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STRUCTURE, GENESIS, AND PRESENT EVOLUTION OF AMAZONIAN BAUXITES DEVELOPED ON SEDIMENTS

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Developed on late Cretaceous sandy-loam sediments, bauxites of Central Amazonia consist in complex associations of several kaolinitic, gibbsitic and hematitic facies. From petrographical and mineralogical studies, the chronological succession of the constitutive facies is established. Then only a few hypothesis on the genesis remain possible amongst the many which have been rewiewed. These formations have been formed in situ, and successive stages of genesis are (1) lateritization of the sediment, giving quartz grains a protection from ulterior dissolution (2) desilicification of the underlying layers, and formation of macrocristalline gibbsite facies, which is the main constituent of the more aluminous layers, (3) present resilication of these aluminous layers, which are replaced by more kaolinitic material both from the top and from the base.

Rates of formation of those bauxites are given by calculation from the chemical balance of the profile. The fast present chemical evolution of the bauxites is assessed by the study of the transition between cemented layers on plateaux and stone-lines on plateaux slopes. This demonstrates that the dissolution and withdraw processes are fast with regard to the mechanical erosion on slopes.

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STRUKTURA, GENEZA I SADAŠNJA EVOLUCIJA AMAZONSKIH BOKSITA NASTALIH NA SEDIMENTIMA

Nastali na gornjokrednim i pješčano-glinastim sedimentima, boksiti centralne Amazonije obrazuju kompleksne asocijacije više kaolinitskih, gipsitičnih i hematitskih facija. Kronološki redoslijed facija utvrđen je petrološkim i mineraloškim ispitivanjima. Zato je od mnoštva proučavanih hipoteza o genezi boksita ostalo tek malo mogućih. Formacije su nastale in situ, i uzastopne su genetske faze slijedeće: 1. lateritizacija sedimenata, sa zaštitom kvarcnih zrna od kasnijeg rastvaranja, 2. desilifikacija donjih slojeva i tvorba makrokristalnih facija gibsita kao glavnog sastojka jače aluminijastih slojeva, 3. sadašnja resilifikacija tih aluminijastih slojeva koje postepeno zamjenjuje jače-kaolinitski materijal i odozgo i odozdo.

Brzina tvorbe tih boksita utvrđena je proračunima na bazi kemijske ravnoteže profila. Sadašnja brza kemijska evolucija procijenjena je putem izučavanja prijelaza od vezanih slojeva na platoima na labave (frakcionirane) pruge na padinama platoa. Taj razvoj pokazuje da su procesi rastvaranja i odnošenja brzi u usporedbi s mehaničkom erozijom na platoima.

(R. M.)

INTRODUCTION

Extensive areas north and south of the lower Amazon are characterized by a low plateaux landscape, in altitudes 100 ÷ 250 m above the seal-level (Fig. 1). The profiles on these plateaux consist of threee main layers:

— at the base, thick layers of weathered sandy-loam clastic sediments, which are considered from the Cretaceous Alter-do-Chao Formation [15];

— over, layers characterized by the accumulation of Fe and Al oxydes and hydroxides, ranging from nodular layers (Fe- and Al-nodules in a kaolinitic clay matrix), to continuous bauxitic cemented layers;

— in the upper part, a kaolinitic clay layer varying in thickness from 1 to 10 m.

Most of the authors have considered the lower saprolite and sometimes the nodular or the bauxitic layers as autochtonous, but the upper clay layer (also called »Belterra Clay«) as allochtonous, resulting from various continental sedimentation processes following an erosive cut [4, 7, 10, 16, 17, 20]. In the case of weathering covers which comprise a nodular layer, recent studies have demonstrated that the clay upper layer as well as the nodular layer are formed in place by weathering and pedogenetic processes [9, 13, 14]. The purpose of this paper is to establish, in the case of weathering covers which comprise bauxitic cemented layers, the chronological succession of the constitutive facies, and to give the frame of their genesis. Then, the past and present processes of formation of these bauxites will be discussed.

