar behavior to sodium, with a tendency to remain longer in the profile as a consequence of being in phases more stable in surfacial conditions, as feldspar.

Each facies can be characterized by its chemical composition. Clay facies has a composition with similar proportions of Si and Al, typical of clays that are included in the kaolinite group. The higher concentration of Al and Fe denotes the increase of minerals as gibbsite and goethite. The relation among chemical composition, mineralogy and facies was used to create a correlation index with the objective to divide and classify chemically each facies of the profile. This index takes into account aspects as mineralogy, chemical composition and other characteristics of each facies, especially those facies which constitute the isalteritic zone. Using this index, three facies (Fig. X.3) of profile are represented by:

1 - Fresh rock/weathered rock: $i' < 80$
2 - Clay facies: $80 < i' < 200$
3 - Bauxite facies: $i' > 200$,

The association among elements can be evaluated studying two elements with a contrastant behavior in the supergenic environment, as aluminum and silicium. The association of those two elements with other chemical elements, using the degree of correlation, resulted in (Fig. X.10):

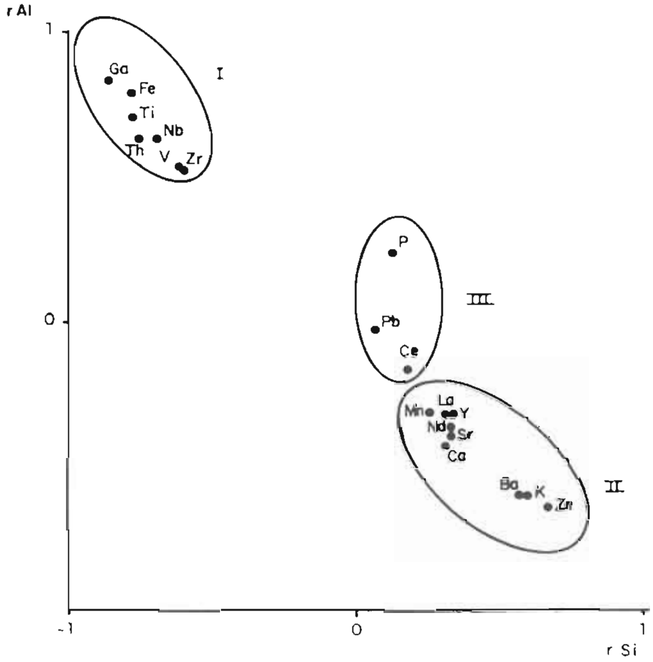
[a) Elements which are similar to aluminum, with a low mobility in the supergenic environment: Fe, Ga, Ti, Th, Nb, V e Zr;

[b) Elements which are similar to silicium, and with higher mobility in the Lages weathering conditions: Ca, Na, K, Sr, Zn, Cl and rare earth.

[c) Elements with independent behavior: P, Pb and Ce.

Figure X.11 shows the distribution of some chemical elements through the profile. Aluminum and iron keep a constant concentration as Zr, Nb, Th and Ga due to their residual character. The curve of silicium is irregular and in some places evidence the existence of blocks of phonolites (not totally altered). In the top of the profile, in the aloteritic zone, the influence of pedogenesis increase the concentration of chemical elements as K, Ca and P.

Manganese has an irregular behavior, and probably, it is a consequence of its low concentration in the rock (0,5/100 cc), and because it tends to concentrate in veins. The association with veins shows a higher mobility than the iron. Tardy (1969) observes that velocity of oxidation of divalent manganese is lower than divalent iron and consequently its mobility is higher.



I- Chemical elements with a high correlation with aluminium
II - Chemical elements with a high correlation with silicon
III - Chemical elements with a weak correlation with aluminium or silicon

Figure X.10 - Affinity among chemical elements related to Al and Si pearson correlation coefficient (number of analyses=107).

In general, Zr has a tendency to remain in the weathering profile as a residual element. When the behavior of Zr is studied in comparison with elements considered to be immobile, as iron, titanium and aluminium, it is observed a tendency of zirconium to present negative values which characterizes some mobility. Studies using biogeochemistry (Lima et al., 1990) give more evidence of the Zr mobility. The behavior of zirconium is a consequence of taking part in minerals which are unstable in supergenic environment, as eudyalite and lavenite, common zirconosilicates in alkaline rocks of Lages. The strong correlation with Ca in the fresh rock emphasizes the Zr association with zirconossilicates. No zircon is present. A direct correlation of zirconium with elements as titaniun and iron is observed in nodules enriched in iron found in the upper portion of the profile.

Rare earth elements are mobilized by the weathering, with exception of Ce, which exhibits commonly a positive anomaly. In a general

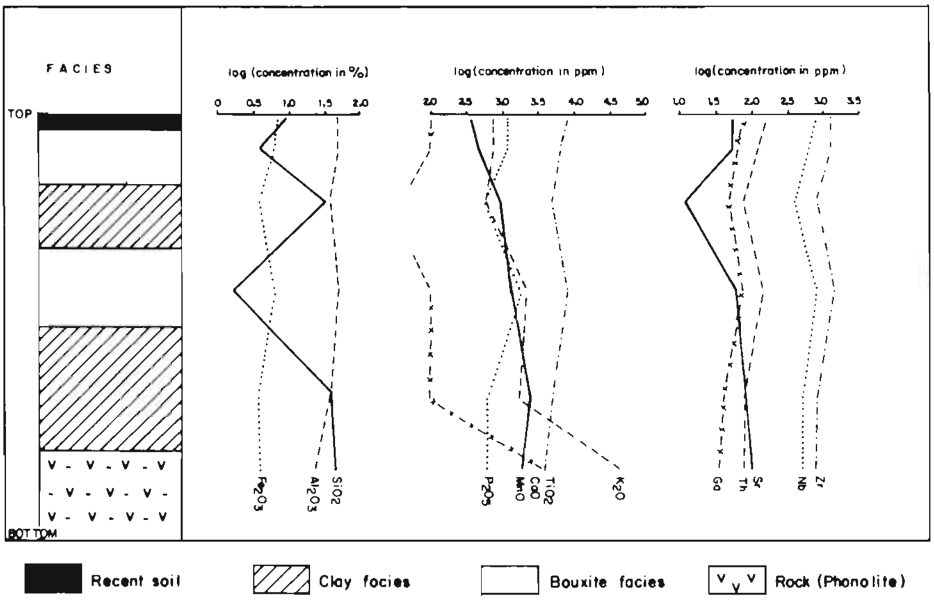


Figure X.11 - Variation of some chemical elements in profile of weathering (Pit nº 20, Fig. X.4)

view, the rare earth concentration is lower in altered products than in fresh rock (Fig. X.12). Also, the ratio Ce(N)/Yb(N) shows the tendency to increase the light rare earth elements in relation to the heavy ones (Fig. X.13). In pits (Fig. X.14), it is evident the decrease of the rare earth concentration when increases the distance from the fresh rock. In the bauxite facies, the concentrations of rare earth elements is lower than in typical clay facies. Both halloysite and gibbsite have lower ability to fix trace elements. Manganese minerals are the main carriers of rare earth elements, and anomalies are especially related to those minerals. Analyses of some lithiophorites show concentrations of cerium around 36000 ppm.

