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Developments in Earth Surface Processes 2

WEATHERING, SOILS & PALEOSOLS

Edited by

I.P. MARTINI and W. CHESWORTH
Department of Land Resource Science, University of Guelph, Guelph, Ont. N1G 2W1, Canada

Chapter 15

ELSEVIER
Amsterdam — London — New York — Tokyo 1992

Chapter 15

Diversity and terminology of lateritic profiles

Y. TARDY

Introduction: definition of laterites

This chapter will deal with the definition and the terminology of a related series of materials ranging from laterites, lateritic bauxites, lateritic soils to all kinds of intertropical weathering products, of detailed features characterizing the different horizons, of horizons constituting a large variety of profiles, and of profiles within a large intertropical climatic area.

The term laterite (from the Latin *later*, brick), is commonly attributed to Buchanan (1807) who described, in Malabar, surficial natural hard materials used as bricks. In some African dialects, surficial materials which are generally red are called brick earth (Maignien, 1964) and the term laterite refers to blocs used in construction (Prescott and Pendleton, 1952, in McFarlane, 1976). A controversy over the definition of laterite has been going on for 150 years (Maignien, 1958; 1966; McFarlane, 1976). Today, two positions emerge. First, many scientists have used the term laterite to designate weathering products generally formed under tropical conditions, rich in iron and aluminum, and either hard or subject to hardening upon exposure to alternate wetting and drying (Pendleton, 1936; Kellog, 1949). Laterites also include certain highly weathered material with sesquioxide-rich, humus-poor nodules, that may be surrounded by earthy material that does not harden (Sivarajasingham et al., 1962). The term also includes all kinds of plinthites (from the Greek *plinthos*, brick) which are laterites in the restricted sense (Mohr et al., 1972, but excludes soft kaolinitic lithomarges, fine saprolites and non-indurated ferrallitic soils. Second, for Maignien (1964) and Millot (1964) followed by Schellmann (1983, 1986) the word laterite is not restricted to indurated materials but largely includes all kinds of tropical weathering products.

I recommend usage of the term laterite in its broadest sense, that is as products of intense weathering made up of mineral assemblages that may include iron or aluminum oxides, oxyhydroxides or hydroxides, kaolinite and quartz, and characterized by a ratio $SiO_2:(Al_2O_3+Fe_2O_3)$ which does not exceed the value required to

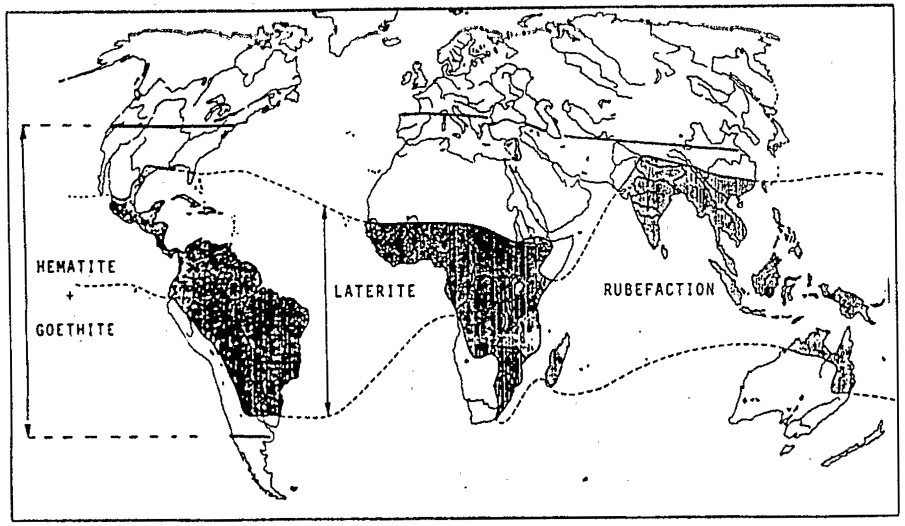


Fig. 15.1. The zone of rubefaction (Pedro, 1968) coincides with the intertropical area of laterite formation, characterized by the development of kaolinite and hydroxides, oxi-hydroxides or oxides of iron and aluminum. Laterites are limited northwards or southwards, under semiarid or arid climates, by belts of silcretes, calcretes, vertisols or other smectitic weathering profiles. The two unbroken lines drawn by Schwertmann (1988) delineate the two cold climatic domains characterized by absence of hematite from the hot intertropical zone characterized by presence of hematite in almost all soils and weathering profiles.

characterize quartz and kaolinite.

Thus the term laterite includes bauxites, ferricretes, iron or aluminum duricrusts, mottled horizons, "carapaces", "cuirasses", plinthites, pisolite or nodule bearing materials and is extended to the formations or horizons which are parts of red or yellow ferrallitic soils, tropical ferruginous soils and other formations such as kaolinitic lithomarges which are soft, cannot be hardened but therefore are, for example, commonly associated with indurated ferricretes. I propose here that the zone of the present-day laterite formation would correspond to the rubefaction zone of Pedro (1968) (Figure 15.1).

The three domains of common lateritic profiles

In typical lateritic profiles Bocquier et al. (1984) have distinguished three zones or major horizons (Figure 15.2):

(a) zone of alteration, at the base;
(b) a glaebular zone, located in the middle part; and
(c) a soft zone, non indurated, located in the higher part of the profile.

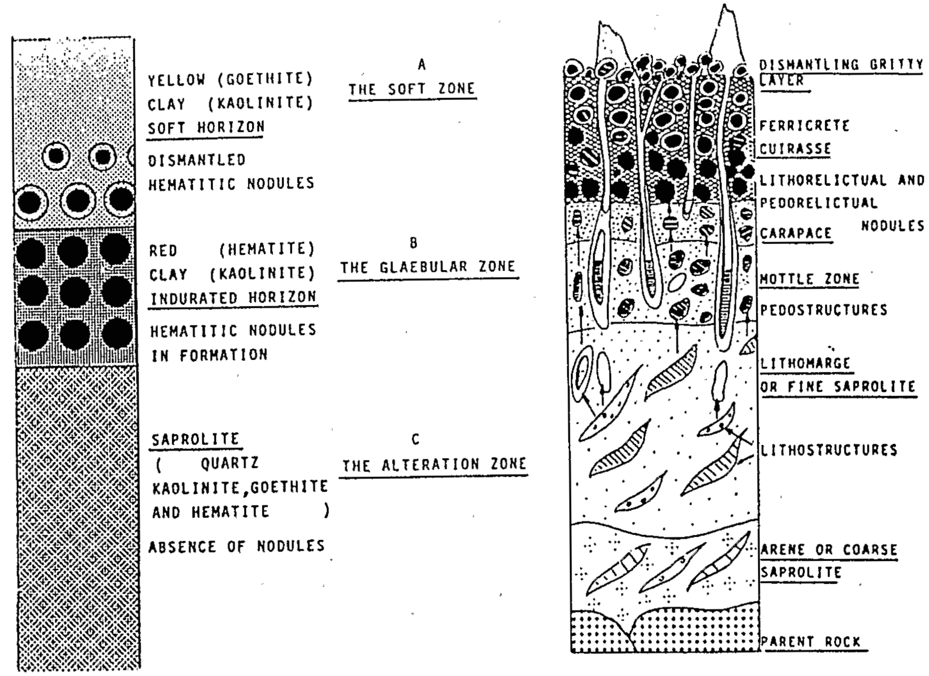


Fig. 15.2. Schematic representations of a lateritic profile capped by a ferricrete and of the three major zones of a nodular lateritic profile: alteration zone (*A*), glaebular zone (*B*) and soft surficial zone (*C*). In the alteration zone, quartz, kaolinite, goethite and hematite form together. In the glaebular domain hematitic nodules form in a red kaolinitic clay matrix. In the soft zone, hematitic nodules are dismantled together with the development of a secondary goethite.

