

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

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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.

Latent 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 *con-crescere* 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; $T > 25^{\circ}\text{C}$)

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 ₂ O 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 ₂ O 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 ₂ O 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 ₂ O	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; $T > 25^\circ\text{C}$), or under subtropical climates, humid but cooler ($P > 1300$ mm/yr; $T < 25^\circ\text{C}$).

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

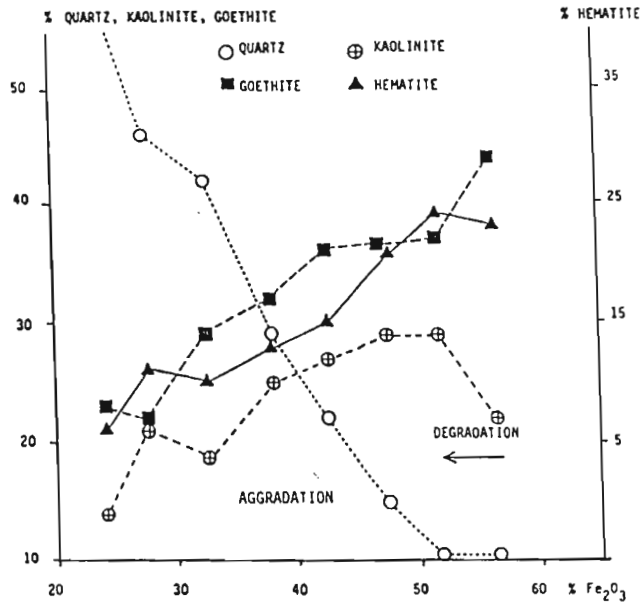


Figure B.1 - Chemical and mineralogical compositions of a serie of 190 ferricretes developed on schists, in Burkina Faso. Notice that hematite and kaolinite ponderal concentrations increase or decrease together, so that their fluctuations are used to discriminate two domains in the process of the ferricrete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

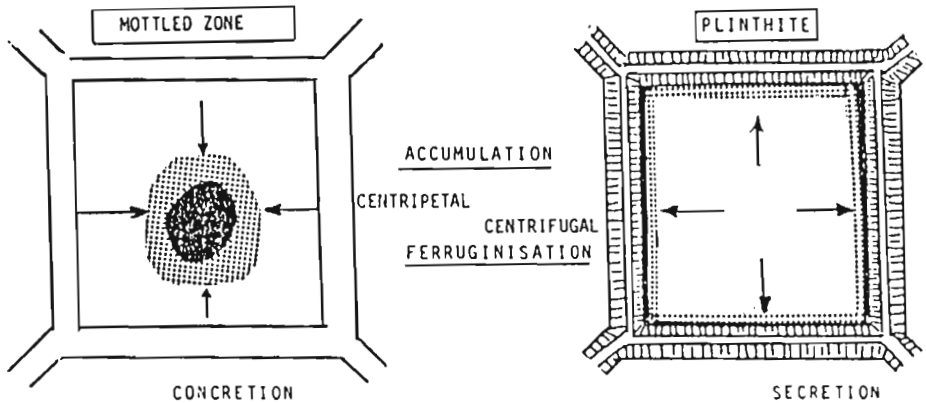


Figure B.2 - Concretion (mottle and nodule formation) versus excretion (reticular cutan formation): two processes of iron accumulation which may allow, if acceptable, to distinguish ferricretes from plinthites (from Tardy, 1993).

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 evolving towards cryptobauxites. However, products of ferricrete dismantlement, red latosols, oxisols or "sols ferrallitiques rouges désaturés" 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	N°	Depth (cm)	Granulometry		Chemical analysis (%)				Ratio	
			% < 2µm	% > 2µm	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	H ₂ O	SiO ₂ /Al ₂ O ₃	Fe ₂ O ₃ /Al ₂ O 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	N°	Depth cm	Kaolinitic clays (%)					Quartz Q	Ratio SiO ₂ /Al ₂ O ₃	Ratio Gib/Kaol	Al ₂ O ₃ Am/Gib	Kaolinites	
			T	K	M	H	G					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: SiO₂/Al₂O₃ of secondary minerals; Gib/Kaol: Gibbsite/Kaolinite; Am/Gib: Al₂O₃ 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