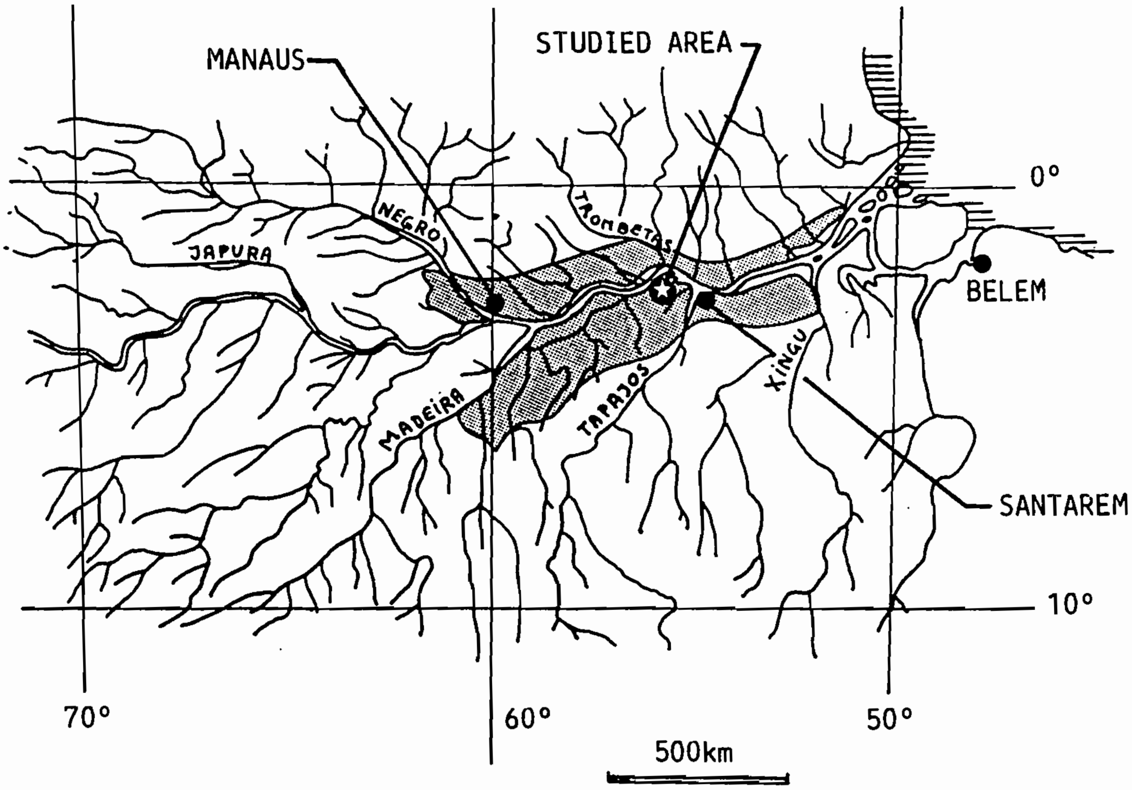

Fig. 1. Location of the studied area. In grey, area of low plateaux landscape

MATERIALS AND METHODS

This study was realised with the technical support of Omnia Minerios Ltda. the study area is located 2° 30' S and 56°14' E, which corresponds to 40 km south of the town of Juruti (see Fig. 1). The present climate is equatorial, of Amazonian type, with an average rainfall of 2100 mm and a sligth dry season. The vegetation is a dense, humid, evergreen forest. Landscape consists in plateaux in altitude 120 to 170 m above the Amazon level.

The macroscopic investigations were done in 5 to 25 m deep surveying shaft and on road cuts. Microscopic investigations were done by optical microscopy on thin section, and by SEM and STEM observations. Mineral constituents were identified and studied by X-rays diffractometry, thermogravimetric analysis and IR spectrometry on global samples and on microsamples collected by microdrilling of small volumes. Chemical analysis were done by atomic absorption spectrometry after strontium metaborat melting, and by microprobe analysis on thin sections.

RESULTS AND DISCUSSIONS

A. General description

As seen in Fig. 2, the three main layers which form the plateaux profiles consist in diverse facies which vary progressively along the profile. The description which follows is given from the base to the top of the profiles.

— At the base of the profile is a soft, white and purple kaolinitic clay. Further up is found a macrogibbsitic facies which is formed by large gibbsite crystals. This facies appears as septa in the clay, and further up as a saccharoid cemented material which forms columnar stuctures.

— The transition between the inferior soft level and the cemented layer is progressive: the macrogibbsitic septa become more abundant, and the whole horizon gets a boxwork-like structure; the kaolinitic clay is reduced to rounded aggregates which float in the cells of the boxwork; the abundance of the sacharoid facies increases; the whole horizon is impregnated by hematite, which gives a red colour.

— At the upper part of the cemented layers, the saccharoid facies becomes more abundant and forms a continuous matrix which surrounds spots of massive ferruginous facies (breccia-like strucure). From the base to the top, the size of those ferruginous spots progressively decreases from 10 ÷ 15 cm to 1 ÷ 3 cm, as their shape varies from angular to rounded. At the top of the cemented layers, the ferruginous facies often includes quartz grains.

— The transition between the cemented layers and the yellow clay upper layer is irregular and glossy. At this interface, and even in sharp glosses, is found a yellow-coloured facies of porcellaneous aspect, whose main constituent is microcrystalline gibbsite. This facies is called in this paper microgibbsitic facies (also called »porcellanous gibbsite« by some authors). This facies forms a thin (1 ÷ 30 cm), irregular, cemented horizon which is indented at its top by glosses of yellow clay. Further up, the microgibbsitic facies forms more or less anastomosed gibbsitic nodu-