In the zone of alteration (coarse saprolite or arene, fine saprolite or lithomarge), the parent rock volumes and structures are roughly conserved. This domain is essentially characterized by the incongruent dissolution of primary minerals and by the leaching of most of the soluble materials; the least mobile elements (Al, Fe), liberated by weathering, reorganize almost *in situ* with little or no transport.

The glaebular domain, generally shows indurated accumulations of iron or aluminum, either continuous (ferricretes or bauxites) or discontinuous (nodules or pisolites) resulting in a reorganization of the original material and in an absolute accumulation of iron and aluminum crystallized in various oxides, hydroxides oxyhydroxides and also kaolinite.

The soft zone, non-indurated, is characterized by a relative accumulation of primary minerals such as quartz, or secondary minerals such as kaolinite and oxyhydroxides, either resulting from dissolution, degradation and dismantling of glaebular material or reworking from below by termite activity.

Most of the lateritic profiles clearly show three typical domains but in several situations one or two of these zones are absent either by incomplete formation or by posterior erosion.

Saprolites and the so called alteration domain

The so called alteration domain, including different kinds of saprolites, is common to all lateritic profiles. These horizons are normally located below the ground water table in the saturated zone, that is in permanently wet conditions. Here, the mineralogy of the alteration domain is less sensitive to climatic conditions than that of horizons located above the ground water table. Two kinds of saprolites are normally distinguished (Figure 15.2).

The coarse saprolite

At the bottom of lateritic profiles, is the unweathered parent rock. Immediately above, lies the coarse saprolite, where abundant fragments of unweathered rock and primary minerals are conserved, with original structures intact. On granitic rocks, the coarse saprolite is traditionally called "arène" (from Latin *arena*, sand; Leneuf, 1959; Millot, 1964; Tardy, 1969). The limit between parent rock and coarse saprolite is not generally a horizontal plane and the weathering fronts progress irregularly, penetrating deeper down cracks, fractures and so on, and leaving unaltered boulders, fragments of rocks and relicts of primary minerals sometimes far up the profile. This gives a fairly diffuse weathering front. Under certain circumstances, the coarse saprolite may be thick [as frequently observed on granitic rocks (Leneuf, 1959)], or very thin [as generally observed on basic rocks (Delvigne, 1965)]. Furthermore, the thickness of the saprolite is reduced in the humid tropics and relatively enlarged in arid and in temperate regions (Tardy, 1969; Boulet, 1978).

In the early stages of weathering, the first steps of alteration of primary minerals develop imperfectly closed systems (Tardy, 1969; Trescases, 1973; Nahon et al., 1977; Nahon and Bocquier, 1983), where the secondary minerals formed are site-specific. Their nature depends on the rate of weathering of each primary mineral, and on the rate at which the initial closed systems become progressively open to the circulating solutions.

Weathering products in the coarse saprolite may be either a single mineral phase such as vermiculite, smectite, kaolinite, gibbsite, imogolite, amorphous and hydrated aluminosilicates, or assemblages such as vermiculite–kaolinite, smectite–kaolinite, kaolinite–gibbsite (Leneuf, 1959; Tardy, 1969; Novikoff, 1974; Novikoff et al., 1972). In a normal succession of minerals the most soluble phases (calcite, smectites) appear in closed systems, while the less soluble ones (kaolinite, gibbsite) appear in the most open systems, at the contact with circulating solutions. Consequently, as demonstrated by Tardy et al. (1973), kaolinite and especially gibbsite occuring in open systems are good indicators of the drainage conditions. On the contrary, smectites found at the base of the lateritic profiles (in the coarse saprolites or arenes) are controlled by the specificity of the primary mineral closed microsystems and do not show any climatic significance.

The fine saprolite or lithomarge

Above the coarse saprolite is the fine saprolite (or lithomarge) in which the structures of the parent rock and the original volumes are still preserved (Leneuf, 1959; Millot, 1964; Tardy, 1969). The progress of weathering is petrographically expressed by an increase in porosity, a complete or partial transformation of most of the parent rock minerals and a decrease in induration of the rock (Tardy, 1969; Nahon 1986). Beside quartz, which dissolves slowly, and small pieces of resistant primary minerals remaining partly undissolved, the dominant species are secondary kaolinite and ferruginous hydroxides, oxyhydroxides and oxides (goethite, hematite and amorphous phases).

Finally, in the fine saprolites, located below the ground water level, there is no important loss or gain of aluminum or iron (Table 15.1), nor important migration observable under the microscope (Tardy and Nahon 1985). Compared to the glaebular horizon located above, in which element transfers are important, iron and aluminum, in lithomarges, are almost immobile elements.

Leaching or accumulation of iron and aluminum in lithomarges

There are three types of lithomarges, as related to movement of iron and aluminum: leaching, lixiviation or accumulation (Figure 15.3, Table 15.1).

A lithomarge sensu stricto, or an idealized lithomarge called a C horizon, the definition of which corresponds to the description given in the previous paragraph.

A leached lithomarge or lithomarge Ca_2, in which a_2 stands for an excess of leaching which corresponds to the definition of the pallid zone which includes: (a) the removal of iron around voids, canalicules and channels from a fine saprolite which locally becomes white, (b) out of these previously iron-poor areas, the removal of kaolinite which is either dissolved or mechanically leached, and (c) the dissolution or the mechanical transport of quartz which finally leads to the formation of some large cavities which may look karstic in origin (Tardy, 1969; Ambrosi and Nahon, 1986). Often, at the top of the fine saprolite and below the ferricrete, exists a horizon, rich in coarse grained quartz, depleted in fine grained quartz and kaolinite, and showing some convergence of characters with stone lines or with the A_2 horizon, described by Leprun (1979) as the result of dismantling a lower ferricrete horizon.

A lithomarge Ca_{2b}, in which the letter b stands for a secondary, either neoformed or deposited kaolinite, accompanied by goethite, filling the small or large karstic