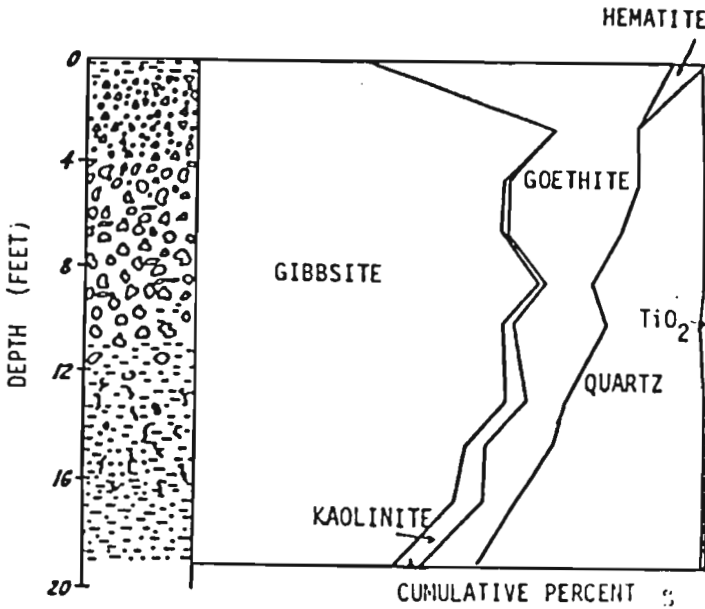


Figure B.3 - Mineralogy of the bauxite of Jarrahdale in Australia (from Grubb, 1971).

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 ₂ O ₃ (%)	Al ₂ O 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 ₂ O ₃	Fe ₂ O ₃	SiO ₂	TiO ₂	H ₂ O	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 (%))

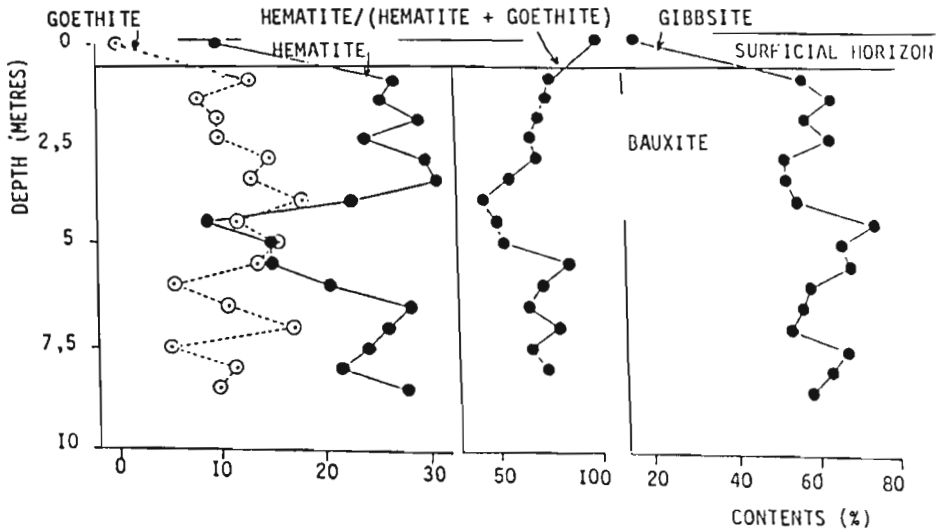


Figure B.4 - Mineralogical evolution in a red orthobauxitic profile of Famansa, South-Mali, Africa, (from Tardy 1993).

