The CORLAT Handbook

Draft Version 1.2

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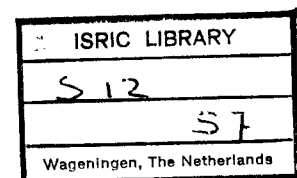
INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

The

CORLAT

Handbook

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Title: CORLAT Handbook

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Proposed subtitles

Guidelines and background information for the description of laterites and laterite profiles for interdisciplinary use

Plinthites, laterites, bauxites, ferralites; an effort to definitions and descriptions for interdisciplinary use

Guidelines and background information for the definition and description of in situ weathering products in humid tropical climates (laterite, ferralite, plinthite, etc.); an interdisciplinary effort

Lateritization, ferralitization, bauxitization and plinthisation

Laterite, bauxite, plinthite, ferralite and other weathering-related surficial deposits. An effort to provide interdisciplinary guidelines for their description and the related nomenclature

PROLOGUE

Laterites are curious rocks and difficult to define — see Table II.

They were recognized as representing something different by the medical doctor Buchanan (1807): he suggested the name laterite, from *later*, the Latin word for brick.

Later, laterites were studied by geologists, e.g. Lacroix (1913), Fox (1932), Fermor (1911), Harrison (1898, 1910), by soil scientists e.g. Van Bemmelen (1904), Alexander & Cady (1962), and by geographers/geomorphologists, e.g. Walther (1889, 1915), McFarlane (1976).

The representatives of each of these disciplines recognized the relation of laterite with the surface of the Earth and with climates different from those of the present. As a result, laterite became — for some scientists — synonymous with iron crusts, or markers of planation surfaces, or fossil soils. As each discipline contributed to the now existing descriptive terms, there exists some confusion in terminology. It should be possible to resolve this by adhering to the mostly clear, original definitions of the terms used.

Weathering, for the geologists, is the re-equilibration of the mineral assemblages (paragenesis) of a rock, mostly representing high temperature and pressure domains (igneous rocks and gneisses), to the chemical and physical circumstances that reign at or near the surface of the Earth, e.g. ~ 1 atmosphere = $101\ 325\ Nm^{-2}$, and 0 - 30 °C, variable humidity up to ~ 100% relative humidity, and sufficient rainfall (> 1200 mm/annum) to promote leaching and the removal of soluble weathering products from the actual site of weathering. In addition, organisms are present at the surface; they die, and their remains decay, producing organic acids which promote the leaching processes.

Pedogenesis is the term used by soil scientists to indicate the processes of soil formation, which is the transformation of the local, partially weathered rock under the influence of the atmosphere and living organisms, into soil, the substratum for most types of vegetation.

In other words, weathering *sensu lato* is a precursor of pedogenesis *sensu lato*, with the main difference that weathering is studied by geologists in a centrifugal way (from the earth's core outward to the surface) and pedogenesis by soil scientists in a centripetal way (from the surface downward).

Additional confusion resulted from the influence of the Pleistocene glaciations with their severe influence on the earth's climates: temperature and humidity, the two main factors controlling the speed of chemical reactions, hence mineral re-equilibration. The glaciations also caused a break — or at least a discontinuity — in the weathering profiles, and this discontinuity more or less marks the boundary between the geologist's laterite and the pedologist's soil, including its plinthites with their skeletic phases.

Warning: This draft for the CORLAT Handbook has been compiled and largely written by a geologist, originally specialized in the petrology of igneous and metamorphic rocks.

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1. Introduction

A renewed interest in laterites and their formation was initiated by the International Geological Correlation Project No. 129 – Lateritization Processes (1975-1983). The project generated two symposia (with Proceedings) and a Final Report:

(i)   Trivandrum 1979, India (Verkatesh & Raman, eds., 1981);
(ii)   São Paulo 1982, Brazil (Melfi & Carvalho, eds., 1983);
(iii) Final Report "Lateritisation Processes" (Banerji, ed., 102 pp, 1986).