VIII. Lateritic Processes Correlated with the Bauxite of Lages

The plateau in which Lages is situated represents a surface where paleosoil sequences occur with many of them having lateritic affinities, proving that lateritization was a regional event and its development and occurrence were dependent of external factors as the existence of periods with favourable wheathering with simultaneous outcrop of rock and

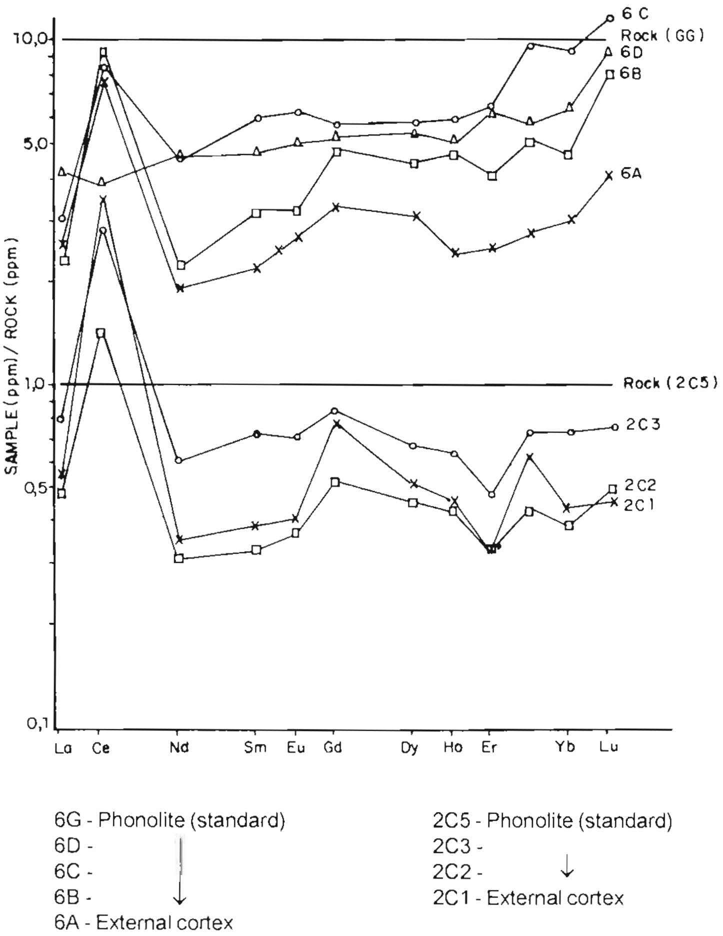


Figure X.12 - Distribution of REE in two lateral profile of rock to cortex.

preservation conditions against erosive agents.

Phonolites of central and southern part of Lages and nepheline syenite massif have weathering profiles in which the rocks are weak altered, and the dominant processes are sialitization. Associated with those lithologies, products of strong weathering occur locally with aspects that remind basal horizons of laterite profiles. Plotting in a triangular diagram (SiO_2-Al_2O_3-Fe_2O_3), the composition of samples taken in the weathering sequence of the southern area phonolites (Fig. X.15) gives a concentration of points which are located in the area of siallitization, with a minor proportion of samples occurring in allitization area. Other factors, besides environment, must be very important, and probably may explain better the peculiar distribution of bauxite in Lages. Products of a very deep weathering occur normally with characteristics

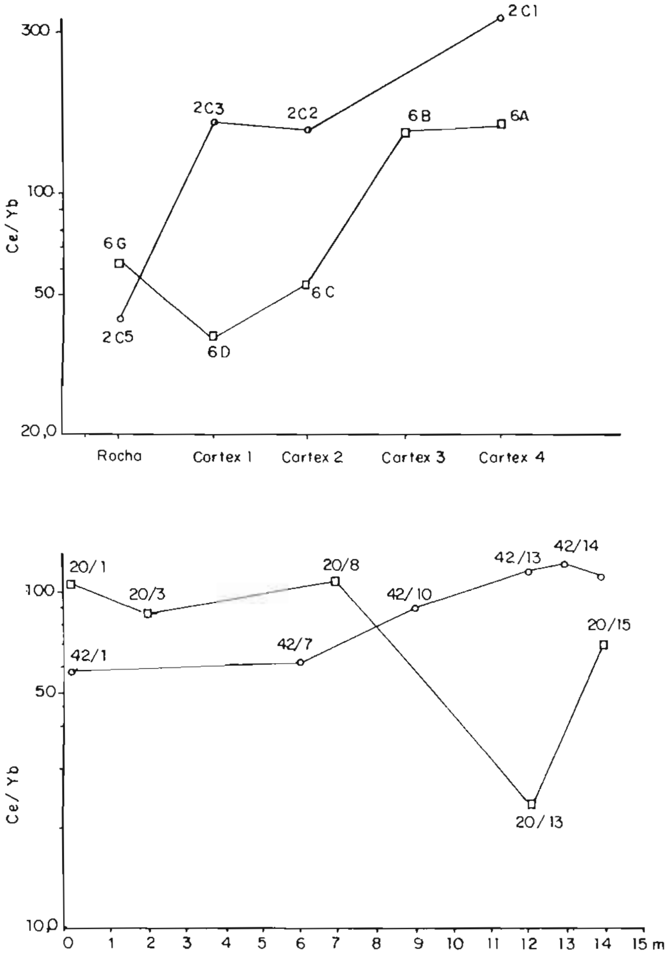
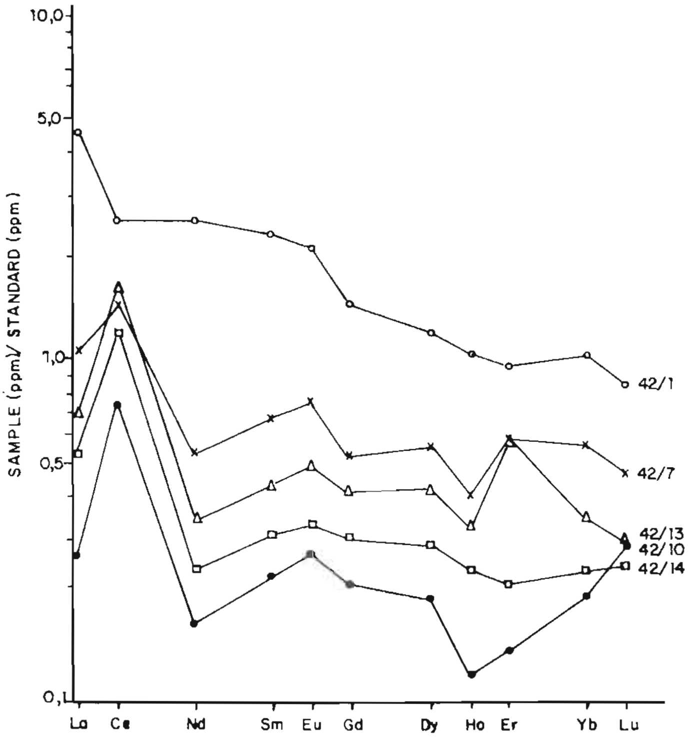


Figure X.13 - Ce/Yb ratio lateral profile RC and 6 (aboue) and in vertical profile, Pit 20 and 42 (below).

similar to laterite, with gibbsite, manganese oxydes and halloysite veins and brown-yelloow colours in various rocksof Lages.

Carbonatites present a weathering profile, with a thickness up to 2 meters, which form also a weathering crust. Preliminary studies show a soft-brown material, with an homogeneous appearance which contain an enrichment in Mn and an anomaly of other elements as Ba, Ce, Nd, Th and V, with a strong natural radioactivity.

Basalts and diabases occur surrounding the Lages dome and covering the major part of the plateau, and both are similar in chemical and mineralogical composition (Fig. X.16). Diabases occur in Farinha

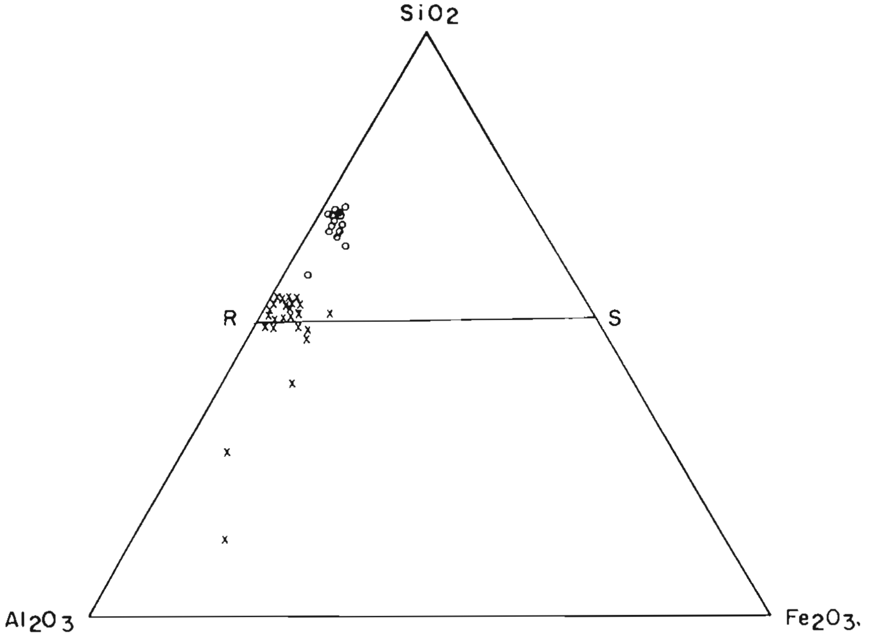


Sample	Facies
42/1	Rock
42/7	Clay
42/10	Bauxite
42/13	Bauxite
42/14	Soil

External standard: shale SCO-1 (Jarvis & Jarvis, 1985)

Figure X.14 - Distribution of REE in a vertical profile (Pit 42).