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

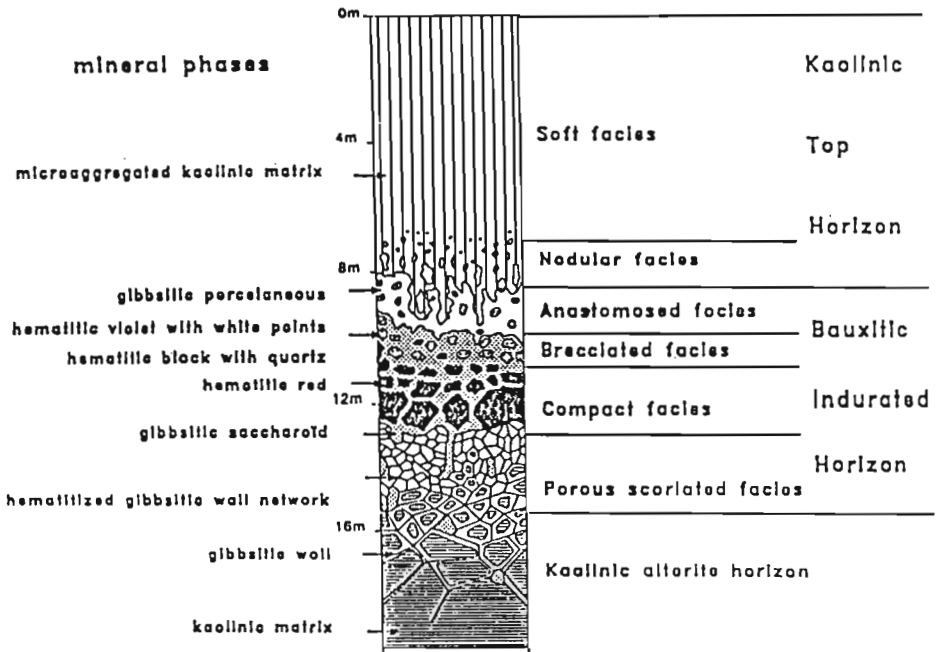


Figure B.5 - Cryptobauxite profile from Juriti in Amazonia, Brazil. Three horizons are distinguished: a soft kaolinitic layer at the surface; a bauxitic layer in an intermediate position within a dismantled ferricrete; a kaolinitic lithomarge in the lower part of the profile (adapted from Lucas, 1989).

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 ₂ O ₃ (%)	Fe ₂ O ₃ (%)	SiO ₂ (%)	TiO ₂ (%)	H ₂ O (%)	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)

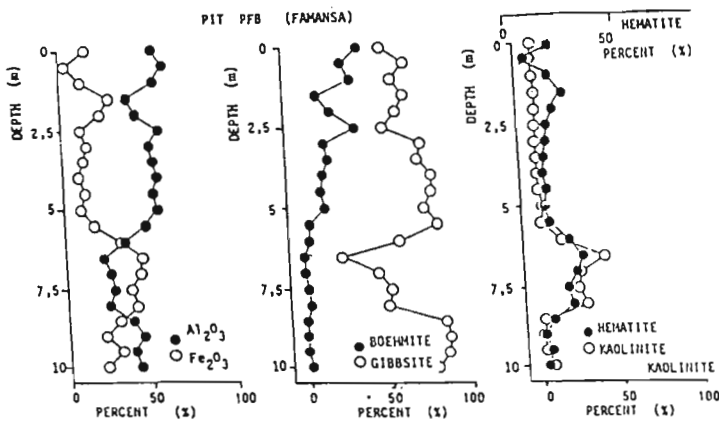


Figure B.6 - Mineralogical evolution in a white metabauxitic profile in Famansa, South-Mali, Africa, (from Tardy, 1993).