Also related to the IGCP Project were the following Congresses:

(iv)   ICSOBA Congress 1985, in Tapolca, Hungary (Traveaux, 1987);
(v)   ICSOBA Congress in São Paulo & Poços de Caldas, Brazil, 1988 (Lahodny-Šarc, ed., 1989),

At the 2nd International Seminar on Lateritization Processes, São Paulo, Brazil, 1982, the meeting recommended that ISRIC at Wageningen should start the preparation for the establishment of an Interdisciplinary Laterite Reference Collection (CORLAT).
The purpose of the Collection is to provide reference materials and guidelines for classification of laterites, using a rational descriptive terminology. The potential users of the collection include geologists, mineralogists, soil scientists, geomorphologists, and the practical users of these sciences, such as civil engineers, agronomists, etc.

By far the most common laterites have an iron/aluminium composition, resulting from the weathering of acid to fairly basic igneous, metamorphic and sedimentary rocks, if not specified otherwise, these are the laterites discussed in this book. There are other types of parent rock that produce laterites, be it of considerably deviating nature: peridotites (nickel laterites), highly manganiferous rocks and iron formations. They are not discussed in detail in this text because of their, in some respects, deviating characteristics.
For the terms and words marked with an asterisk (*), an explanation or definition is given in the Glossary at the end of this book.

1.1 Interdisciplinary use

This text has included in its title the qualification: "for interdisciplinary use". It is all but impossible to use – throughout these guidelines – only those terms which have exactly the same meaning in all related disciplines. Creating new terms, or redefining the existing ambiguous terms, does not seem an acceptable solution for this problem – it would only add another term to the already large technical vocabulary.
When perusing guidelines for description in related sciences, e.g. the Handbook for Soil Thin Section Description (Bullock et al., 1985; published under the auspices of the International Society of Soil Science), it appears that – in soil science – there is only one term which is defined in a way clearly deviating from its definition in petrology, viz. the term "texture".

The Glossary of Geology (Bates & Jackson, 2nd edition, 1980) explains the difference with the following entries (following the order in which they appear in the Glossary):

"*Texture (petrology)** The general physical appearance or character of a rock, including the geometric aspects of, and the mutual relations among, its component particles or crystals, e.g. the size, shape, and arrangement of the constituent elements of a sedimentary rock, or the crystallinity, granularity, and fabric of the constituent elements from an igneous rock, The term is applied to the smaller (megascopic or microscopic) features as seen on a smooth surface of a homogeneous rock or mineral aggregate. The term *structure* is generally used for the larger textures of a rock. The two terms should not be used synonymously, although certain textural features may parallel major structures. Confusion may arise because in some languages, e.g. French, the usage of *texture and structure* are the reverse of the English usage."
"*Texture (soil)*. The physical nature of the soil according to the relative proportions of sand, clay and silt."

Brewer (1964) suggested the term 'field grading' instead of texture, as the particle size distribution is the essential characteristic of soil texture. The term is derived from the practical field procedure to determine this characteristic.

In Bullock et al. (1985), page 95, 'texture' only occurs in connection with pedofeatures: "textural pedofeatures are pedofeatures consisting of accumulations of particles of any size and in variable proportions."
And "pedofeatures" are defined as "discrete fabric units present in soil materials recognizable from adjacent material by a difference in concentration in one or more components, e.g. a granulometric fraction, organic matter, crystals, chemical components or internal fabric".
And 'fabric' or 'soil fabric' refers to "the total organization of a soil, expressed by the spatial arrangements of the soil constituents (solid, liquid and gaseous), their shape, size and frequency, considered from a configurational, functional and genetic viewpoint" (page 17).

In the FAO Guidelines for Soil Description (FAO, 1990), under the heading 2.3.1 Texture of fine earth, the ISO particle size classes of fine earth, i.e. < 2 mm, are given, followed by the names and codes of the soil texture classes, wich were taken from those of the Manual (Soil Survey Staff, 1951).

The following convention will be used to handle this distinct difference in the meaning of "texture" between Geology and Soil Science (and other such instances will be solved similarly):

In places in the text or figures, where confusion might occur with respect to the meaning of the term 'texture', this will be prevented by using the prefix 'rock' in case the geological meaning of the term is meant, e.g. in Annex IIIa, group C is marked as *rock textures,* i. e. the geological meaning of texture, see above under "texture (petrology)". Where the soil science's meaning of texture has to be specifically indicated, the prefix 'soil' will be used. This procedure will be followed for all terms and at all places where confusion might exist.