Seca, close to the alkaline rocks, and are altered to aluminum laterite according to Aleva (1982). Rocks with different chemical composition as diabases and phonolites can converge to similar weathering products, if local conditions were favourable. The thickness of weathering profile of diabases is not more than 4 meters much lower than thickness of profiles associated with phonolites. The characteristics of diabase weathering is its development from fractures and diaclases, having a sharp zone of transition between fresh rock and isalterite. The primary mineralogy is plagioclase and augite, with a rock density of 2.7. In the weathered rock, the density goes down to 1.5 and the porosity increases to values near 50% with a dominant mineralogy formed by gibbsite, goethite and with



o Fresh rock
x Weathered rock

Figure X.15 - Distribution of analysed samples of central/south phonolite in SiO_2 - AL_2O_3 - Fe_2O_3 diagram (Schellmann, 1981)

minor minerals of kaolinite group and quartz. The weathering profile presents veins of manganese and clay surrounding the blocks of altered diabases.

Preliminary studies of weathering characteristics of those basalts, show that ferralitization was a regional event. Although the complexity of sialitization and ferralitization processes, locally they have the same evolution of the diabases found in Lages. Profiles with those characteristics are found near Lages or as far as Vacaria, in Rio Grande do Sul State, situated 150 km distant, but in the same plateau in which Lages is located. In general, they are found in high altitudes, associated with ancient surfaces which during certain time, have suffered the action of erosive and reworking events, responsible for the present profiles. In Vacaria and along the road of Vacaria to Lages, profiles (Photo X.5) normally have a sequence of facies which starts with basalt rocks at the bottom, followed by inhomogeneus facies, with an alternation of laterite facies, and clay facies, together with blocks of basalts forming core stones and "pain de epice". In the laterite facies, the secondary minerals are gibbsite,

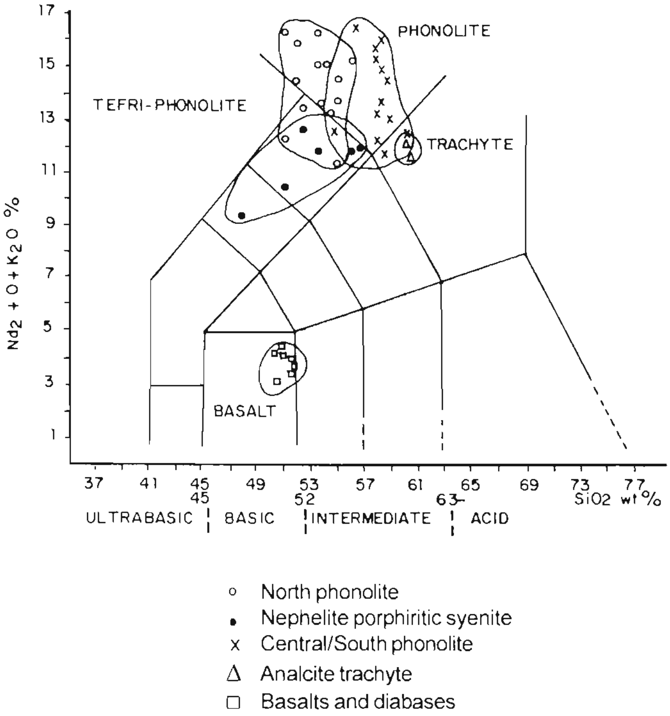


Figure X.16 - Distribution of some rocks of Lages in the total alkali-silica (TAS) diagram.

iron minerals (goethite) with yellow-orange colours and relict texture. The clay facies have reddish colours and the dominant mineral is halloysite. Small veins of white halloysite and manganese minerals cut the profile. Going towards top and before reaching the recent brown organic soil, layers of red colour, poor in structures, (only with polygonal structure) occur related to expansion and contraction of this horizon, described as the red clay upper horizon. Frequently, the bottom laterite facies has a sharp contact with the red clay upper horizon and in this interface is found a line of stones of basalt blocks, quartz and geodes of chalcedony. That line of stones represents not only a physical discordance, but also a mineralogical and environmental discordance, with the bottom laterite facies often composed by, gibbsite, goethite and halloysite, and the upper red clay layer, above that line, has hematite and kaolinite minerals (Kampf & Schwertmann, 1983 and Kampf & Dick, 1984). Although this subject needs be more detailed, the upper red clay layer shows evidences that was originated by the reworking of bottom laterites. The line of stones divides ferralitization alterite and the upper red clay linked to ferrassialitization processes. At present time, it is a common sense,

Photo X.5 - Weathering profile developed over basalts of Serra Geral Formation. A line of stones separates the lateritic facies from the red latosoils.

that laterite facies on basalts has a widespread occurrence, and may be correlated with the bauxite facies of Lages.

Figure X.17 shows the average chemical composition of weathering facies of profiles associated with basalts and diabases in Lages and Vacaria. They are very similar exhibiting a geochemical correlation. A tendency to ferralitization with higher concentration of iron, aluminium and titanium with the increasing weathering is observed. Chemical analysis of samples (Fig. X.18) shows that the material is not homogeneous, occurring facies in which sialitization predominates, and others with alitization, but in general, large number of samples locates in the field of strong lateritization (Schellman, 1981).

As a conclusion, besides alkaline rocks other lithologies were affected by the lateritic process, giving origin to products of advanced weathering which may be considered cogenetic with the bauxite of Lages.

IX. Estimated Age of Lateritization (Bauxite of Lages)

Geomorphological analyses, associated to climatic variations during the past time, have contributed with important informations for

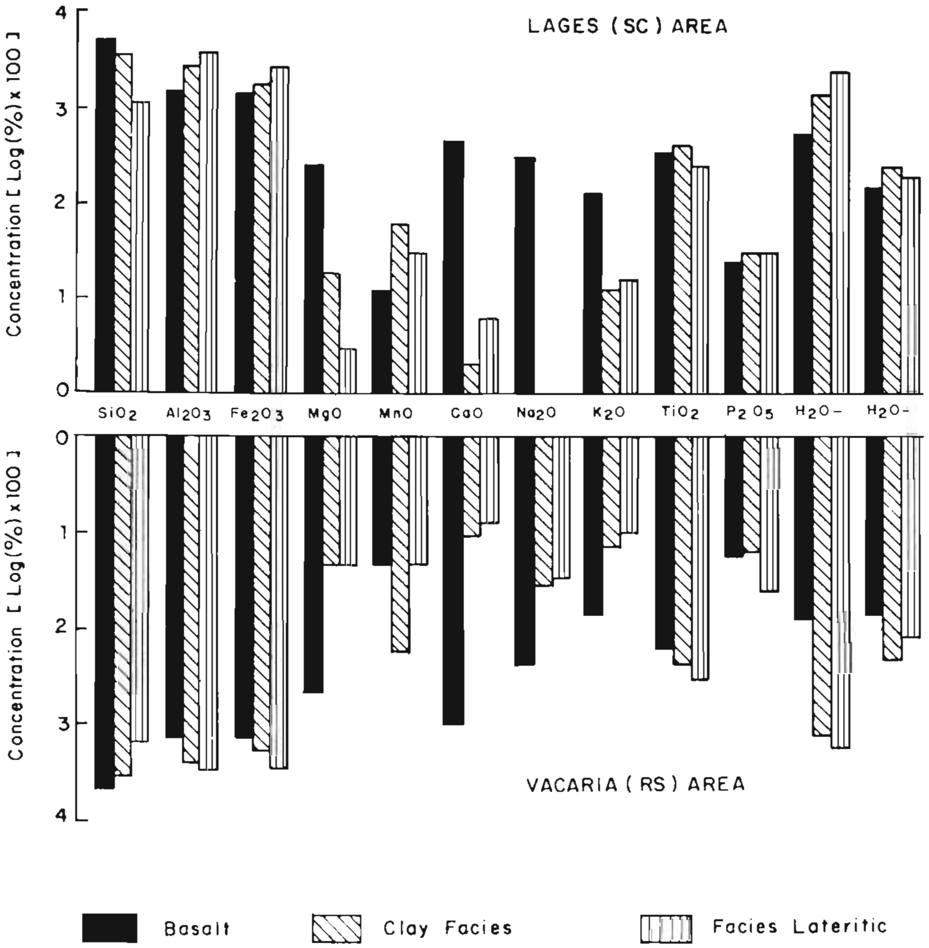


Figure X.17 - Average chemical concentration of major elements in facies of weathering identified in basalts of lages and vacaria area.

definition of alterites in time and in space.