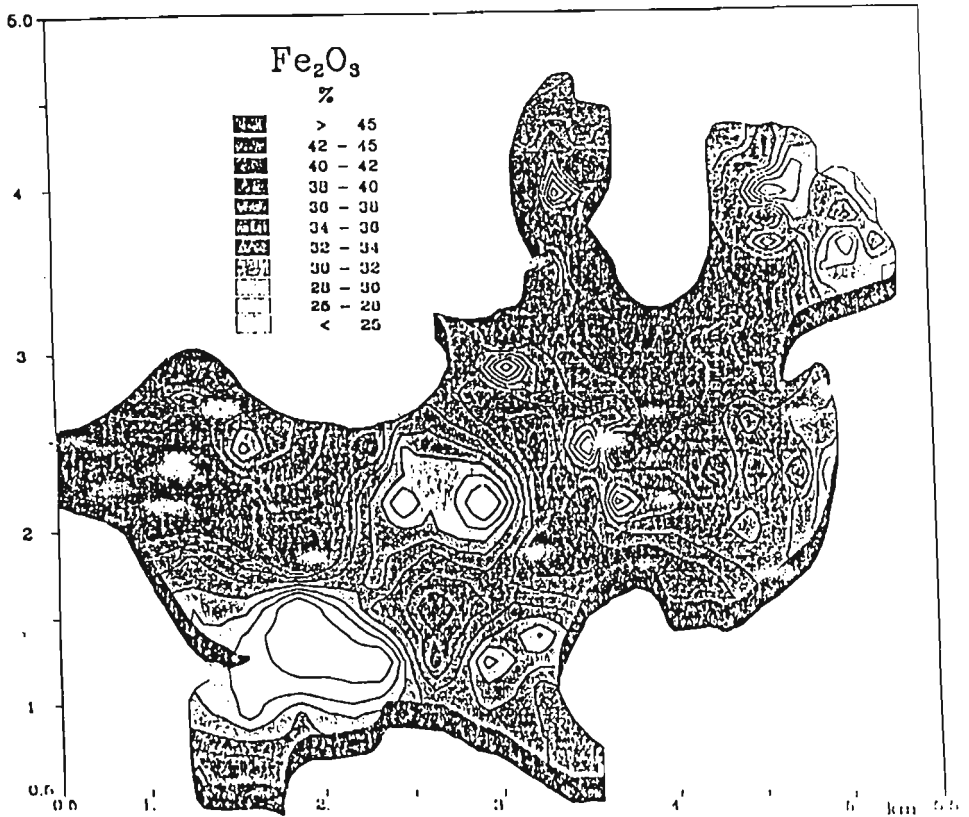


Figure B.7 - Distribution of aluminium and iron contents in superficial horizons of orthobauxitic (rich in iron) and metabauxitic (poor in iron, rich in aluminium) profiles of the plateau of Famansa, South-Mali, Africa, (from Tardy, 1993).

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 ₂ O ₃	S.	40.69	41.54	39.35	42.10	39.34	41.19	38.48	40.39
Al ₂ O 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 ₂ O ₃	S.	32.05	32.97	34.24	29.61	32.05	27.09	27.49	30.79
Fe ₂ O 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 Al₂O₃/SiO₂ (index of desilication)

RAF: ratio Al₂O₃/FeO₃

RAFSI: ratio Al₂O₃/FeO₃ (S) / Al₂O₃/FeO₃ (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)

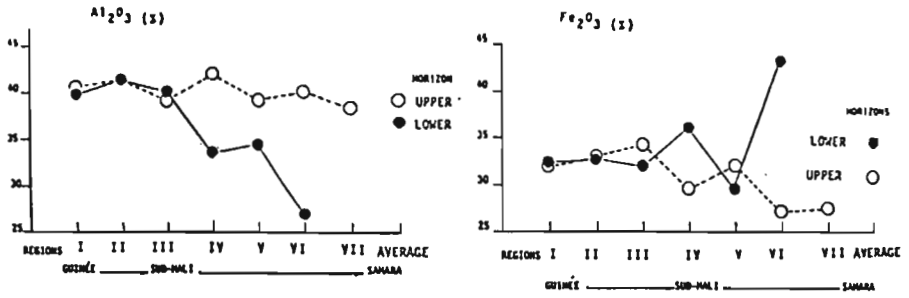


Figure B.8 - Evolution of aluminium and iron contents in bauxites of Guinea and Mali (from Tardy, 1993).

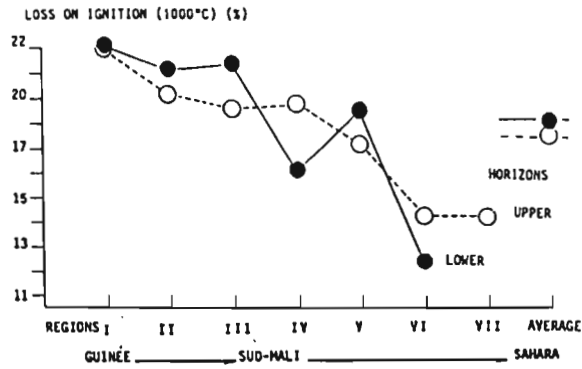


Figure B.9 - Evolution of water content in bauxites of Guinea and Mali (from Tardy, 1993).

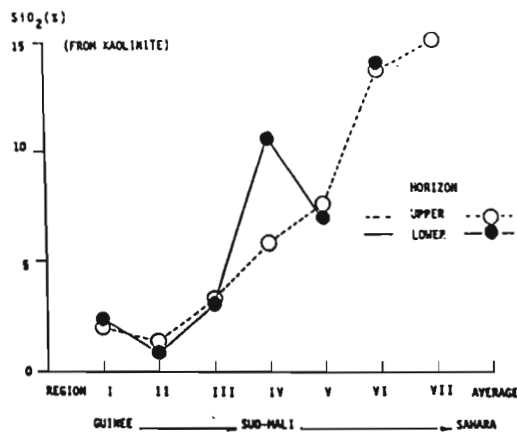


Figure B.10 - Evolution of kaolinite content of bauxites of Guinea and Mali (from Tardy, 1993).