Annex III provides detailed suggestions for the consistent description of lateritic rocks, including structures, textures, pisoids, voids, and also a terminology to describe physical condition and abundance.

1.2 The place of laterite and plinthite in the family of rocks

In geology, three major groups of rocks are distinguished: igneous, metamorphic, and sedimentary rocks, each having their own, more or less well defined physical environment of formation.

Pedology studies the impact of the physical and the biological environment on the upper layers of the earth, i.e. the formation of soils and their degradation as a substrate for the natural vegetation or the growth of crops.

In the past, and at various times, large surfaces of the earth crust have been exposed to the atmosphere, which must have resulted in the formation of reaction products comparable to present day soils, taking into account the principles of uniformitarism (actualism). Some of these products have been fossilized and may be discernable in the rock record of the earth crust: among them laterites and saprolites.

Table I — Characterization of rock-forming processes at or near the surface of the earth, gives an overview of the most common of these rocks or soils, with a short description (in horizontal direction: starting material —> processes at work —> resulting rock with rock name, while vertically the succession in time of the processes and the resulting rocks are indicated. However, Leprun (1979) has shown that a clayey, montmorillonitic layer at the base of the laterite must have been formed *after* this laterite layer was already in existence. At the base of the chart the solid rock is indicated, the parent rock at the time the environmental actions/reactions started, i.e. magmatic, sedimentary or metamorphic rocks,

The chart clearly separates the plinthites and their hardened phases from the laterites, but the separation is essentially a separation in time. Soils are generally of recent to sub-recent age, while laterites generally seem to be older than the Cainozoic periods of glaciation with their extreme changes in climate world-wide.

Table I

Table I. Characterization of rock-forming processes at or near the earth surface

AGE and REALM	STARTING MATERIAL	PROCESSES and RESULTS	ROCK NAME
Recent to subrecent realm of soil taxonomy	Surficial, in situ, mineral and organic matter transformed by various recent environmental processes (chemical, physical & biological)	Soil with continuous layers of indurated material, Fe as important cement, organic matter absent	Petroferric phase
		Soil with ≥ 40 % coarse oxidic concretions of hardened plinthite fragments, ironstone, etc., ≥ 25 cm thick, top within 0.5 m of the surface	Skeletic phase
Fossil realm of the saprolite-regolith taxonomy	Transported, unconsolidated material, - no original structures and textures - original volume unknown	Transported in an abundant low density medium (water, air)	Alluvium USC ≤ 1.0 MPa*) Density ≤ 1.8 g/cm^3
		Transported as a high density, water-solid matter mixture	Colluvium, USC ≤ 1.0 MPa
		Transition zone (type of solifluction)	Carpedolith or stoneline
	In situ material, - no change in volume - original structures present - chemically weathered during former hot and humid climates to the extent that most rock-building silicate minerals are destroyed and most alkali and alkaline-earth elements are removed in watery solutions	Accumulation of sesquioxides, producing new structures and textures, superimposing the original ones: some horizons may become hard to very hard	Laterite (if rich in Al: bauxite)
		Completely composed of weathering residues: quartz, clay minerals (mainly kaolinite), refractory minerals; unconsolidated	Saprolite
		Transition zone	Proto-saprolite
Realm of petrology	Magmatic, sedimentary and metamorphic rocks	Original material	Fresh rock

N.B. The extent of the time hiatus between the processes of saprolite weathering and the formation of recent soils is unknown. Most laterites and saprolites will have experienced some mineralogical changes from the present day climate.