Conventional methods of absolute datation have not a confident application for age determination because the supergene environment is an open system and in general the secondary phases do not retain the initial isotopic ratios. Classical stratigraphycal methods concerning relative ages are not applied to Lages as is in Arkansas (USA). On the other hand, after the formation of bauxites, a combination of uplift and intensification of erosive processes occurred with denudation of the region. The supergene alteration zone represents relics of a former rolling

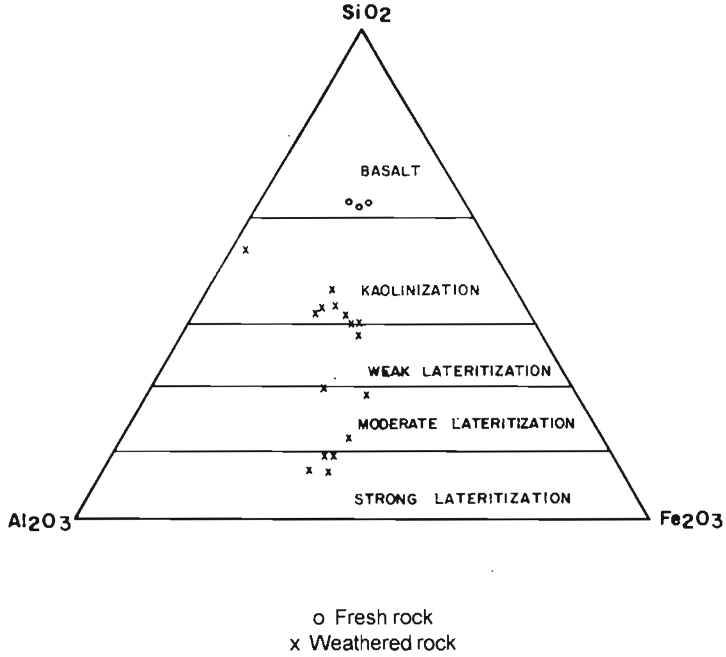


Figure X.18 - Fields of basalts and diabases weathering stages of lages in the SiO_2 - Al_2O_3 - Fe_2O_3 diagram.

land surface (Lower Tertiary) (Valeton et al., 1989). It is dissected by younger erosion.

Along the east coast of Brazil, numerous bauxite deposits occur which are presumed to have been developed as a more or less continuous bauxite "belt" in past time. The type of lateritic deposit is in a hilly landscape connected to Pre-tertiary to Tertiary planation surfaces in the Santa Catarina region. The Gondwana or Post Gondwana plain of the Sulamericano Cycle (King, 1962), may be regarded as initial landscape. Younger dark red latosols as well as Quaternary podzols overprint the bauxites and are reponsible for their polyphasic and polygenetic transformation.

X. Bauxite Genesis

In Lages, as was pointed out, the characteristic of bauxite deposits is their concentration in some special sites, especially in the area of Farinha Seca. The reasons for this nonuniform distribution were important to explain the principal factors that influence directly the genesis of the bauxite. Among those factors, it is important to take into account the chemical composition of the subjacent rock. Alkaline rocks have highly unstable phases in weathering conditions. On the other hand, the detrital sedimentary rocks have a mineralogy more adapted to surficial conditions, composed mainly of clay minerals and quartz. In sedimentary rocks, the events of lateritization gave origin to yellow brown colors. Rocks with an original high concentration of aluminium are the basic target to ore prospection in Lages, as noticed by Valeton (1985). But this is not the only important parameter, because similar products of strong weathering are found associated with other types of rock, as diabases and basalts and it may be completely absent in some high favourable alkaline rock bodies in this area. In this way, Bardossy (1979 and 1982) and McFarlane (1976) have pointed out, that the composition of the rock is important to bauxite generation, but not suficient, and in a global view, there are examples of bauxite related practically to almost all kinds of rocks.

A comparison among the alkaline rocks of Lages may be established using a rate that estimates the degree of rock resistance to weathering. This rate was established using the relation among some major elements. The concentration of SiO_2 over the sum of Al_2O_3, Fe_2O_3, Na_2O and K_2O is used. In alkaline rocks, a decrease in silica implies in an increase of aluminium, total iron, sodium and potassium, represented in the fresh rock by unstable felsic and ferromagnesian minerals, as feldspathoides and pyroxenes (Fig. X.19). The analcite traquite group has a higher ratio than phonolites and consequently have a higher sta-

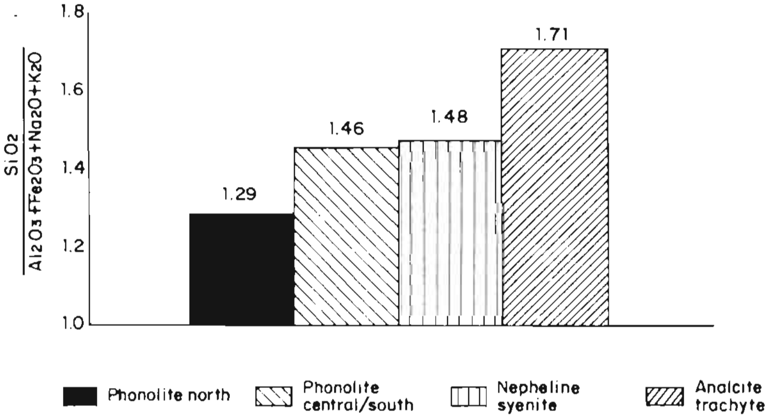


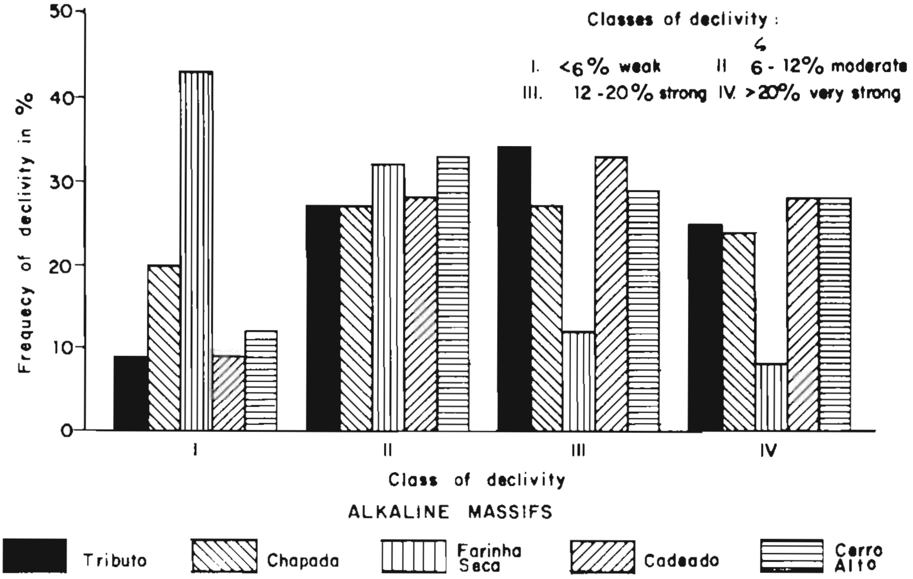
Figure X.19 - Relative resistence to weathering of main alkaline rocks of lages.

bility to weathering. In the other extremity, the Farinha Seca phonolites are located with a lower ratio and resistance to supergenic alteration. With intermediate values, syenite and southern area phonolites present quite similar ratio. Taking into account the geochemistry view point, these results nicely reflect the relations between bauxite and Farinha Seca phonolites. The chemical composition described above does not explain why alkaline rocks of quite similar compositions to Farinha Seca phonolites as southern phonolites, are less intensely bauxitized than different rocks as basalts (Fig. X.19).