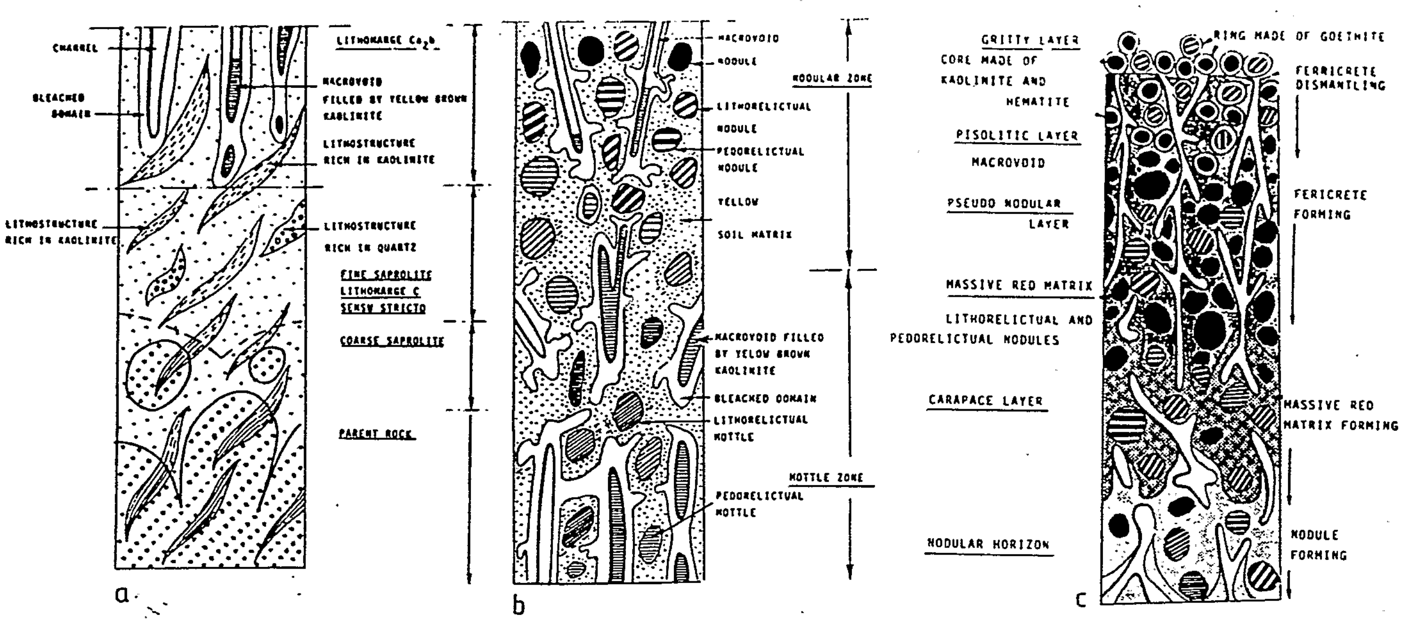


Fig. 15.3. a. Alteration zone: coarse saprolite or arène, fine saprolite or lithomarge (C horizon *sensu stricto*), leached lithomarge (Ca_2) and illuviated lithomarge (Ca_{2b}). b. Mottle zone and nodular horizon: channels, macrovoids, bleached domains, yellow-red soil matrix, litho- and pedo-relictual mottles and nodules. c. Ferricrete zone and surficial horizon: a progressive nodulation towards the top of the profile and a secondary development of pisolite close to the soil surface can be distinguished. Three types of nodules are distinguished: lithorelictual (white), pedorelictual (striped) and undifferenciated (black).

TABLE 15.1

Isovolumetric chemical balance (in g per 10 cm^3 of rock) of lithomarges and fine saprolites (horizon C), showing that some samples appear leached and depleted in both Fe and Al (Ca_2) while others appear enriched in kaolinite, goethite, Fe and Al (Ca_{2b})

Nature of rock	Density	Quartz	SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	CaO	MgO	Na_2O	K_2O	H_2O
Parent rock unaltered	2.60	70	188	35	6	0.08	0.5	4	1.5	10	12	1.0
Lithomarge C	1.40	60	93	28	5.5	0.03	0.8	0.2	0.2	0.1	0.2	12.0
(leached) Ca_2	1.20	55	87	25	2.0	0.01	0.2	0.1	0.1	0.1	0.1	8.9
(illuviated) Ca_{2b}	1.80	65	223	40	7.5	0.17	3.0	0.3	0.3	0.1	0.3	17.5
Lithomarge (calculated)	1.65	70	111	35	6	0.0	0.0	0.0	0.0	0.0	0.0	13.0
Mottle zone	1.49	54	93	33	8.0	0.03	0.9	0.3	0.3	0.2	0.1	13.5

Source: Tardy (1969).

cavities characterizing the lithomarge Ca_2. This accumulation, brown in color, contrasts clearly with the pale colour of the void and channel surroundings which often appear decolored (Tardy, 1969). When most of the initial porosity is filled, a massive saprolite is produced (Ambrosi and Nahon, 1986).

Lithomarges Ca_2 and Ca_{2b} both are located at the top of the fine saprolite zone, underlining the mottle zone.

Problems of terminology

In my opinion, fine saprolite, lithomarge, pallid zone and variegated clays refer to the same thing. They all designate the same quartz–kaolinite–iron oxyhydroxide formation, previously described. However, the two last terms produce possibilities of confusion and interpretive error.

The use of the term variegated clays (argiles bariolées) instead of lithomarge or fine saprolite (Leprun, 1979; Ambrosi, 1984) introduce risks of confusion with mottled clays (argiles tachetées) which are, genetically speaking, entirely different. Variegation was used to describe differences in colour due to the original distribution of iron-rich (biotites, amphiboles) and iron-poor (quartz, feldspars) primary minerals. Mottles are differences in colour due to a pedogenetic or a secondary redistribution of iron, removed from some domains and reconcentrated in other domains.

The distinction between mottle zone and pallid zone is due to Walther (1915). Nevertheless, the term pallid zone, introduced by McLaren (1906) and Simpson (1912), according to Prescott and Pendleton (1952) and McFarlane (1976), also creates confusion. In fact, it has been understood by definition as a zone, pale-colored due to leaching of iron, which is considered as the source of iron enrichment in the overlying mottle zone ferricrete. McFarlane (1976) has presented a series of arguments showing that this cannot be the case mostly because there are no relations between the thickness of the pallid zone and the amounts of iron accumulated above it, and also because some so called pallid zones do not show any iron release, according to the observations described below. Consequently both terms variegated clay or pallid zone should be avoided.

Smectitic saprolite and pistachio horizons

Under semi-humid or semi-arid conditions (rainfall < 1000 mm per year) within the coarse and the fine saprolites, a smectitic horizon called sometimes the pistachio horizon because of its pale green color, may be developed. This horizon is generally overlain by a smectitic soil in a dynamic equilibrium reflecting the local climate, that is, rainfall 800–900 mm per year, temperature 25–30°C, for a typical Vertisol (Bocquier, 1973). It may also be covered by a lateritic soil consisting of a lithomarge, a mottle zone and in some cases a carapace and a ferricrete. The pistachio horizon has been considered as secondarily developed, after the formation of the lateritic profile, in peculiar cases, when the climate has been changing from humid (laterite) to arid (Vertisol). The mechanism was observed in Senegal and in Burkina Faso by Leprun (1979) and also described by Boulet (1978), Pion (1979), Ambrosi (1984) and Ambrosi and Nahon (1986) (Figure 15.3).

In this case, the development of smectite, associated with kaolinite, invading a part of the fine saprolite has a climatic significance according to Tardy et al. (1973). This secondary development of underlying smectitic horizons is interpreted as one of the most probable mechanisms of the secondary degradation of the basal horizons of the ferricretes previously formed during humid periods and then subjected to semi-arid climates.

In summary, arene and lithomarge, equivalent to coarse and fine saprolites, are basal weathering domains (C horizons) in which (a) volumes of the parent rocks are preserved, (b) amounts of iron and aluminum and amounts of quartz are, conserved within 10%, and (c) porosity is due to the leaching of the alkaline, alkaline-earth elements, and silica in excess of that required to form kaolinite and to remain as primary quartz. At the top of the lithomarge *sensu stricto* (C horizon) one may observe additional leaching (Ca_2) or secondary enrichment (Ca_{2b}) of kaolinite and iron hydroxides. However, there are neither short scale movements nor reconcentration of iron and consequently no mottle formation. Both lithomarge Ca_2 and Ca_{2b} are transitional with the overlying mottle zone, they are part of the alteration zone and are not part of the glaebular zone which includes mottle and nodular horizons.