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2. Some definitions and descriptions

2.1 Laterite*

Origin of the name: Dr Buchanan, M.D. (1807), reports in Volume II, page 440-441 of his Indian travel journal dated 20-21 December 1800, on his visit to Angadipuran (Kerala State):

> "What I have called indurated clay is not the mineral so called by Mr. Kirwan, who has not described this of which I am now writing. It seems to be the *Argilla lapidea* of Wallerius I, 395, and is one of the most valuable materials for building. It is diffused in immense masses, without any appearance of stratification, and is placed over the granite that forms the basis of *Malayala*. It is full of cavities and pores, and contains a very large quantity of iron in the form of red and yellow ochres. In the mass, while excluded from the air, it is soft, that any iron instrument readily cuts it, and is dug up in square masses with a pick-axe, and immediately cut into the shape wanted with a trowel, or large knife. It very soon after becomes as hard as brick, and resists the air and water much better than any bricks that I have seen in India. I have never observed any animal or vegetable *exuvia* [cast, skin, shell, covering] contained in it, but I have heard that such have been found immersed in its substance. As it is usually cut into the form of bricks for building, in several of the native dialects, it is called brickstone *(Itica culla)*. Where, however, by the washing away of the soil, part of it has been exposed to the air, and has hardened into rock, its colour becomes black, and its pores and inequalities give it a kind of resemblance to the skin of a person affected with cutaneous disorders; hence in the Tamil language it is called *Shuri cull*, or itch-stone. The proper English name would be *Laterite*, from *Laterites*, the appellation that may be given to it in science".

And in Vol. III, page 66-67:

> "The strata at Tulwa, near the sea-coast, resemble entirely those of Malayala, and consist of *Laterite or brickstone*, with very few rocks of granite interspersed. This granite is covered with a dark black crust, and is totally free from veins of quartz, or feldspar. In many places large masses of the granite immersed in the *Laterite* are in a state of decay; the black mica has entirely disappeared, and the white feldspar has crumbled to powder, leaving the quartz in angular masses" [also quoted by C. S. Fox, 1936, p. 393/4].

This description by Buchanan is a feeble basis for a clear definition of laterite; in addition it took a long time before scientists started to understand the working of the processes that lead to lateritization*.

L.L. Fermor (1911) summarizes his ideas on laterites in 13 points, most of which are quoted here to illustrate the properties of laterite and the — partly still existing — confusion about its terminology. Quoted also from a paper by C.S. Fox (1932).

> 1. The term laterite is used in two ways, namely, *stratigraphically* as the name of a geological Formation, and *petrographically* as the name of a tropical superficial rock. The following discussion relates only to the use of the term as a rock name.
> 2. *Laterite* (or rather some varieties of it) is formed by a process, the *modus operandi* of which is not discussed here, by which certain rocks undergo superficial decomposition, with the removal in solution of combined silica, lime, magnesia, soda, potash, and with the residual accumulation, assisted, no doubt, by capillary action, metasomatic replacement, and segregative changes of a hydrated mixture of oxides of iron, aluminium, and titanium, with

more rarely, manganese. These oxides and hydroxides of iron, aluminium, titanium, and manganese are designated the *lateritic constituents**.

3. This residual rock is *true laterite*, and the presence of any considerable proportion (> 10 percent) of non-lateritic constituents requires expression in the name, as it always indicates want of completion in the process of lateritisation. True laterite contains, then, 90 to 100 percent of lateritic constituents.

4. There is often a gradation in composition between true laterite as defined above and lithomarge*, which is taken as the amorphous compound of composition $2H_2O.Al_2O_3.2SiO_2$, corresponding to the crystalline mineral kaolinite of the same composition. For rocks intermediate between laterite and lithomarge the terms *lithomargic laterite* and *lateritic lithomarge* are available, the former being applied to forms containing 50-90 percent of lateritic constituents, and the latter to forms containing only 25 to 50 percent of lateritic constituents.

5. The presence of any considerable amount of quartz, either residual or secondary (this form has not yet been noticed, so far as I am aware, in Indian laterites), should be indicated by naming the rock a *quartzose laterite*, unless the amount of quartz and other non-lateritic constituents exceed 50 percent, when the word *laterite* should appear only in the adjectival form, as in paragraph 4.

6. Many rocks to which the term laterite has been applied would be more aptly termed *soils, earths, clays, and sands*, with (if >25 percent) or without (with <25 percent of lateritic constituents) the attributive *lateritic*. [See the final remark of this section 2.1].