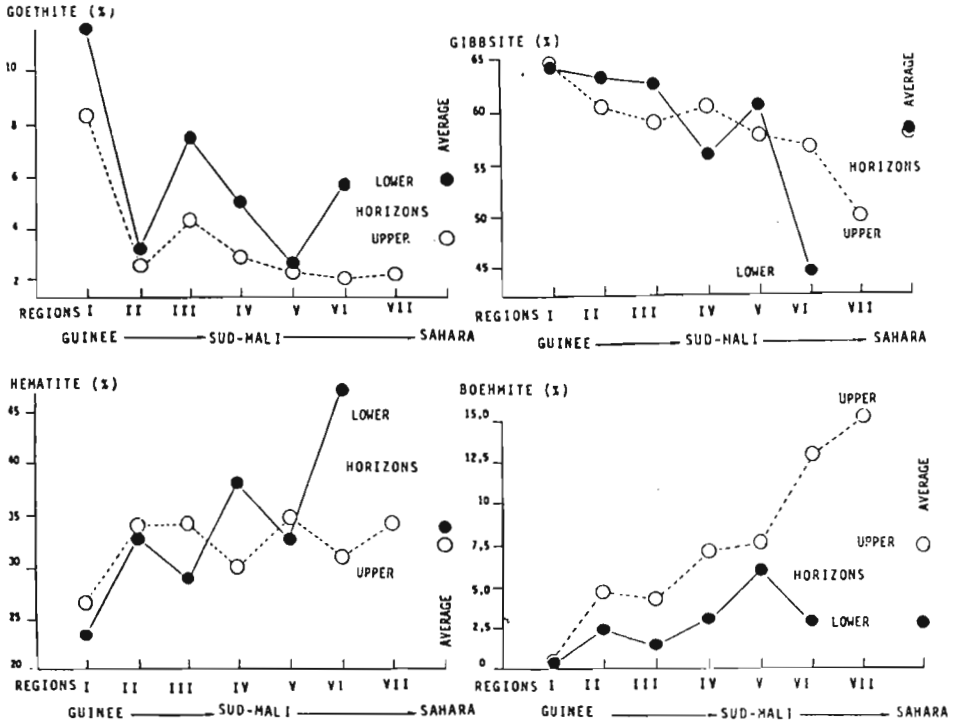


Figure B.11 - Evolution of the mineralogical composition of bauxites from Guinea to Mali (from Tardy, 1993).

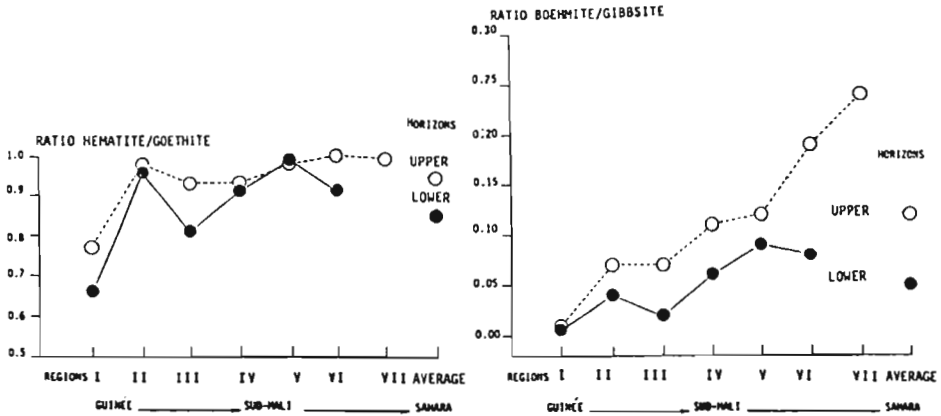


Figure B.12 - Evolution of the index of dehydration measured by ratios RBG (boehmite/(boehmite + gibbsite)) and RHG (hematite/(hematite + goethite)) in bauxites from Guinea to Mali (from Tardy, 1993).