Fine saprolites or kaolinitic lithomarges can be very thick. Several tens of meters are not exceptional (McFarlane, 1976) and an order of magnitude of 100 m is not uncommon (Pham et al., 1988; Freyssinet, 1990).

Glaebular domains and the ferricrete profile

Under contrasted tropical climates (T = 25–30°C, rainfall = 1500 mm per year, 5 months of dry season, relative humidity of the air, HR, = 65%) and above fine saprolites and lithomarges, iron is generally redistributed and concentrated to characterize a glaebular zone, in which ferricrete may develop. A typical ferricrete profile consists of three major horizons: mottle zone, ferricrete itself (carapace and cuirasse) and, at the soil surface, a gritty layer and dismantling horizon.

Mottle zones and nodular horizons

The mottle zone is characterized by a contrast between bleached domains and Fe-mottles which can be easily distinguished on a centimeter scale, in outcrops and in samples, and on a micrometer scale, under the microscope (Figure 15.3).

Bleached domains consist mainly of quartz and kaolinite and exhibit a white or gray colour due to the de-ferruginization of the previously associated kaolinite and

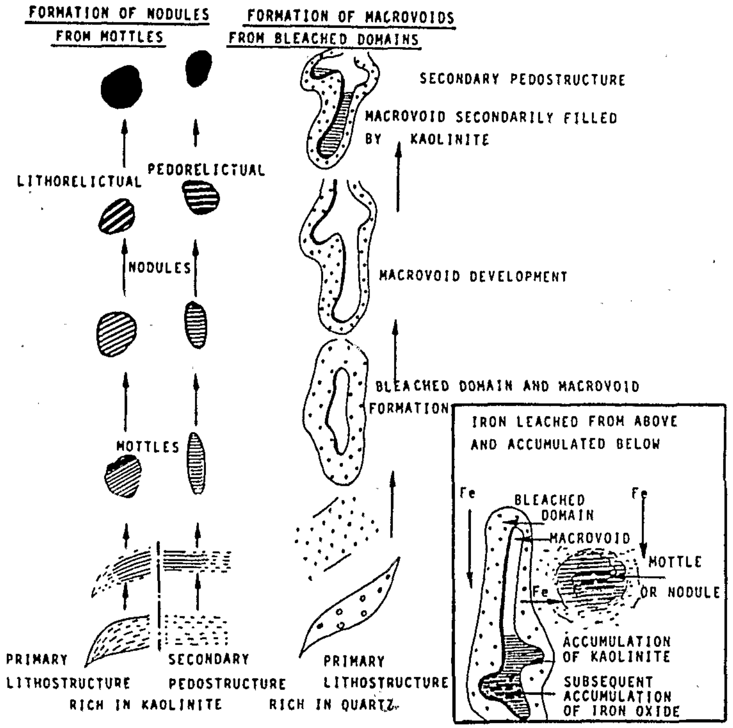


Fig. 15.4. Formation of mottles and nodules, in originally kaolinite-rich domains, leading to lithorelictual features developed in primary lithostructures and pedorelictual features, developed in secondary pedostructure. Formation of bleached domains, macrovoids and channels from originally quartz-rich domains. Secondary formation of pedorelictual mottles or argilomorphous nodules in previously formed macrovoids.

iron oxyhydroxides. Original kaolinite aggregates, free of iron, can be dispersed and kaolinite particles can migrate and even be leached out. These changes are accompanied by a strong increase of porosity, leading subsequently to the formation of macrovoids, such as tubules and alveoles. At that stage quartz also can precipitate in the generalized eluvial migration (Figure 15.4; Nahon, 1986). Quartz and kaolinite removal are probably due to termite activity (Eschenbrenner, 1987).

The de-ferruginization takes place in domains originally enriched in quartz and poor in kaolinite. It begins at the top of the fine saprolite (lithomarge Ca_2) and becomes progressively more important towards the top of the mottle zone, where channels and tubules are abundant (the mottle clay zone: "argile tachetée", which was sometimes called channel clay zone: "argile à canaux").

Fe-mottles, mostly of a brown red colour, are diffuse glaebules (Brewer, 1964) and result in a concentration of iron which precipitates mainly as goethite and as

hematite together with kaolinite. Thus, domains of previous accumulation of kaolinite are natural hosts for secondary accumulation of iron in mottles and nodules (Figure 15.4).

In the mottle zone, there are two situations in which kaolinite accumulation is the precursor of nodule formation: lithorelicts and pedorelicts.

Lithorelicts and pedorelicts. Lithorelictual mottles or nodules are iron accumulations in which the original structure of the parent rock can be seen (Figure 15.4). They are more accurately called alterorelicts by Faure (1985) and are mostly primary assemblages of aluminum and iron-rich minerals which, by alteration, give secondary stable associations of kaolinite and iron oxyhydroxides, in which porosity is small in size. This is the case for schists, amphibolites and layers of migmatite which are particularly rich in biotite, for example. Granitoid rocks including aplitic and quartzo-feldspathic veins, initially poor in iron and consequently sensitive to leaching of kaolinite, are not ideal parent rocks for the further accumulation of this element.

Pedorelictual features (or pedorelicts) are due to secondary accumulation of kaolinite, filling voids previously created in the bleached domains. They are relicts of soil forming processes. Kaolinite, derived from solution or translocation from overlying upslope layers, followed by precipitation or deposition lower in the profile. These secondary accumulations of kaolinite and associated quartz are generally accompanied by a secondary accumulation of iron-generating brown-red colored clays, providing a contrast with the white-gray decolored areas, located around the tubules and channels (Nahon, 1986). Higher in the ferricrete, these mottles evolve into nodules as accumulation progresses. They are what Nahon (1976) has called the argilomorphous nodules, which are old voids, filled by kaolinite and iron oxyhydroxide. Mottles and nodules of this kind are traces of the secondary pedogenetic activity occuring in the unsaturated zone. In the nodular zone, lithorelicts are more abundant on schists and amphibolites while pedorelicts dominate on sandstones and granitic rocks rich in quartz (Figure 15.4).

Towards the top of the profile, the mottle zone evolves towards either a nodular horizon (Ambrosi et al., 1986) or a ferricrete (Figure 15.3; Nahon, 1976).

The ferricrete formation

The ferricrete profile has been described by Nahon (1976), Nahon et al. (1979) and Leprun (1979). Its mechanism of development has been studied and interpreted by Didier et al. (1983a, b, 1985), Tardy and Nahon (1985), Nahon (1986), Muller and Bocquier (1986) and Ambrosi et al. (1986).

Above the mottle zone and the non-indurated nodular horizon, one finds successively, from the bottom to the top, variously indurated horizons (Figure 15.3).

Carapace is intermediate between mottle zone located below and cuirasse located above. It corresponds to a progressive accumulation of iron and as a consequence, to a progressive development of hematitic iron nodules, either pedorelictual or lithorelictual. The bleached zone is progressively reduced in size, so that the yellow-white colored domains decrease in size while the purple-red indurated domains enlarge and develop.

Cuirasse or *ferricrete* or *iron duricrust sensu stricto* is indurated, purple-red in color, considerably enriched in iron, particularly in hematite. In ferricrete *sensu stricto*, the bleached zones are almost absent. Furthermore channels may be reduced in size but always survive in abundance. The edges of the channels often appear lined by iron accumulations in which goethite dominates. The channels are commonly empty but may be filled by kaolinite and fine quartz. They are progressively transformed into argilomorphous, pedorelictual nodules in which iron accumulates as hematite (Nahon, 1976).