7. *Varieties* of the rock defined as true laterite are those in which one of the constituents is present in relatively large amounts, namely, the highly aluminous variety, *bauxite**, the highly ferruginous variety, *lateritic iron-ore*, and the highly manganiferous variety, *lateritic manganese-ore*. From this it follows that alumina cannot be regarded as an essential constituent of laterite, although it is usually present in smaller or larger quantity.

8. The property of *hardening on exposure* to the air is characteristic of many varieties of laterite, but it is not an essential property, for some laterites do not exhibit it, whilst cases have been recorded of rocks that show this property and yet cannot possibly be termed laterite, although they probably contain a certain quantity of hydroxides of iron and aluminium, to the hydration of which the setting of laterite is usually ascribed.

10. Certain lateritic rocks have been formed by metasomatic replacement at the outcrop of a variety of rocks, and which cannot be regarded as residual products of the decomposition of the underlying rocks, have been designated *lateritoid* . . .

12. The most so-called laterites of the Guianas, as described by Harrison and Du Bois, are not true laterites unqualified, but are either quartzose or *lithomargic laterites*, or *lateritic earths*. Many of them are detrital rocks, sometimes rich enough in lateritic material to be called *detrital laterite* or *lateritite**. True laterites do, however, also occur.

13. Fermor's last point: The classification of laterite . . . put forward in this paper . . . is of course of a more or less tentative nature . . .

C.S. Fox (1936): On the urging of L.L. Fermor, the then Superintendent of the Geological Survey of India, C.S. Fox, studied the type area where Buchanan coined the term laterite. His mission included in particular the collection of samples for chemical analysis of the rocks which caused Buchanan to suggest the name laterite. He had the chemical analyses made through the kind intermediary of Prof. A. Lacroix — the laterite specialist of his time — by Mr F. Raoult of Paris. Thanks to this specialist-chemist, the analyses provide a differentiation between the silica

contained in the weathering minerals, i.e. kaolinite, and that present in the parent rock silicates or as quartz. Annex I gives the results of the chemical analyses of one vertical section of four, successive samples, each 5 ft (152 cm) long. No mineralogical analyses were made, but the normative composition for an epi-norm mineral association has been computed and is also incorporated in the table. The upper three samples give an acceptable composition when using gibbsite, hematite and goethite as the minerals present; the epi-norm computation for the lowermost sample does not lead to an acceptable paragenesis.

This 1936 publication by Fox is mentioned in particular, because it gives all essential quotes about laterite that occur in Buchanan's three heavy volumes (which are not readily available in many countries), while it also contains the remarks by Fermor (1911) and the first chemical analytical data on laterites from their type locality.

Alexander & Cady (1962) summarize their findings in their report on Mission 47 of the Organisation for European Cooperation (OEEC) to West Africa in 1951, with a descriptive definition of laterite, which was widely accepted throughout the world; quote:

"Laterite is a highly weathered material rich in secondary oxides of iron, aluminium, or both. It is nearly devoid of bases and primary silicates, but it may contain large amounts of quartz and kaolinite. It is either hard or capable of hardening on exposure to wetting and drying. Except hardening, all these characteristics are possessed by some soils or soil forming materials. In the past the term 'laterite' has been used in many ways, but it is now generally accepted as a name for a material whose composition and properties are within the limits described".
"Interest in laterite developed among soil scientists and geologists because it is a common material, it is a hindrance to agriculture in many places, and some varieties have economic value as iron and aluminium ores, and as building material. Laterite is of theoretical interest because of its mode of formation and because of its potential as a stratigraphic marker and as a possible indicator of past climate and physiography".
"Laterite can be said to be an end product, or extreme example, of processes taking place over a large part of the earth's surface. [italics by GJJA]. True laterite itself interferes with land use in Africa, India and elsewhere in the Tropics. The soil material having some of the same characteristics, or which have been affected by some of the same processes, extend over most of the Tropics and into large parts of the temperate zones".