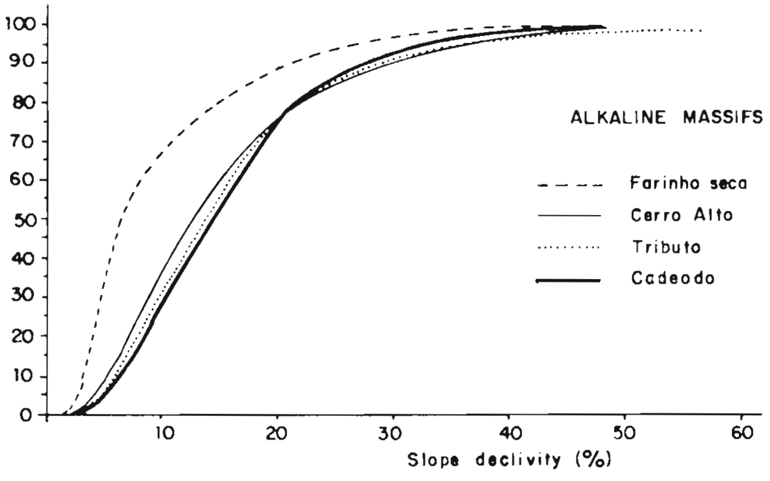
Another fact that was important to bauxite genesis, was the exposure of the rock to weathering during the past lateritic climate. Alkaline rocks of Lages are subvolcanic and they were intruded in the sequence of sedimentary rocks of Paraná Basin, needing a span of time to be exposed on the surface. Some of those bodies are, until now, covered by sedimentary rocks, as in Chapada region.

The typical region with bauxite has a average altitude of 900 to 1000 m. If this altitude denotes a paleosurface, any rock above this height probably was equally affected by lateritization processes. Generally, the alkaline bodies have altitudes that are around 900 m. In some bodies, as Tributo Mountain, the altitude is around 1,240 m. In all these rocks, evidences of strong weathering products are found. As a conclusion the bauxitic weathering is associated with the major part of alkaline bodies, and not only to places where the bauxite has economical importance. Probably, the absence of thick bauxite profile in most alkaline bodies, is more related to local poor conditions of preservation than chemical characteristic of lithologies.

Bauxite formation is a process which occurs on the earth surface in the zone of interaction between lithosphere and atmosphere. Normally, the altered material is loose and also needs adequate geomorphological conditions to be preserved from erosive action. Erosive processes produces continuous flux of water and debris, transforming the potential energy of particles, in cinematic energy. The gravity force is the element that starts the process, in which the intensity is related directly to altimetric amplitude. There is a relation of erosion intensity with slope declivity (Strahler, 1956, Froidefond, 1985), and this parameter was used with the objective of determining the erosion potential of each alkaline massif of Lages (Dani et al., 1989). As a result of the declivity analysis, the Farinha Seca block has a unique behaviour in relation to other alkaline bodies of Lages. Figure X.20. A is a histogram which shows the frequency of each declivity class of each analysed block. In Farinha Seca, 45% of the measures of slope declivity are located in the class of weak



A - HISTOGRAM OF DECLIVITY x FREQUENCY



B - CUMULATIVE FREQUENCY PLOT OF DECLIVITY

Figure X.20 - Geomorphological analyses of main outcrops of alkaline rocks of lages.

declivity; and, in the other bodies, classes of strong to very strong slopes predominate. In the cumulative frequency curves (Fig. X.20.B), again the Farinha Seca block displays a tendency to have slopes with minor intensity of declivity. Spatially, the distribution of declivities in the areas with equal potential to erosion shows just few places where the declivity is strong (Fig. X.21). This is the opposite to other blocks, as Tributo and Cadeado. In the Chapada area, there are some evidences of bauxite weathering, but in the zones favourable to bauxite occurrence, in which weak declivities predominate, alkaline rocks are covered by sedimentary rocks of Terezina Formation which certainly acted as an inhibitor of weathering.

As a conclusion, in Lages it is possible to distinguish two broad group of factors that are important to explain the ore genesis. The first group is related mainly to the susceptibility to weathering of the alkaline rocks. This explains the occurrence of laterite associates with alkaline

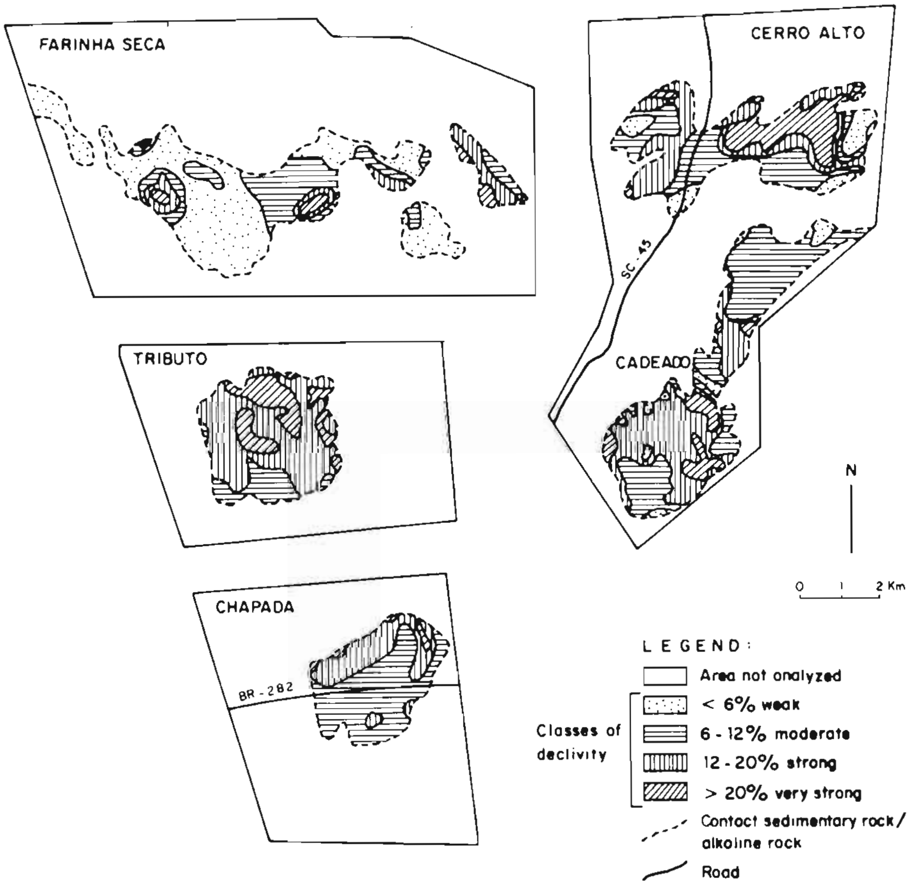


Figure X.21 - Distribution of slope declivity classes on the main aoutcrops of alkaline rocks.

rocks or basalt rocks and not associated with sedimentary rocks. Also it was important the simultaneity of the exposure of the most favourable rocks to optimal conditions of weathering, characterized by a long period of tropical humid climate in the past. Other group of factors acted during and after the profile generation and are related with geomorphological conditions in preservating bauxite against the action of erosive processes.

XI. Final Considerations

The Alkaline District of Lages has some special features. In spite of its secondary economical importance, when compared to other Brazilian occurrences, it represents one of the important places for making studies related to lateritization and climatic changes in Brazil. Lages is the southernmost deposit of bauxite in the country, giving an adequate proof that, in the past, a wider region of Brazil had been affected by a warmer climate.