Towards the soil surface, and from the carapace to the cuirasse, in the discontinuous iron accumulation horizon, hematitic nodules grow and join each other in a way recognized by McFarlane (1976) as the major process of ferricrete formation. However, there are domains in which the clay matrix surrounding the early formed nodules is itself invaded by iron (also as hematite) so that in certain circumstances the resulting ferricretes form an almost continuous accumulation of iron in a kaolinite plasma. This results in a massive structure which may or may not be crossed by large voids and channels. This facies of ferricrete is called for that reason massive and vacuolar, and generally is the most evolved, that is the richest in iron, in hematite, in kaolinite and the poorest in quartz, if present in the original parent rock. The massive ferricrete is equivalent to the *faciès gréseux simple* defined by Nahon (1976) on quartz-rich sandstones.

The ferricrete dismantling horizon. Towards the top, a new system of secondary voids is developed. The hematite–kaolinite nodules are rehydrated and corroded at their edges. Kaolinite is dissolved and Al-hematite is transformed into Al-goethite. A goethitic cortex (concentric yellow brown) develops at the periphery of the purple-red hematitic nodules. The ferricrete facies becomes either pseudo-conglomeratic if blocs are present, sometimes recemented by goethite, or pisolitic if single nodules are individualized (Nahon, 1976).

In summary, a ferricrete is a glaebular domain made of several successive horizons: a mottle zone, a nodular non indurated horizon, a carapace and a cuirasse, massive, pseudonodular, nodular and pisolitic. All these horizons are parts of a single destruction–formation system.

The gritty layer of surface dismantling

A gritty horizon is developed at the top of the profile, made of the products of the dismantling of the pseudoconglomeratic or the pisolitic-underlined ferricrete. At the soil surface, over the indurated horizon, two kinds of soft materials are accumulated locally: (a) surficial sandy or silty layer made of corroded quartz liberated by the dissolution of the ferricrete, and mixed with (b) pebbly layer which develops at the expense of the pisolitic iron crust and which comes from the early formed hematitic nodules. The size of the pebbles diminishes with time while goethite develops at the expense of hematite. Iron, aluminum and silica leached from the surface in the dismantling upper horizon precipitate in a deeper horizon and thus reconstitute the ferricrete below. The formation of gritty layers at the surface is a component of ferricrete metabolism and is an essential phase of its reconstitution.

The A_2 leached horizon and sub-surface ferricrete dismantling

Below the ferricrete, the top of the lithomarge and the lowest part of the mottle zone often appear decolored and leached, so that a stone-line (labelled A_2) made of large quartz grains, underlies the carapace and the ferricrete and sometimes replaces entirely the mottle zone. The impoverishment of all of the fine fractions in a coarse material characterized by a high permeability over a lithomarge richer in clay and less permeable, produces a perched water table. Here, water circulates laterally and creates a reduced zone where iron is solubilised. This leads to the destabilization of iron-kaolinite aggregates, which induces the leaching of the kaolinite particles (Chauvel, 1977) and the dismantling of the overlying ferricrete. In humid regions, the A_2 horizon may be attributed to termite activity inducing a selective upward and downward motion of fine material (Eschenbrenner, 1987). In less humid regions, close to the Sahelian fringes, this phenomenon, described by Leprun (1979) is general. In dry climate areas, the pistachio smectitic horizon, sometimes well developed, may also induce a lateral circulation of ground water high in the profile, favorable to a sub-surface dismantling of ferricrete previously formed under more humid climates (Leprun, 1979).

Terminology

Mottle zones, nodular horizons, nodular ferricretes (carapace or cuirasse) and pisolitic horizons are all part of the glaebular zone. Glaebules are three dimensional units within the s-matrix, recognized in this case by a greater concentration of iron, the edges of which are either sharp (nodules) or diffuse (mottles) (Brewer, 1964). Clearly, the mottle zone is a part of the glaebular zone. Chatelin (1972) has introduced a distinction between alterite and alloterite. The first stands for saprolites and was extended to mottle zones in which the parent rock structures are distinguishable and the original volume is conserved. They are clearly isovolumetric alterations in the sense of Millot and Bonifas (1955). Alloterite, on the contrary, stands for horizons in which the original primary architecture of parent rocks is destroyed. Thus, in most cases, carapaces, cuirasses and more generally bauxites and ferricretes can be considered as alloterites (Boulangé, 1984). Herbillon and Nahon (1988) have distinguished two major zones: a relative accumulation zone including most saprolites and in some cases, mottle clays, and an absolute accumulation horizon including all the ferricrete layers. Muller et al. (1981) have described a mottled alterite distinct from a nodular zone, so that a certain ambiguity is introduced, concerning a possible difference between mechanism of formation of mottles in mottle zones and nodules in nodular horizons. Mottles and nodules form in response to an identical filiation process. Both diffuse mottles and sharp edged nodules are glaebules, so that mottled zone and ferricrete must be included in the glaebular zone. Despite this, the so-called mottled clay horizon is generally isalteritic, though the results of the beginning of the mobilization and the absolute concentration of iron can be seen.

An essential distinction is proposed between (a) coarse and fine saprolites, permanently located in wet conditions, below the ground water table and in which little if any movement of iron is detected, and (b) mottle zones, nodular horizons and ferricretes, located in the unsaturated domain, seasonally hydrated and dryed, in which mass transfer of iron is currently observed.

Conclusion: ferricrete metabolism

An iron crust is generally built at the top of the lateritic mantle by a combination of successive small-scale migration of iron, leaching or dissolution of kaolinite and quartz grains, formation of voids, secondary accumulation of kaolinite together with small quartz crystals, and ferruginization of these accumulations (Nahon, 1986).

Several remarks can be added.

(a) Despite some lateral and upward vertical movements, particularly observed downslopes, where the water table is close to the soil surface, the transfers of iron and aluminum are supposed to be essentially vertical and downwards.

(b) Kaolinite-rich domains are selective hosts for hematitic iron accumulations. They evolve towards lithorelictual nodules if kaolinite accumulation comes directly from the original parent rock (lenses of schists, mica-rich layers in migmatites, aluminous-rich domains in basic rocks) or towards argilomorphous pedorelictual nodules if kaolinite comes from a secondary accumulation either by neoformation or by mechanical deposition in the macrovoids. They are small sized porous domains, in which thermodynamic activity of water is commonly low (Didier et al., 1983a, b; Tardy and Nahon, 1985).

(c) By contrast, primary quartz-rich domains appear as selective sites for decoloration, deferruginization and destabilization of the iron-clay aggregates. Consequently, they are also privileged sites for chemical or mechanical leaching of quartz grains and finally for creation of channels, glosses and zones of water circulation. They appear generally to have large pores and are seasonally filled by water of high thermodynamic activity, close to the conditions of saturation (Tardy and Novikoff, 1988).

(d) Finally these two types of facies taking over from one to another in space, are the two privileged sites for the two simultaneous stages of ferricrete metabolism: (1) a destructive or dismantling stage in which dissolution and degradation takes place close to the soil surface, in pores of large size temporarily hydrated, together with (2) a formative or a reconstitutive stage in which precipitation concretion and nodule formation takes place in clay-rich and small sized pore domains of deeper horizons temporarily dehydrated. In the first case (1) of the process, goethite, a hydrated mineral, prevails, while in the second case (2), hematite, a dehydrated mineral, dominates. The first stage (1) takes place during the wet season and is dominated by circulation in pores of large diameter, leaching and reactions occuring in saturated domains and high water activity. The second stage (2) takes place during the dry season and is dominated by imbibition and impregnation of pores of small size, occuring in unsaturated domains and low water activity.