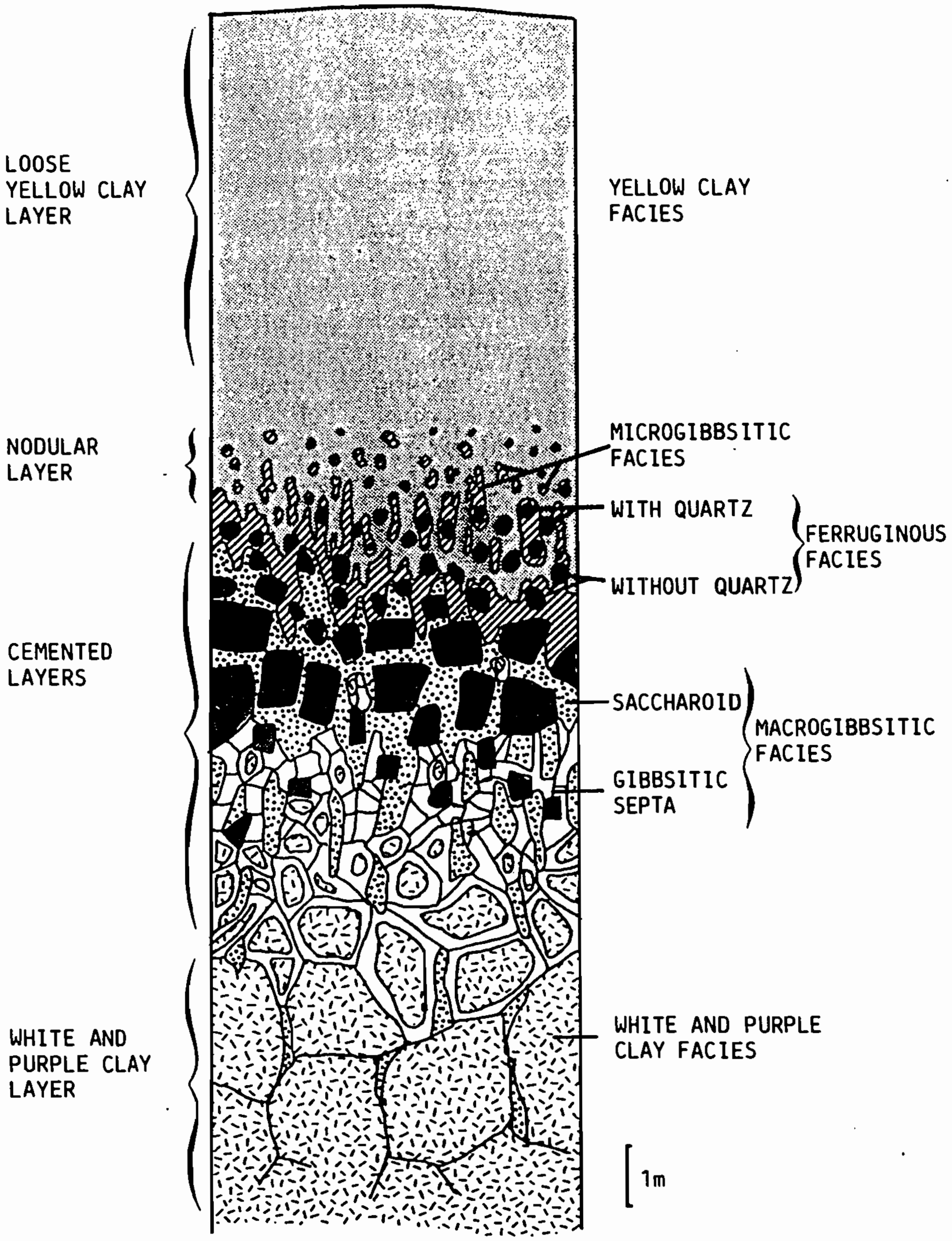

Fig. 2. Sketch of the plateau bauxitic profile

les whose size and abundance diminishes progressively. Rounded small spots of ferruginous facies can be observed in these nodules.

The above description corresponds to the more frequent vertical succession of facies. However, as seen on the section of Fig. 3, the five main facies which form this weathering cover can be divided in two groups:

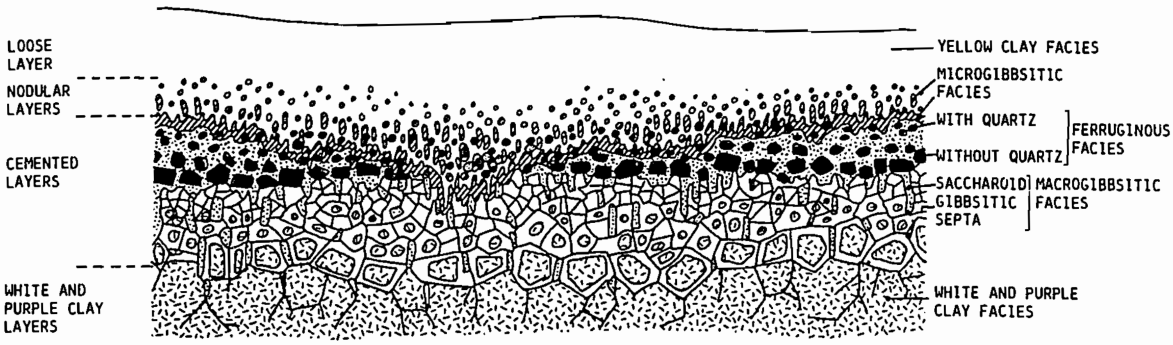

Fig. 3. Cross-section of a bauxitic plateau

* A first group, whose the interpenetrated vertical succession is regular:

(1) the kaolinitic white and purple clay facies at the base;

(2) the macrogibbsitic facies, as septa at the lower part of cemented layers, and as a continuous matrix at the upper part of cemented layers;

(3) the ferruginous facies, as spots which vary in size and shape from the base to the top, and which includes quartz grains at the top of cemented layers;

* A second group, uncomformable on the former group:

Table 1. *Chemical and mineralogical composition of the different facies. Normative values in % weight.*

Type of facies	Chemical composition				Mineralogical composition				
	SiO_2	Al_2O_3	Fe_2O_3	Ti_2O_3	Kaolinite	Gibbsite	Iron Ox. (as Fe_2O_3)	Quartz	Anatase
Yellow clay	47,3	41,2	8,6	3,0	76,1	7,2	8,3	5,9	2,6
Microgibbsitic facies	5,6	86,5	5,1	2,8	8,4	86,2	3,5	0	1,9
Ferruginous facies (examples)	3,5	4,1	90,5	1,8	2,2	,4	93,1	2,4	1,8
	10,5	26,4	62,3	,8	20,3	22,9	56,1	0	,7
	27,9	24,2	46,8	1,1	55,5	,3	43,2	0	1,0
Macrogibbsitic facies (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
	26,6	70,1	1,9	1,3	43,1	54,9	1,1	0	1,0
Kaolinitic Purple	51,4	44,5	1,7	2,3	95,5	1,9	,6	0	2,0
clay: White	47,7	43,6	5,4	3,4	88,5	4,7	3,9	0	2,9

(4) the microgibbsitic facies, at the interface of cemented layers and the upper yellow clay, and as nodules at the base of the yellow clay layer; (5) the yellow clay facies in the upper layers.