2. The most developed profiles are associated to alkaline rocks and they are concentrated in the region of Farinha Seca, in the northeast of Lages District. On the other hand, small occurrences and evidences of lateritization are widespread (basalts, carbonatite and sedimentary rocks). Geomorphologically, Lages is part of an uplifted and extensive area which comprises the northeast of Rio Grande do Sul and southeast of Santa Catarina. This high land is deeply dissecated by rivers, showing that this ancient surface is still being eroded. The rocks which occur are mainly basalts. In many places, principally in areas more protected from erosion, it is possible to observe weathering profiles with secondary products associated to lateritization.

3. Similarities between the bauxitic profiles of alkaline rocks of Lages and laterite associated to basalts are observed. In both cases, the profiles display clayey facies in which halloysite is the dominant mineral, and a lateritic or bauxitic facies in which gibbsite and goethite predominate. The clayey or bauxitic facies are in the isalteritic zone. Above the aloteritic zone, in bauxite of alkaline rocks, a clay material occurs which may be correlated with a clay red-brown horizon in profiles of basalt. In spite of similarities, more differences occur, as the thickness of the profile, which is thicker in alkaline rocks, (up to 20 m), whereas in basalts normally is around 5 m.

4. Field and micromorphological observations enable characterization of the bauxite deposits as residual with dominant relict fabric with the pores and larger empty spaces related mainly to the dissolution of

nepheline, orthoclase and pyroxenes.

5. Nepheline tends to be altered at the first stage which is showed by the loss of sodium in nepheline grains and even in the entire profile. Feldspars show a dual behaviour which, depending on the local mycrosystem, leads to 10Å halloysite or directly to gibbsite. Intermediate amorphous phases with various SiO_2/Al_2O_3 ratio are also formed. Pyroxenes are replaced by primary goethite plasma and gibbsite is precipitated in dissolution cavities as a transference plasma with an external source of aluminum.

6. Under the geochemical view point, the bauxitization process is characterized by the higher mobility of Na, Ca. Mg, K, Si and weaker mobility of Al, Fe, Ti and P. The rare-earth elements are partially leached and the light rare-earth are less mobilized than the heavy ones. Cerium displays a unique behaviour being concentrated in the manganese minerals (lithiophorite up to 36000 ppm). Zirconium is also mobilized and is enriched in iron and titatium minerals.

7. In Farinha Seca area, 45% of the measures of slope declivity are located in the class of weak declivity. Also the Farinha Seca block displays a tendency to have slopes with minor intensity of declivity, different from other places (Morro do Tributo, Cadeado). This fact explains the preservation of bauxite in Farinha Seca block.

8. The reserves of bauxite in Lages are about five million tons. They are small deposits in comparison with other Brazilian occurrences but are situated in good geographical location for using in aluminum sulphate making.

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CONCLUSION

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The Brazilian bauxite ore deposits present a wide latitudinal distribution (from the Equator to the Tropic) and a variety of parent rocks, with different stratigraphy and geological structures (Table 1). As a consequence, it is rather difficult to assemble all the ore deposits in the same evolutionary pattern. Nevertheless, considering some petrological and geochemical features, it is possible to place most of the studied deposits in the known patterns of the lateritic bauxite evolution (Boulangé & Millot,1988; Tardy, 1993).

1. Petrological characteristics

According to the classification proposed in the introduction of this book, it seems that all the bauxites, developed from eruptive and metamorphic rocks of the Serra da Mantiqueira and the South-eastern zones, are orthobauxite type. These bauxites are normally formed by direct transformation of the parent rock with preserved structure. However, in some deposits, as for example, in Lages region, the bauxite is originated from an indirect transformation, forming firstly kaolinite and then gibbsite (Millot,1964).

In the case of the Quadrilátero Ferrífero deposits, in the absence of fresh rock occurrence, it is rather difficult to know if the bauxite formed on phillites are also orthobauxites. However, the distribution of gibbsite crystals in the nodules of Macaquinho and Fraga deposits, can be interpreted as resulting from direct transformation of the parent rocks (phyllites and sediments). Thus, here again, these bauxites could be also considered as orthobauxites.

Similarly, the harden bauxite layers that form the essential part of Porto Trombetas, Juruti and Paragominas deposits are included in the same type. As a matter of fact, it was shown, on Juruti deposit, that these bauxite layers are originated from the direct transformation of the kaolinite of the sediment, and so, they are also orthobauxites.

These orthobauxites or alumino-ferruginous crusts, as a function of their geomorphological situation and the climatic variations, will be submitted to evolution processes, which will induce the formation of new facies.

Thus, at the top of the orthobauxites layer, the aluminium can be removed and the iron concentrated, forming a compact alumino-ferruginous crust, named conakryte. These crusts or "canga", nearly absent in the south-eastern region, are rather frequent in the Quadrilátero Ferrífero deposits, where they occur sometimes in topographic and structural continuity with the ferruginous crusts, or ferricretes, simultaneously developed on the itabirites.

Frequently, these orthobauxites are submitted to internal degradation related with deferruginisation and resilication processes. This process, occurring particularly in the Amazonian deposits and also in the deposits of the Quadrilátero Ferrífero depressions (Fraga, Vargem dos Óculos) (Table C.1), gives origin to a friable cover and basal clay-bauxitic layers, with kaolinite and gibbsite, named cryptobauxites. The removed iron is accumulated in a subjacent layers to form a true ferruginous crust, named petroplinthite. It is interesting to notice that, in West Africa, these degradation lead to a restructuration forming pseudobrecciated, nodular or pisolitic bauxite with bœhmite (Boulangé & Bocquier, 1983) or metabauxites (Tardy, 1993), that, curiously, do not occur in Brazil.

Table C.1 - Comparation of the main bauxite deposits of Brazil, according to the parent rock and the types of bauxite.

REGION	DEPOSITS	BAUXITE TYPE	PARENT ROCK	AGE
Amazonia	Juruti	cryptobauxite	sediment	Cretace (Alter do Chão)
	Porto Trombetas	petroplinthite		
	Paragominas	orthobauxite		
	Carajas	cryptobauxite petroplinthite	basalt	Precamb. (Grão Para Gr.)
Central Mantiqueira Province and Quadrilátero Ferrífero	Quadrilátero Ferr.			Precamb (Caue-Gandarela F.)
	- Batatal		phyllite	
	- Fraga :	*slope*: conakryte orthobauxite	phyllite	
	- V. dos Oculos	*depression* cryptobauxite	rhyodacite?	Precambr. (Nova Lima?)
	- Macaquinho	conakryte orthobauxite	sediment	Eocen (Fonseca F.)
	Cataguazes		gneiss	Precambr. (Juiz de Fora C.)
	Nazare Paulista	orthobauxite	amphibolite	Precambrian
	Curucutu	"	diabase	
	Mogi das Cruzes	"	granit	"
Southeastern	Poços de Caldas		syenite	Cretace-Eocen (Intrus. rock)
	Passa Quatro	orthobauxite	syenite	
	Lages		basalt, diabase phonolite	Cretace Eocene

2. Geochemical characteristics.

Usually, the geochemical evolution of the rocks into bauxites are studied as a function of the ore deposits economic quality (Table C.2). Thus, it is taken into account only the variations of the three main constituents (silica, alumina and iron) and the associated mineral paragenesis which are quartz, gibbsite, hematite and gœthite.

Other elements, occurring in a very low content or as trace elements (Ti, Cr, V, Zr...), as well as the rare earth and actinide elements, not very important in the economic point of view, can be quite essential for genetic purpose. Unfortunately, these elements are not often considered in the deposits studies.

Therefore, even having partial data, it was decided to consider, here, only the variation of Ti and Fe, rather than those elements (Si, Al and Fe) related to the ore quality aspects.

Amongst the major elements, iron is the most stable under oxidising conditions prevailing during the orthobauxite formation. Its concentration factor is always higher than aluminium. On the other hand, in reducing conditions, its mobility will mark all the steps of the evolution of these bauxites into meta- and cryptobauxites. Thus, the iron has an es-

Table C.2 - Mean chemical compositions of the bauxite deposits.