The soft zone

In tropical areas a large number of glaebular soils are capped by a soft horizon (Figure 15.2), the origin of which is diverse or subject to different interpretations.

Three possible origins

In some regions, such as Amazonia for example (Lucas, 1989), the soft horizon is very thick (several meters) and is regularly and widely distributed. This so called "argilla de Belterra", 2–10 m thick, has been alternately considered either as a sedimentary cover (Sombroek, 1966; Tricart, 1978; Putzer, 1984; Truckenbrodt and Kotschoubey, 1981) or as an *in situ* alteration of the sedimentary parent rock (Chauvel et al., 1983; Irion, 1984). The question is not yet settled.

In Africa, soft horizons cover large tropical or subtropical areas, overlying in most cases, a glaebular zone or a ferricrete. In the latter situation the soft horizon or the surficial sandy layer, non indurated and characterized by a relative accumulation of primary minerals such as quartz, or secondary minerals such as kaolinite and goethite, generally shows some geochemical relationship to the underlying ferricrete and has been considered as an *in situ* dismantling product (Nahon, 1976; Leprun, 1979; Muller et al., 1981; Rosello et al., 1982; Chauvel et al., 1983; Fritsch, 1984; Bocquier et al., 1983). However, despite a surficial degradation of the underlying ferricrete, the soft horizon as a whole cannot entirely derive from the ferricrete. The soft horizon may be due to upward transfer of material coming from the mottle zone, by termite activity.

Concretion and pisolite formation in Ultisols or Oxisols

Concretions and pisolites are widespread in non-indurated laterites (Maignien, 1958; 1964; Martin, 1967; Stoops, 1968; McFarlane, 1976) and nodular soils are widely distributed in South America and in Africa (d'Hoore, 1963).

In western Africa, they appear distributed in two major climatic zones (Maignien, 1958). The first zone corresponds to the highly contrasted tropical climates under which Ultisols (sols ferrugineux tropicaux) show a B horizon enriched in kaolinite, in which mottles, ferruginous concretions and nodules are currently developed (Maignien, 1958; Fauck, 1973; Leveque, 1975; Boulet, 1978; Leprun, 1979). The second zone corresponds to humid tropical climates under which Oxisols (sols ferrallitiques) also show a nodular or pisolitic horizon (Martin, 1967).

These kinds of soft but nodular Oxisols or ferralitic soils have been extensively described by Muller et al. (1981) in Cameroon, Gabon and Congo, and by Eschenbrenner (1987) and Eschenbrenner and Badarello (1987) in Ivory Coast, all regions subjected to humid tropical climate.

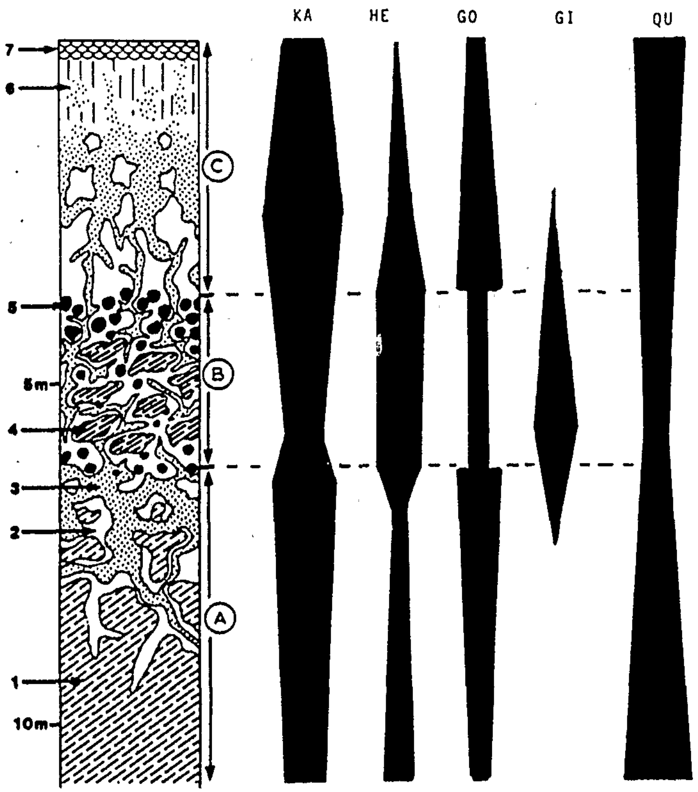


Fig. 15.5. Nodular Oxisol profile in Cameroon (from Muller, 1987). Distinguishable are the alteration zone (*A*), the glaebular zone (*B*) and the soft horizon (*C*) and within them: (*1*) saprolite with inherited rock structure and texture; (*2*) red and compact matrix; (*3*) yellow and friable matrix; (*4*) ferruginous lithorelict; (*5*) argilomorphous nodules; (*6*) yellow and compact matrix; (*7*) organic matter accumulation (from Muller and Bocquier, 1986). The mineralogical distribution of kaolinite (*KA*), hematite (*HE*), goethite (*GO*), gibbsite (*GI*) and quartz (*QU*) (from Muller, 1987).

Muller (1987) described in detail the soil-sequence of Goyoum in the Eastern part of Central Cameroon. Above the fine saprolite, the glaebular domain comprises a red hematitic clay in which dark red nodules are individualized. The soft red clay is, diffusely impregnated by hematite and goethite (hematite > goethite), associated with kaolinite in microstructures. Within the soft red clay matrix two types of nodules are developed: (a) argilomorphous, with a structure similar to that of the clay matrix, or (b) lithorelictual, showing a structure similar to the petrographic organization of the parent rock. Nodules are in general made up of an assemblage of kaolinite and hematite. Towards the top of the profile, the red clay matrix becomes progressively yellow and goethite dominates over hematite. The hematitic nodules are surrounded by a goethitic cortex the thickness of which also increases towards the top of the profile. Close to the soil surface, the red nodular horizon is dismantled and replaced by a soft clayey horizon, made of an assemblage of goethite, kaolinite and quartz.

In Ultisols nodules or pisolites can be of two different origins: (a) either (Figure 15.5) they are relatively recent secondary nodules growing within the clay-rich soil matrix, en route to the development of a ferricrete, and following a similar process of accumulation of iron as hematite; or (b) they are primary hematitic nodules generated by a secondary disagregation of older ferricretes, today covered by a soft goethite–kaolinite horizon and en route to being dismantled through the formation of a nodular stone-line. The first process is generally accepted and nodular oxisols are often considered as the precursors of the ferricrete (McFarlane, 1976, 1983). The second was recently discovered with the realization that the equatorial rain forest was previously underlain by ferricretes which are now being dismantled (Novikoff, 1974; Tardy et al., 1988; Martin and Volkoff, 1989; Nahon et al., 1989).

Oxisols with no glaebular development

Mohr et al. (1972) state: "typical oxisols without plinthite are deep, friable soils. Horizon differentiation is indistinct and there is generally no clay movement. These soils are porous and are rapidly drained. The oxic horizon does not harden upon exposure to air; there is no segregation of iron; its distribution is very homogeneous and concretions are absent or near absent. If the solum is very deep, it is sometimes underlain by a mottle clay horizon. Otherwise the solum lies directly on the weathered rock", that is on the lithomarge or the fine saprolite. These red ferralitic soils, also known in Brazil as Latosols, are developed on various parent materials under humid tropical or equatorial climates in regions covered by rain forest and particularly in the well drained upslopes of landscapes (Chauvel, 1977; Volkoff, 1985); they typically show a micronodular structure made up of an assemblage of kaolinite and quartz cemented by iron oxides (Figure 15.6; Bennema et al., 1970; Pedro et al., 1976; Chauvel and Pedro, 1978a, b).