A typical chemical profile is given in Fig. 4. However, the chemical composition of the profiles is variable, as seen in Fig. 5 in which chemical values for 15 profiles are superposed. The chemical and mineralogical composition of the facies are given in Table 1. The compositions of white and purple clay, microgibbsitic and yellow clay facies are little variable. The compositions of macrogibbsitic and ferruginous facies are much variable, according to their microscopic heterogeneity.

B. Microscopic study

The following results can be pointed out from the petrographic study of the different facies and of their relationship:

* *Compact ferruginous facies.* Where this facies appears in the cemented layers, its structure is identical to the structure of the kaolinitic clay facies, and the microscopic transitions between these two facies are progressive. For example, laminar voids are identical in abundance, size and shape. This sugests that the compact ferruginous facies is formed by an hematitic impregnation of the kaolinitic

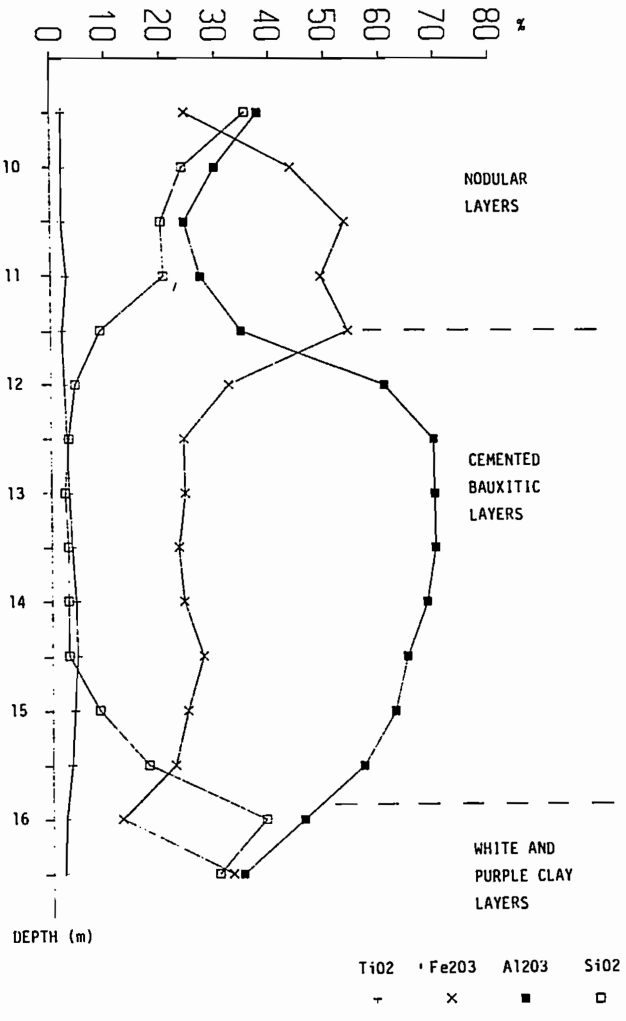

Fig. 4. Typical chemical composition of a bauxitic profile of the plateaux

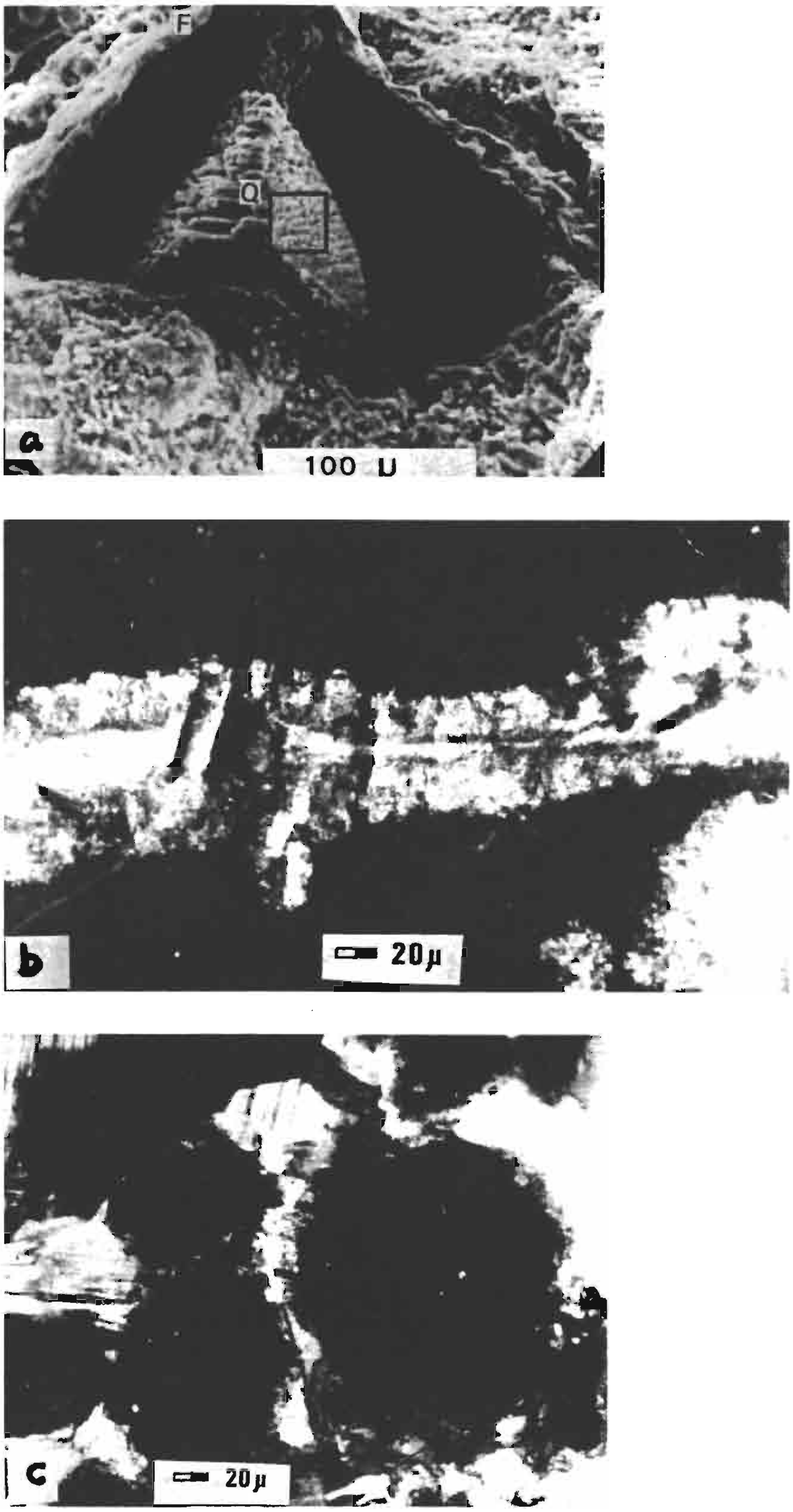

Fig. 6. Microscopic features. *6a* (SEM view): Corroded quartz grain floating in a pseudomorphic hematitic cavity (ferruginous facies), *6b* (thin section): Gibbsitic septa in a kaolinitic matrix (base of the cemented layers), *6c* (thin section): Corrosion of gibbsite macrocristals and their replacement by kaolinitic matrix as tiny spherules (base of the cemented layers)

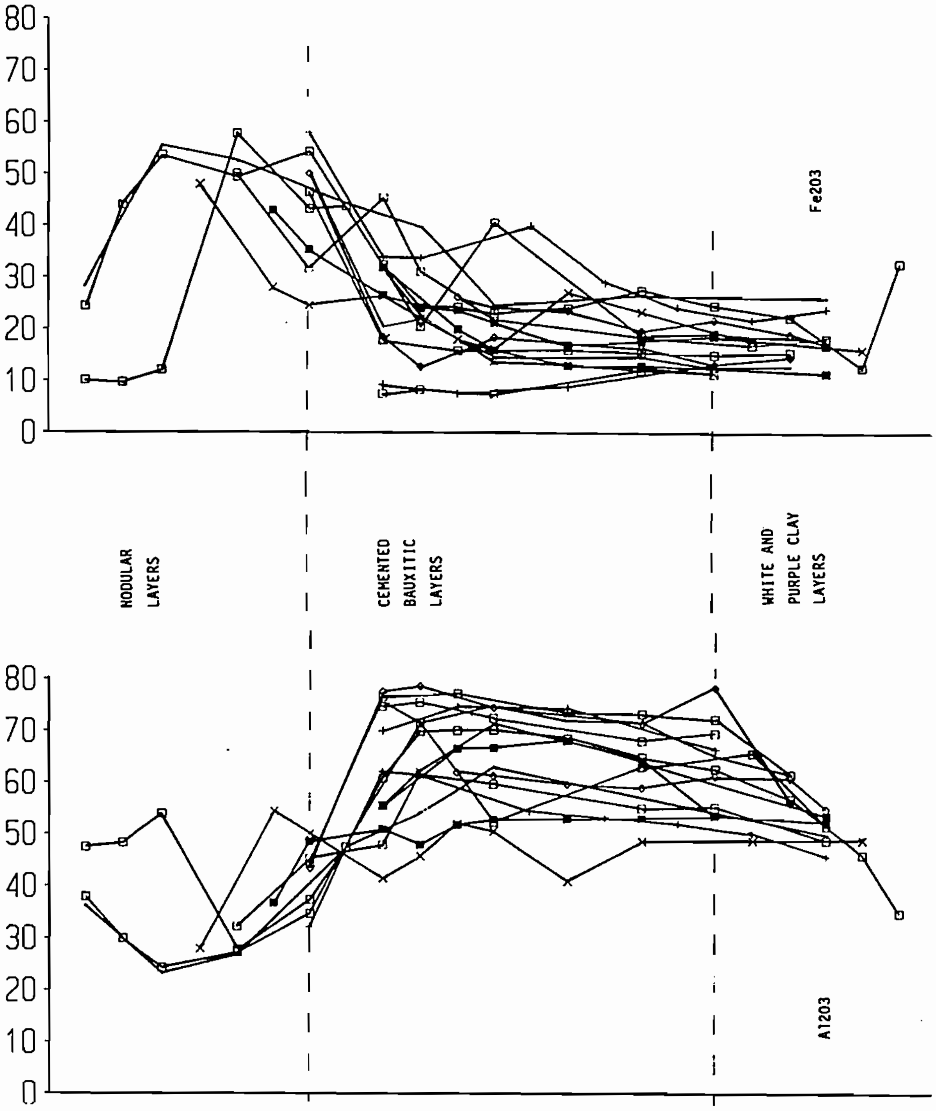

Fig. 5. Variability of the chemical composition of the bauxitic profiles. Superposition of ponderal values in percent for 15 profiles