REGION	DEPOSITS	PARENT ROCK	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	LOI	BAUXITE TYPE
Amazonia	Juruti	sediment	3.0	52.40	17.70	2.9	(27.5)	cryptobauxite orthobauxite
	Porto Trombetas		3.6	52.21	14.64	1.15	27.91	
	Paragominas							
	Carajas	basalt	1.57	39.13	22.17	3.79		cryptobauxite
Central Mantiqueira Province and Quadrilátero Ferrífero	Quadrilátero Ferr. - Batatal	phyllite	1.1	46.8	21.9	1;7	26.3	orthobauxite
	- Fraga :		0.9	49.3	24.6	2.3	23.0	
	- V. dos Oculos	rhyodacite?	1.2	59.0	5.0	4.1	30.5	cryptobauxite
	- Macaquinho	sediment	2.0	48.1	20.4	2.2	27.2	orthobauxite
	Cataguases	amphibolite gneiss	2.32 9.11	40.73 45.44	27.19 17.31	2.98 2.45	23.83 24.67	orthobauxite
	Nazare Paulista	amphibolite	8.1	37.4	29.3	1.9	22.8	
	Curucutu	diabase	1.94	41.98	19.82	1.82	33.74	
	Mogi das Cruzes	granit	19.2	52.1	3.0	0.6		
Southeastern	Poços de Caldas	syenite	4.83	55.42	7.28	0.68	30.01	orthobauxite
	Passa Quatro	syenite	1.73	57.64	6.68	1.45	30.90	
	Lages	basalt. phonolite	8.97 4.74	35.86 53.36	27.62 6.67	2.91 0.79		

sential role in the structure formation of the derived facies and the associated ferruginous crusts (Boulangé & Bocquier, 1983).

In the studied Brazilian deposits, deferruginisation processes are always related with resilication and, consequently, with the formation of cryptobauxites, as in Vargem dos Óculos and Fraga deposits of the Quadrilátero Ferrífero and in the Amazonian deposits.

The titanium, with no more than 5-6% in the bauxites, is also considered as a rather immobile element during the bauxitisation processes (Bardossy & Aleva, 1990). Originated from the ferromagnesian silicates, Ti is locally fixed in the form of anatase. As opposed to hematite and goethite, always very susceptible to dissolution, anatase is a very stable secondary mineral. Thus, the titanium, fixed under oxidising conditions, will not be removed under reducing conditions, remaining associated with meta- and cryptobauxites, that will lead to a residual concentration increase (Boulangé et al., 1990).

So, Ti contents are high in the cryptobauxites, that include the deferrruginised white bauxite of the Quadrilátero Ferrífero depressions (Vargem dos Óculos, Fraga), (3 to 4% TiO_2) and in the upper and lower kaolinitic layer of the Amazonian deposits (2 to 4.5% TiO_2) , as well as in the bauxite deposit of Carajás (3,6 to 5%). On the other hand, the ferruginous crusts, (petroplinthites) subjacent to the bauxite, will be Ti-depleted as in the Porto Trombetas (1% TiO_2) or in Carajás (3% TiO_2) deposits. The TiO_2 contents in the ortho- and cryptobauxites depend on its amount in the parent rock (Table C.3).

Other elements would certainly be of interest, but having only few data, it is difficult to take them into account. That is the case of Cr and V, that seems to have a behavior close to iron: low contents in meta- and cryptobauxites and higher contents in the petroplinthites. Zr is also an interesting element and when the data exist, a good correlation between Ti and Zr would be expected. So the Zr contents, as that of Ti, would increase from the parent rock to the ortho- and cryptobauxites.

A recent study on the separated zircon grains from samples of Passa Quatro has shown that their size do not exceed 20 m (Boulangé & Colin, 1994). But all the Zr is not obligatory linked with the zircon mineral. So in Poços de Caldas bauxite it was show (Melfi et al., 1996) that Zr, mainly present in the easily weathered zircon-silicates (giannettite and sodic-amphibole), can migrate during the first stage of weathering. It was also shown that the bauxite present a higher Zr content (2,000 ppm) concentrated mainly in amorphous ferric oxides and goethite associated with other elements (Ti, Nb, Ce).

Thus, the Fe_2O_3, TiO_2 (and Zr) variations and their relationships are a good marker for the bauxites evolution. So, it seems clear that the orthobauxites are always richer in Fe_2O_3, TiO_2 (and Zr), as compared to the parent rock; the cryptobauxites present always lower Fe_2O_3 and higher TiO_2 and Zr contents than the orthobauxites, and the petroplinthites are always Fe_2O_3 richer and TiO_2 poorer, as compared with the orthobauxites (Table C.3). On other hand, even considering that the data are not so consistent, the TiO_2 amounts seem to be, for all the cases, a function of the parent rock content. Thus, the TiO_2 content of a bauxite facies keeps the geochemical memory of the parent rock. It is clear that only one element is not enough and that, for the bauxites, as well as for the weathering profile, a rigorous genetic interpretation needs analyses of other trace-elements (Zr, Nb, Y, REE....).

3. Historical Synthesis - An Essay

The formation of the bauxite profiles depend on the weathering conditions of the parent rock. These conditions are related to various factors, as nature of the parent rock, climate (concerning the T^o, redox potential, silica activity in the percolating solutions and water activity), situation of the deposit in the landscape (referred to the tectonic and/or the geomorphological evolution).

Table C.3 - Fe_2O_3 and TiO_2 contents in relation of the parent rock in the main bauxite deposits of the Brazil.

	Parent rock		Orthobauxites		Cryptobauxites		Ferroplinthites	
	Fe_2O_3	TiO_2	Fe_2O_3	TiO_2	Fe_2O_3	TiO_2	Fe_2O_3	TiO_2
Syenite	<2	0.5	<10	2				
Phonolite	<2	0.5	<10	2				
Diabase	10	1	20	2				
Amphibolite	15-20	1	30	2				
Basalte	10-15	0.5	20-30	3.5	20	5	50	2
	10-15	4	20-30	6.5				
Gneiss	<10	1	20-30	4		(6)		
Phyllite	<5	1.5	20-40	3	<10	4	50	1.5
Sediment	<20	0.5	<20	0.5-1	<10	4	50	1

Thus, as it was noticed previously, the formation of the orthobauxites and the overlaying alumino-ferruginous crusts (conakrytes), needs a strong water activity, favored by a wet tropical climate, a high topographic position, a parent rock rather susceptible to the weathering, allowing, thus, the opening of an important porosity. On the other hand, the formation of the cryptobauxites needs a low water activity favored by a contrasted dry and wet tropical climate, a topographic position not allowing a good drainage of the water table, a reduced porosity by material moving (transfer, volume reduction).

In this way, every bauxite profile is the reflection of the regional climatic and geomorphological history. Each of the authors, in the different chapters of this book, often noticed a complexity of the facies succession within a same profile, showing a polyphasic history. The question is whether the common characteristics of this history could be applied for the whole of the Brazilian bauxite deposits.

In the South-eastern region all the bauxite deposits are of orthobauxite type. It was established for the Passa Quatro deposit (Sigolo, 1988) that two periods of bauxitisation has occurred.

- A first period (late Cretaceous-Eocene) would affect simultaneously the syenites (70 Ma) and the gneisses of the basement. This period ended at the time of the Paraíba rift opening, gave origin to the colluvial deposits (syenite and bauxite blocks) on the bauxitised gneisses.
- After the Oligocene, a period known as cold and dry by the sediments analysis of Resende and Taubaté basins (Lima & Amador, 1983; Melo et al., 1985), a new wet period begins at the Miocene. During this period, it was formed on the hilltops, the present orthobauxites, enriched in iron originated from the old profile. Meanwhile, in the colluvial pediments, the bauxite blocks were submitted to a partially resilication and the syenite blocks were partially weathered into kaolinite.

In the Lages deposits, clayey facies with no preserved structure are intercalated with orthobauxites with preserved structure. Nevertheless, these clayey facies does not exhibit a particular increasing of Ti (and Zr) content, which would allow to consider them as cryptobauxites. However, the Fe_2O_3/TiO_2 relationship remains positive and linear, which is a characteristic of the orthobauxite type. Thus, these clayey facies could be only related to the local variations of the weathering conditions and not to a time succession of bauxitisation episodes.