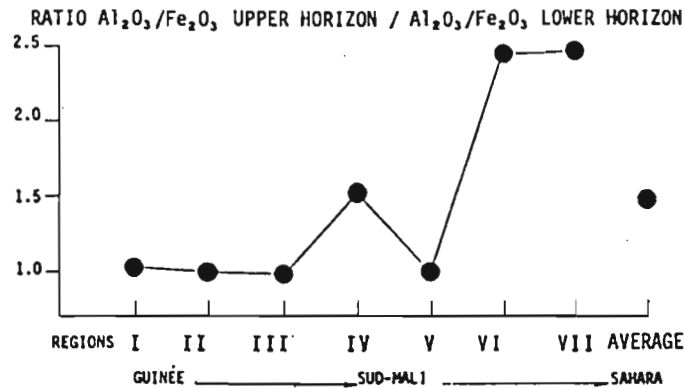


Figure B.13 - Evolution of the index of transfer of iron measured by the ratio $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ (S)/ $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ (l) (from Tardy, 1993).

boehmite increase;

- kaolinite content increases;
- the contrast between ratios: $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ in the upper horizon versus $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ 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

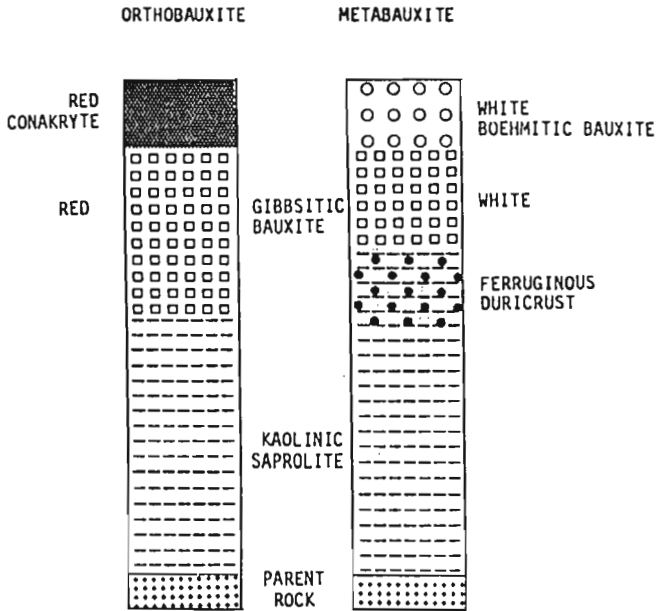
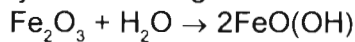


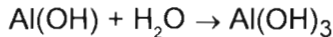
Figure B.14 - Schematic distribution of boehmite, gibbsite, kaolinite and hematite in conakrytes associated with orthobauxites in one hand and in ferricretes associated with metabauxites in the other hand (from Tardy and Roquin, 1992 and Tardy, 1993).

contrasted climates.

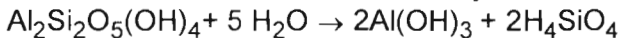
Hematite is less hydrated than goethite:



Boehmite is less hydrated than gibbsite:



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



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 crystalliplastic 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	crystalloplasmic	poor	abundant	large	present	present	absent	absent
Fercrete	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	microglobular	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	Geochemical composition
Conakryte(1)	hydro-ferrallite	goethite, hematite, gibbsite	$Fe_2O_3 \cdot H_2O \cdot Al_2O_3$
Conakryte(2)	ferrite	hematite, goethite	$Fe_2O_3 \cdot H_2O$
Fercrete	xero-ferralsite	hematite, kaolinite	$Fe_2O_3 \cdot SiO_2 \cdot Al_2O_3 \cdot H_2O$
Orthobauxite	hydro-alferrite	gibbsite, goethite, hematite	$H_2O \cdot Al_2O_3 \cdot Fe_2O_3$
Metabauxite	xero-allite	boehmite, hematite	$Al_2O_3 \cdot Fe_2O_3$
Red latosol	xero-sialferrite	kaolinite, hematite, goethite	$SiO_2 \cdot Al_2O_3 \cdot H_2O \cdot Fe_2O_3$
Yellow latosol	hydro-sialferrite	goethite, kaolinite, gibbsite	$H_2O \cdot Al_2O_3 \cdot SiO_2 \cdot Fe_2O_3$
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		Paleoclimatic evolution	Parameters		
		H	T		H1	H2	T1
Conakryte(1)	humid	medium	high	constantly humid tropical	→	→	→
Conakryte(2)	undifferent	—	—	undifferent	—	—	—
Fercrete	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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