clay. Further up, the ferruginous facies progressively becomes more porous, as cavities appear and become larger and more abundant. The angular shape and the internal hematitic septa of these cavities are pseudomorphic of quartz grains and of their cracks, as those can be observed in the sediment in depth. Many cavities are filled by gibbsite macrocrystals. Ont the top of the ferruginous facies, the larger pseudomorphic cavities are often occupied by a strongly corroded quartz grain which floats in the cavity (see Fig. 6a).

* *Macrogibbsitic facies.* The gibbsitic septa in depht are formed by macrocrystals of gibbsite oriented normal to the plane of the septa (see Fig. 6b). Most of the gibbsite macrocrystals in depht present features of corrosion and in-place replacement by kaolinite (at the base of the profile, as tiny spherules, see Fig. 6c) or hematite (further up, as ferrans on septa and cavities). The macrogibbsitic facies is un-

comformable to the structures of the ferruginous facies. This demonstrates that the macrogibbsitic facies is posterior to, and replace in-situ, the ferruginous facies.

* *Microgibbsitic facies and yellow clay.* In blocks and nodules of microgibbsitic facies are found geodic veins of coarser gibbsite crystals, which become more abundant from the base to the top. These veins may suggest that the microgibbsitic facies is anterior to the macrogibbsitic facies, as supposed by **Dennen** and **Norton** [7]. However, the uncomformity of the microcrystalline facies to the structure of the macrocrystalline facies as well as the ferruginous facies (see Fig. 6 c) demonstrates that the microcrystaline facies is posterior to, and replace in-situ the other cemented facies, and that veins of gibbsite macrocrystals in the microgibbsitic facies are due to dissolution-generation and reorganization in the gibbsitic material. In the same way, it can be seen that yellow clay is posterior to all cemented facies.

C. Discussion

Genesis of the bauxitic formations

A conclusion of the petrographic study is that the different facies replace each other in place, which implies geochemical processes. The facies temporal succession is as follows: (1) ferruginous facies, with or without quartz; (2) macrogibbsitic facies; (3) microgibbsitic facies; (4) yellow clay.

— The ferruginous facies has been formed by the hematization of an initial material, and the ulterior dissolution of quartz grains has left pseudomorphic cavities, in a few of which remain corroded relicts quartz grains. The progressive variation of abundance and size of these cavities from base to top reflects an heterogeneity of the initial material. The vertical sequence of size, shape and microscopic features of the ferruginous spots reveals that the rounded shape of relictual iron spots is here due to geochemical processes.

— The macrogibbsitic facies is posterior to the genesis of the ferruginous facies. The stucture of the gibbsitic septa in depht suggest a genesis by progressive growth in the structural cracks of the clay material, where the subsurface water flows. The physico-chemical conditions were sufficiently stable to give large cristalline edifices. However, the corrosion features of most of the gibbsite macrocrystals demonstrates a posterior resilication at the base of the profile, and further up an hematitic impregnation.

— An other conclusion is the geochemical origin of the uncomformity of the yellow clay on the profile formed by the kaolinitic, macrogibbsitic and ferruginous facies. It is deduced from the glossy geometry and the microscopic features of this transition. The yellow clay progress in place, by geochemical processes, at the expense of the underlying layers, and is preceded by a transient microgibbsitic facies.

Thus, all the present transitions between layers and facies in the profile have a progressivity, a geometry and microscopic features which attest their geochemical origin, unconsistent with sedimentological processes. Then, no allochtonous hypothesis on the profile genesis (as an erosive cut followed by a detritic overlying)