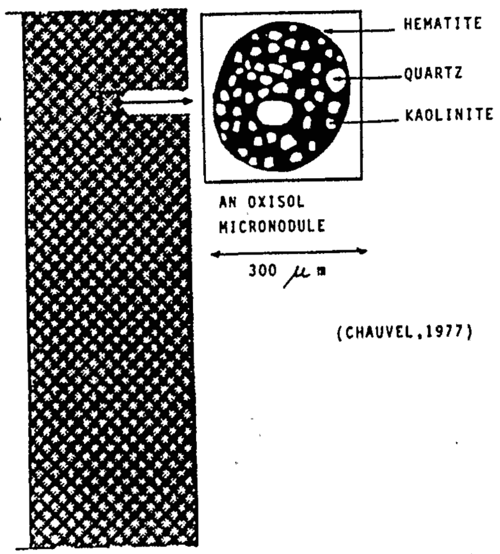


Fig. 15.6. Typical Oxisols do not generally show clay movements, colour gradients and subsequent horizon differentiations. Because of their micronodular structures made up of an assemblage of hematite, kaolinite and quartz, they are porous and characterized by rapid drainage (from Chauvel, 1977)

There are few studies devoted to the composition of iron minerals in these kinds of soils. As suggested by the red colour they are mixtures of ferrihydrite, goethite and hematite (Schwertmann, 1988). Gibbsite is also common and sometimes abundant in Oxisols or Latosols (Sieffermann, 1973; Bourgeat, 1972). The mineral distribution within the profile is a function of depth: hematite increases towards the top of the soil-surface while kaolinite or gibbsite may either increase or decrease (Leneuf, 1959; Schellmann, 1964; Sieffermann, 1973; Delvigne, 1965; Mohr et al., 1972). Furthermore Volkoff (1985) pointed out that the mineralogical composition may depend on the nature of the parent rock: kaolinite, hematite, gibbsite on basic rocks; quartz, kaolinite, goethite on sandstones.

Lateritic bauxites

A bauxite is a thick accumulation of aluminum resulting from long term lateritic weathering under humid tropical or equatorial climates (Millot, 1964; Valeton, 1972; Bardossy, 1982; Boulangé, 1984; Lucas, 1989).

The rainfall required for the separation between a ferricrete and a bauxite is probably about 1700 mm a year. Above this limit, ferricrete dismantling takes place while gibbsite forms, develops and accumulates. The humidity of the air and temperature are also determinant factors. Ferricrete and iron accumulation are favored

by a relatively low thermodynamic activity of water and relative humidity of the air ($HR = 60\%$, annual average) and high temperature ($T = 28°C$) while bauxite and aluminum enrichment can stand lower temperature ($T > 22°C$) and are favored by a higher thermodynamic activity of water and a higher relative humidity of the air ($HR > 80\%$; Tardy and Novikoff, 1988; Tardy et al., 1988a, b).

Some of these lateritic bauxites are very old and have been evolving under various tropical climates, since the Jurassic, the Cretaceous, the Paleocene or the Eocene (Michel, 1973). Others are younger and may have formed since the Miocene, the Pliocene and even the Quaternary (Bardossy, 1979). Lateritic bauxites are widespread all around the world and appear under different latitudes.

The old bauxitic profiles which have been submitted to climatic fluctuations show in general a large variety of petrographical facies and a high complexity of mineral distribution.

Distribution of gibbsite

Several lateritic bauxite profiles, representing quite a large variety of situations, were recently described by Boulangé (1984) and by Lucas (1989). Most profiles show two different gibbsitic layers. The first one occurs in the coarse saprolite at the bottom of the profile and close to the contact with the parent rocks. The second one, bauxitic, *sensu stricto* is located at the top of the profile close to the soil surface. In between, a kaolinite-rich horizon, from which gibbsite may be absent, appears similar to the fine saprolite or lithomarge already described. However other situations are also described. In some cases only kaolinite is found in the coarse saprolite, while in others, gibbsite may occur all through the profile. In the latter situation, kaolinite, always present in the fine saprolite, disappears in the bauxite (Figure 15.6).

The bauxite zone itself occurs in different major facies. The most classical bauxitic profiles show the development, more than 10 to 15 m deep, of a massive gibbsitic accumulation. Towards the top, vacuoles develop within a goethite–gibbsite yellow plasma while nodules red in color, made of an assemblage of hematite–gibbsite, are individualized (Boulangé, 1984). The formation of pisolites is not observed.

The second type remarkably, shows a secondary development of boehmite together with a large formation of pisolites (Tardy et al., 1988a, b).

Secondary formation of pisolites and boehmite

Boehmite forms in some bauxitic profiles, particularly those located close to the edges of a plateau and in an horizon close to the soil surface. When this occurs, the gibbsite–hematite original plasma is reorganized into pisolites and a strong segregation of hematite is observed.

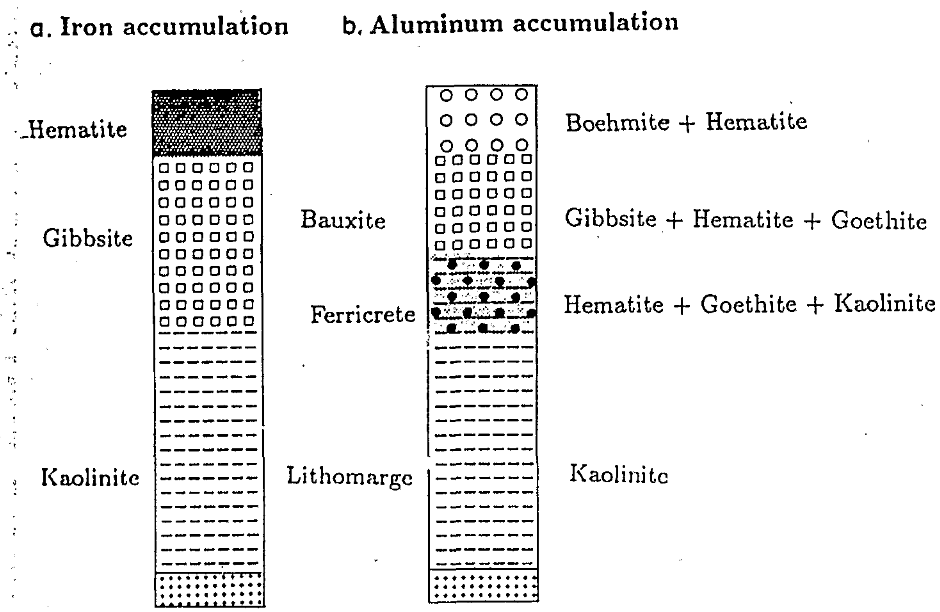


Fig. 15.7. Distribution of iron and aluminum in bauxites: iron generally tends to accumulate close to the top of gibbsitic profiles (a), while it tends to concentrate at the bottom of boehmitic profiles (b).

These pisolites rich in boehmite are progressively transformed towards the soil surface and secondarily surrounded by cortex, septarias and a cristalliplasma of gibbsite. In an intermediate horizon together with the formation of nodules of boehmite and hematite, dehydrated minerals form in abundance. This layer is interbedded between two horizons in which gibbsite, a hydrated mineral, is formed (Figure 15.7).