In the deposits of Cataguases, it was observed the same alternation, i.e., isalteritic gibbsitic facies and alloteritic kaolinitic facies. The parent rock heterogeneity (amphibolite, biotite-gneiss) reflects in a large correlation band for Fe_2O_3 / TiO_2. Nevertheless, a positive correlation, characteristic of an evolution towards orthobauxites, is clearly observed. Here, a slight TiO_2 enrichment is observed, but not enough for an evolution towards cryptobauxites. More significant is the fact that an influence of a tectonic phase is observed, which assures the dismantling of the Sul-Americana surface. The process finishes up with bauxite caps on the high topography and at the same time, favoring the deposition of colluvial bauxite on the slopes (Valeton & Melfi, 1988). Even having a reduced extension, these deposits are comparable to the pediments of Passa Quatro Massif. The surface dismantling, starting at the Eocene, and the vertical succession observed in the profiles are compatible with the two previously proposed periods of bauxitisation.

In the Quadrilátero Ferrífero deposits, the hypothesis of two periods of bauxitisation could be also put forward, due to the presence, on the high topography, of more aluminous bauxite type and in the depression, of aluminous-ferrous deposits, that change into cryptobauxites. The criteria of absolute dating are restrict. Only the Eocene age of the Fonseca Formation, over which Macaquinho deposit is developed (Maxwell, 1972), seems to indicate that these orthobauxite could be formed during a post-Oligocene period. Other criteria are purely geomorphological, based on the surface distinction (Varajão, 1988), showing that the higher topographies (Batatal, Conta História) are related to bauxites, more nodular and more aluminous, as compared to the recent orthobauxites deposits on the slopes. Moreover, the presence of white cryptobauxites in the depressions (Fraga, Várgem dos Óculos) seems to indicate that a previous bauxitisation process has preceded the recent lateral distribution. The orthobauxites on the slopes would be associated with a post-Oligocene humid period, while the cryptobauxites in the centre of the depressions would come from the simultaneous evolution of an ancient orthobauxite (pre-Oligocene), deposited in these bottoms.

As a matter of fact, the study of the profiles of all these deposits of Southern Brazil seems to confirm the presence of two bauxitisation periods: the first one from the late Cretaceous-Eocene and the other one beginning in the Miocene, separated by a period of intensive tectonic activities, finishing up, in the Oligocene, by a cold and dry period.

The interpretations put forward for the genesis of the Amazonic bauxite deposit are a matter of controversy and the studies carried out up to now are far from being coincident. Three hypothesis are in opposition:

- the bauxitisation precedes the friable covering sedimentary deposit, named Belterra clay (Paragominas),
- a previous alteration of a ferralitic type gave origin to a

lithorelictual ferricrete and later on, a bauxitisation episode would replace partially the ferricrete, forming massive bauxite horizons, by transformation of the clay sediments, finally the actual evolution would be marked by resilication of the bauxitic profile that, on the top of the bauxitic profile would originate the friable covering (Jurutí),

- a first bauxitisation process would be the origin of an ancient orthobauxite profile, that submitted to an evolution (deferruginisation and resilication) would form the friable cover and the subjacent ferruginous crust, and, later on, a second bauxitisation period would be responsible for the formation of the actual subjacent bauxite (Porto Trombetas).

Each interpretation reflects the aspects that were considered in the different studies, based on sedimentological, pedological or geochemical criteria. The petrological and geochemical filiation observed between the parent rock and the friable cover, in the deposits of Carajás, Jurutí and Porto Trombetas, leaves no doubt about the authoctonous origin of all the formations of these profiles. The higher TiO_2 content in the friable cover, considered as a result of the evolution of an orthobauxite towards a cryptobauxite in Porto Trombetas deposits, is also interpreted as resulting from the degradation of an ancient ferralitic profile in the deposits of Jurití and Carajás. No matter what is the case, it seems clear that two periods of ferralitisation has succeeded in the time and these two periods were separated by a deferruginisation process. Thus, one can consider that this part of the Amazon basin remained, after the Cretaceous, under a relatively stable tectonic conditions, with climatic conditions varying from equatorial to humid tropical. As a matter of fact, if bauxitisation requires a very humid period, the degradation of ferralitic profiles needs a more contrasting climate.

However, in the hypothesis of the history of this long geochemical evolution, it still remains the problem of the origin of the silica necessary for the resilication of the ancient bauxite, to give origin to the friable clay cover. The essential question is to know why the friable cover in Carajás is bauxitic and without resilication, while in all other deposits the kaolinitic friable cover results as an evidence of a strong resilication. This difference between the deposits of a same region could be used as an evidence to eliminate the aeolian transport as a main source of silica. It seems to be reasonable to consider only the parent material. As it was observed, the Carajás bauxite formed on basalt are very poor on kaolinite, while the bauxites of Jurutí and Porto Trombetas have always 5 to 8% of kaolinite. Considering that, in these clays, the Ti (or Zr) concentrations are three to four times higher than the ones in the sediments, even bearing in mind the sediment heterogeneity, one can suppose that 90 m of sediment would be necessary to form the actual profile. The residual silica amount (quartz or kaolinite) would be, then, largely enough to assure the formation of the friable cover. This silica could be permanently recycled by the vegetation and the aluminium distributed between the kaolinite of resilication and the absolute accumulation observed in the subjacent bauxite.

4. Final Considerations

In this way, from the North to the South of Brazil, all the deposits are characterised by a succession of facies, which reflect the geological and climatic history of the region.

In the south-eastern region, all the deposits are constituted of orthobauxites with preserved or not preserved structure, which development is produced during the two bauxitisation periods (Late Cretaceous-Eocene and Miocene). The excellent drainage conditions was, maintained as a consequence of a tectonic control (opening of the Paraíba graben), which is responsible for the colluvial deposits, that are also orthobauxites.

In the Quadrilátero Ferrífero, the tectonic control is also important, but the deposits were formed in the interior of large closed depressions, where the orthobauxites have evolved towards cryptobauxites.

In the Amazon region, the crypto- and orthobauxites are always superimposed, evidencing a larger tectonic stability and permanent humid climates. The development of the orthobauxites, underlying the cryptobauxites, would be related with the lowering of Amazon base level (pre-Miocene).

Thus, it seems that the development of orthobauxites need a tectonic control, keeping the profiles continuously under excellent drainage conditions, otherwise it would be destroyed by strong mechanical erosion, giving origin to mass movements (colluvial deposits). On the contrary, the evolution of cryptobauxites is marked by strong climatic control. The fact that, in Brazil, it is not found pisolitic bauxites *sensu stricto*, i.e., metabauxites with boehmite would be related, in the Southeast, with the strong tectonic control and, in the Amazon region, with the absence of strong climatic oscillations wet and dry, as the ones produced in West Africa.

As a final conclusion, it can be said that the present synthesis has no intention of solving all the problems concerning the Brazilian bauxites and, actually, a lot of aspects are still a matter of controversy.

Nevertheless, considering the knowledge accumulated up to now, it is possible to put forward some recommendations that should guide the future studies:

First of all, it has to be mentioned the necessity of precise petrological analysis of the facies which would allow to identify them as orthobauxite or cryptobauxite, the first one being far more interesting under the economic point of view.

On the other hand, a detailed description of the minerals paragenesis is also necessary, particularly in the base and the top of the profiles, where deferruginisation and resilication processes are rather important. As a matter of fact, it is important for the exploiters to know perfectly these paragenesis, the presence of strong amounts of kaolinite affecting the treatment performance (Bayer procedure requires silica contents lower than 5-7%; Bardosy & Aleva, 1990). The presence of large amount of aluminous goethite has a double disadvantage, a loss of alumina incorporated to the gœthite and an aspect of a rejected red mud. The limits of these transformations, often clear in the top of the profiles, are diffused at the bottom of the bauxites. Its misunderstanding could bring important losses to the production.

Finally, it seems that a strength should be pun on the importance of the minor elements (Ti, Zr, Cr, V, Ga,...), that could be good tracers of the deposits history and on the regional geology that is rather important to determine the relative role of tectonic and climatic control.

The research of a constant element or mineral would allow to access the balance estimate and the reconstitution of the deposit history.

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