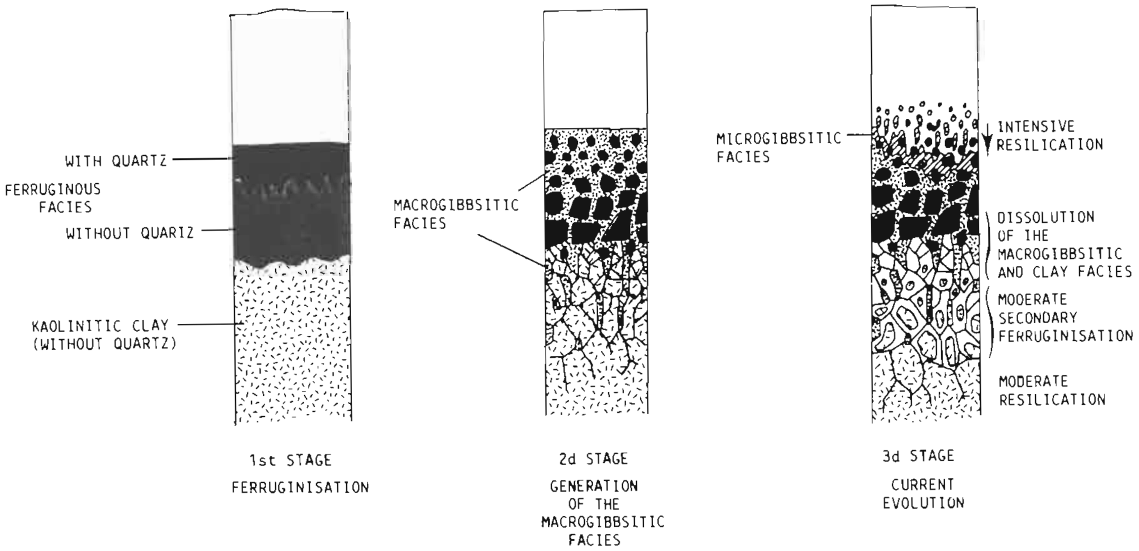

Fig. 7. Successive stages of the bauxitic profile

can be attested by the present structure of the profile. At the opposite, if allochtonous processes has occured during the profile genesis, they have been completely obliterated by the ulterior geochemical evolution.

In the hypothesis of an in-place formation of the whole profile, the successive stages of formations are indicated by the chronosequence of the different facies as follow (Fig. 7):

(1) Lateritization of the sediment and formation of the ferruginous facies, giving quartz grains a relative protection from ulterior dissolution.

(2) Desilication of the underlying layers, and formation of macrocristalline gibbsite facies, which partly replaces the ferruginous facies. This intensive desilication has occured in depht, while a stock of silica as kaolinite was preserved in the overlying layers. The transition between the Alter-do-Châo sediment and the white and purple clay layer was not observed in the studied area. In other places [13], the development of kaolinitic clay layers in depht by strong dissolution of the quartz grains and generation of kaolinite was observed.

(3) Current resilication of these aluminous layers, both from the top and from the base. From the top, resilication is intense, due to the geochemical downward progression of the yellow clay; and from the base resilication is moderate, by diffuse replacement of the macrocrystalline gibbsite by a kaolinitic matrix.

The given chronosequence is of course a minimal sequence. Others stages may have occured, which cannot be deduced from the present structure of the profile.

The transient microgibbsitic paragenesis precedes the yellow clay in its downward progression. This has two consequences:

(1) The microgibbsitic paragenesis is currently generated under a thick kaolinitic layer. To explain the formation of gibbsitic horizons under kaolinitic layers, some authors as **Kronberg** et al. [12] propose a model in which waters flow through the kaolinitic layer at a rate much faster than the rate of mineral-water reactions, then is focused in the gibbsitic zone. This hypothesis cannot be applied to the mic-

rogibbsitic paragenesis, for it is located far over the groundwater level. Moreover, measurement of the water dynamics in the kaolinitic layers reveals that waters percolate slowly in the yellow clay, as a capillary water which is at a pressure potential above atmospheric pressure (except in the two top meters, where free water occurs after rains). Free water only appears at the base of the yellow clay and percolates downwards as laminar films in the coarse pores of the cemented facies. Then, the physical state and dynamic of the percolating waters change at the base of the yellow clay, which modify thermodynamic equilibrium [19]. This have to be taken into account for thermodynamic modeling of the different paragenesis, and will be the subject of further publications.

(2) The generation of the microgibbsitic facies is independent of the chemical composition of the underlying material, which can be ferruginous, with or without quartz, or macrogibbsitic. Thus, this paragenesis only depends on the physico-chemical conditions which prevail where it is formed. In other terms, it is a dynamic equilibrium which only depends on the chemical composition of the waters and the moisture regime. This is in accordance with our results concerning other weathering covers in the same climatic area [13].

The process of generation of a gibbsitic horizon under a more kaolinitic horizon lie outside the bauxite formation problems: in many soil profiles formed under equatorial climates, layers characterized by the accumulation of Al or Fe oxydes and hyroxydes develop in place, in vertical drainage conditions, under more kaolinitic layers [2, 3, 5, 6, 14].

Rates of formation and evolution of the bauxitic formations

The relative enrichment in Al with regard to Si in the bauxitic layers implies an important geochemical descent of the profile in the sediment. In the hypothesis that the bauxitic covers was formed by weathering of a sediment identical to the one at present observed in depht, an estimation of the minimal thickness which have been weathered to produce the average profile can be calculated from the bulk density and the chemical composition of the different layers of the profile. From the volume and composition of the waters leached out off the system, an estimation of the current rates of geochemical evolution of the profile can be calculated. Results are given in Table 2. Assuming the variability of composition of the sediment from 50 to 75 % kaolinite, results give 124 to 89 m as the minimal thickness of sediment weathered to form the present profile. Under present days conditions, it needs 67 to 27 milion years and 158 to 99 m of sediment to form the present profile. It corresponds 67 to 27 m as the subsidence of the soil surface. As the soils studied may have evolved under meteoric conditions since the late Cretaceous, and as weathering was probably more abrasive in the past [1, 18], these results are probably below reality. In any case, such values demonstrate the importance of the geochemical weathering to morphogenesis during the genesis of the studied formations.

Table 2. *Rates of formation of an average bauxite profile.*

Average composition of the profile:
Al_2O_3, 22 t/m²; SiO_2, 10,5 t/m²
Current weathering conditions:
annual rain 2100 mm, ETR 1600 mm,
composition fo waters leached out from the system
(from Furch, 1984): Al_2O_3: 80µg/l; SiO_2: 2,1 mg/l.