Distribution of hematite and goethite

In both the coarse saprolite and the fine saprolite, goethite is more abundant than hematite, while in the bauxitic layer hematite dominates goethite. Furthermore, when boehmite develops, goethite disappears and hematite is the single iron-rich mineral present. This distribution, frequently observed in West African alteritic bauxites (Boulangé, 1984) is similar to that frequently described by Combes (1969) and by Bardossy (1982) in karst bauxites of the South of France, Hungary and Greece.

Conclusion

Aluminum and iron are distributed from the bottom to the top of the profiles, in two mineral sequences:

gibbsite (1) – kaolinite – gibbsite (2) – boehmite – gibbsite (3)
goethite (1) – hematite – goethite (2)

These are ideal sequences and not every layer is always present. However, in both cases, hematite and boehmite which are dehydrated or relatively dehydrated minerals are generally located between more hydrated phases, (goethite and gibbsite).

The gibbsitic profiles developed under humid tropical or equatorial climates are often capped by an iron rich horizon (Grandin, 1976). By contrast, gibbsitic horizons which were later transformed into boehmitic horizons under seasonally contrasted tropical climates are dominantly poor in iron. As a consequence of this secondary change, iron previously accumulated close to the surface moves down below and a ferricrete develops at the bottom of the profile (Figure 15.7).

Conclusion

Lateritic profiles show a kaolinitic lithomarge or in some cases a bauxite at their base. Above the lithomarge either a bauxite or a ferricrete or a lateritic soil develops.

Eight different lateritic soils can be described (Figure 15.8).

(a) Pale colored Oxisols, with a thick surficial horizon, poor in kaolinite and rich in quartz. These soils are developed on sandstones and quartz-rich parent rocks. They may present some characteristics of tropical podzols.

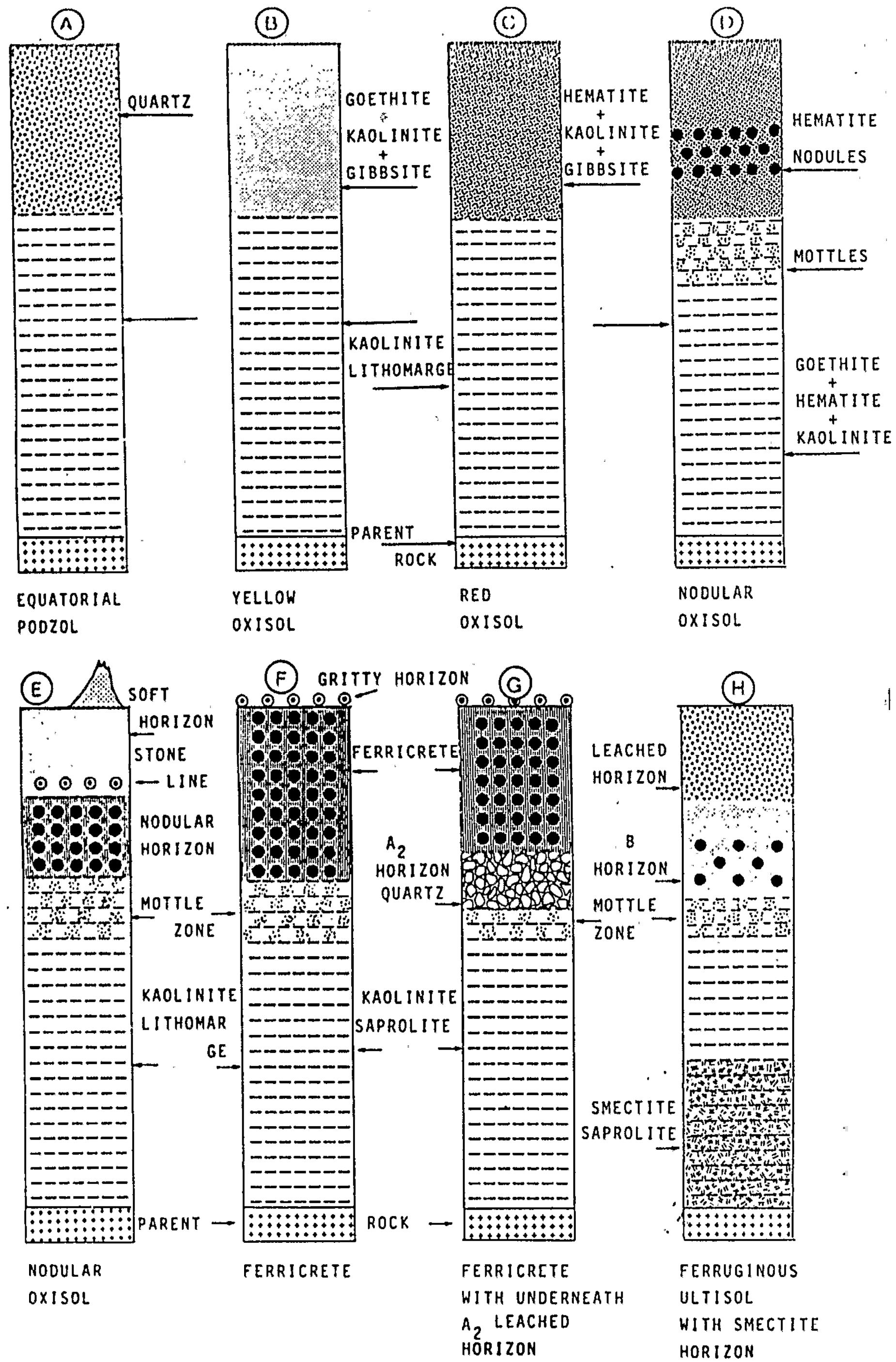
(b) Yellow Oxisols, primarily rich in kaolinite and goethite, with quartz and gibbsite as accessories, are located on quartz-poor rocks particularly on downslope setting of the landscape.

(c) Red Oxisols primarily rich in kaolinite and hematite, with quartz and gibbsite as accessories, are found in the upper slopes of a landscape.

(d) They may or may not have a glaebular horizon, associated in the latter case only with a mottle zone.

(e) Ferricrete profiles may be covered by sandy surficial horizons originating from termite activity leading to the subsequent dismantling of hematitic duricrusts, the product of which remains within the soft horizon as a relictual nodular stone line.

(f) Ferricrete profiles may show the development of sandy, quartz-rich, bleached horizons forming stone lines at the top of mottle zones and leading subsequently to sub-surface dismantling of iron duricrusts.



(h) Beige Ultisols show the development of surficial leached horizons (A_2) overlying horizons (B) in which kaolinite accumulates and in which mottles and hematitic nodules subsequently develop.

All these soils are laterites, characteristic of a large variety of present-day climate, paleoclimates, parent rocks, topographic positions and hydrologic regimes.

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Fig. 15.8. Sequence of lateritic soil profiles from Oxisols (*A*, *B*, *C*, *D*) to iron duricrust (*E*, *F*, *G*) and Ultisols (*H*). In the oxisol group and above the lithomarge and fine saprolite, ferrallitic soil is either pale and made of quartz (*A*), yellow and made of quartz, kaolinite, gibbsite and goethite (*B*) or red and made of quartz, kaolinite, gibbsite and hematite (*C* and *D*). In the ferricrete group some of the profiles are covered by a sandy horizon which may be originated from termite activity (*E*) and some others present a leached horizon below the ferricrete (*G*). Deep saprolites located below Ultisols may present a pistachio colored smectitic horizon (*H*).

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