Mineralogical composition of the sediment	Kaolinite %	25	50	75
	Quartz %		50	25
Whatever the conditions	Minimal thickness of sediment weathered (m)	232	124	89
Under current weathering conditions	Minimal thickness of sediment weathered (m)	523	158	99
	Subsidence of the soil surface (m)	477	112	53
	Time of genesis (milion years)	310	67	27

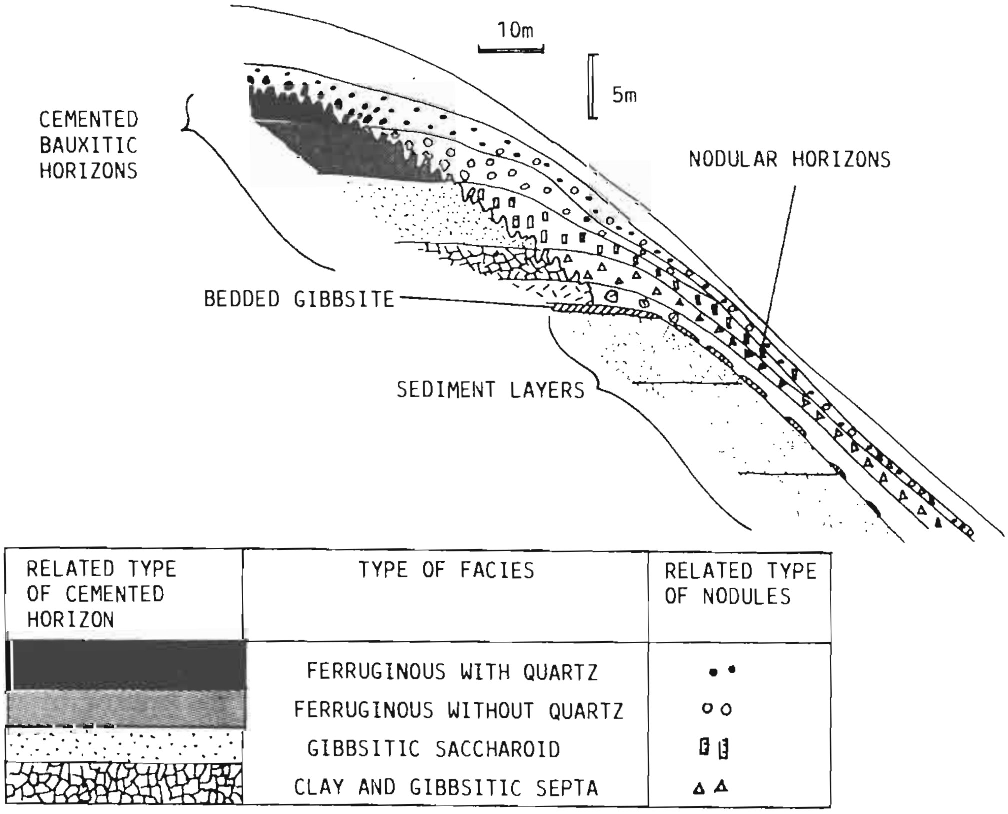

Fig. 8. Transition between the plateau cemented bauxite and the slope stone-line

Others observations gives indirect data on the rates of present geochemical processes compared to landscape morphogenesis. Fig. 8 sketches a lateral transition between the plateau cemented bauxite and the slope soils, which was observed on a road cut.

Description. The stone-line of the slope soils consists in various cemented nodules and pebbles constituted by the same facies than observed in plateaux profiles, with the same vertical succession (in order, from the base to the top, kaolinitic and macrogibbsitic boxwork, macrogibbsitic saccharoid, ferruginous without quartz, ferruginous with quartz). There is a strict continuity between this stone-line and the cemented layers of the plateau. From the plateau to the sloping region, continuous cemented layers are progressively indented by the yellow clay material and carved as anastomosed blocks, they are bended in a parallel direction with the slope, but the vertical succession of the different facies is preserved, except in the top one-two meters of the soil.

Discussion. The coarse fragments of the stone-line are relicts of the cemented layers observed on the plateau. The horizontal limits between the different layers of the stone line in the upper part of the catena demonstrates the absence of slumping movement along the slope, then a strict in-situ formation of these layers, by dissolution of the cemented facies. That means also that the dissolution processes are much faster than the mechanical erosion during the slope backward progression. More down on the slope, the upholding of the vertical succession of the different facies means the absence of important mechanical reworking: this is an in--place zone, where the bending of the horizons is mainly due to the geochemical descent of the soil in the sediment. Thus, the prime processes in current slope evolution are geochemical processes. On the top one-two meters of the slope soils, the mixing of the different types of coarse elements indicates a reworking which can be attributed to the reworking by the roots of fallen woods, and to biological activity.

Moreover, these observations indicates that the presence of lateritic and bauxitic floats on valley slopes and bottoms are not always the sign of erosion and colluvial processes.

CONCLUSIONS

The whole profile of the studied bauxitic formation were probably developed in place. In case allochtonous processes has occured in the past, they have been completely obliterated by the ulterior geochemical evolution. The current gross evolution of the bauxites is a resilication, diffuse and moderate at the base, intense at the top. Upper resilication is due to the geochemical downward progression of the kaolinitic upper layers at the expence of the cemented bauxitic layers. However, a transient bauxitic paragenesis which mainly consist of microcrystalline gibbsite is currently formed at the upper part of the cemented layers. This microgibbsitic paragenesis only depends on the physical state and chemical composition of the percolating water. On slopes, the rate of current geochemical evolution is fast compared to mechanical erosion. Then, the past and current evolution of the bauxitic profiles is mainly geochemical, as well as the current evolution of the landscape.

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