This publication of Alexander & Cady contains a comprehensive discussion, covering a large amount of field observations and related technical data, which in this case has been collected by soil scientists. The authors were ten weeks in the field, visiting Sierra Leone, Guinea, Ivory Coast, Ghana, Dahomey, Nigeria and Congo. Hence, the above characterization of laterite represents most of West Africa. They recognized four types of crusts, based on their geomorphological position:

(i) High-level or peneplain, ferruginous crusts occurring as a cappings on high ridges and on peneplain fragments;
(ii) Foot-slope, or colluvial, seep-cemented ferruginous crusts, formed by cementation of colluvial materials that commonly contained fragments of crust, broken from a peneplain crust of a higher level. The matrix — an iron oxide cement — largely derived from upslope. These deposits are of a more recent age than those of the old peneplain.

(iii) High water table, or low-level, ferruginous crusts, formed in valleys where the water table is high, at least part of the year. Iron may be brought in by the ground water, or it may be only locally translocated by fluctuations of the water table.

(iv) Residual crusts other than the old-peneplain type, related to the distribution of a particular kind of rock, and to an environment in which weathering produces an iron-rich clayey material that is nearly impervious; after exposure it my change to a hard crust.

Alexander & Cady also provide some data on the hardening process through wetting and drying. From Guinea they report: 15 years of wetting and drying causes a 2 cm thick crust; the same material used for the wall of a house, hence continuously dry, was not hardened. Elsewhere, a road cut several years old, showed a hard crust on the face exposed to the sun; the other face was still soft.

Sivarajasingham, Alexander, Cady & Cline (1962), in the chapter dealing with the nature of laterite, restrict the term laterite as follows:

— "highly weathered material;
— rich in secondary forms of iron, aluminium, or both;
— poor in humus;
— depleted of bases and combined silica;
— with or without non-diagnostic substances such as quartz, limited amounts of weatherable primary minerals or silicate clays; and
— either hard or subject to hardening upon exposure to alternating wetting and drying".

Hence they left out — erroneously(?) — the requirement of the residual nature of the parent material, as stated by Fermor (1911) and by Alexander & Cady (also published in 1962 and co-authored by Alexander!)

The Glossary of Geology, 2nd ed. (Bates & Jackson 1980) states:

"Laterite, an older term for a highly weathered red subsoil or material rich in secondary oxides of iron, aluminium, or both, nearly devoid of bases and primary silicates, and commonly with quartz and kaolinite. It develops in a tropical or forested warm to temperate climate, and is a residual product of weathering. Laterite is capable of hardening after a treatment of wetting and drying, and can be cut and used for bricks; hence its etymology: Latin, *latericius*, 'brick' ".

The IGCP Project 129: Lateritization Processes suggested a new definition, prepared by Werner Schellmann (1982, 1983, and in Banerji, 1986):

"Laterites are products of intense subaerial weathering. They consist predominantly of mineral assemblages of goethite, hematite, aluminium hydroxides, kaolinite minerals and quartz. The $SiO_2 : (Al_2O_3 + Fe_2O_3)$ ratio of a laterite must be lower than that of the kaolinized parent rock in which all the alumina of the parent rock is present in the form of kaolinite, all the iron in the form of iron oxides and which contains no more silica than is fixed in the kaolinite plus the primary quartz".

This definition requires that all rock forming silicates of igneous and/or metamorphic derivation are completely broken down — through weathering — into iron and aluminium (hydr)oxide and kaolinite, while alkali and earth-alkali elements, and part of the silicate silica, are transported out of the environment through ground water flow.

The definition indicates the necessary process environment: sufficiently high temperatures to have an adequate speed of the weathering process, and sufficient and continuous fresh (rain) water available to wash out the soluble weathering products. Primary quartz is a neutral mineral with respect to the weathering process; it may even help in providing a skeleton for the laterite rock to be formed.

Groundwater* vs. pedogenetic* laterite: this juxtaposition of terms represents a distinction made by some students of laterites. McFarlane (1976) explains that in groundwater laterites the precipitates develop in the zone of fluctuation of the groundwater level, while in pedogenetic laterites the precipitates are formed in the soil where alternating conditions of wetting and drying occur.

In other words, all major, thick laterite horizons are groundwater laterites, while the thin, surface-related lateritic deposits are pedogenetic laterites. The relation between these pedogenetic laterites and plinthites are nowhere discussed, but they could well be closely related, genetically and in age.

In this connection mention must be made of thin, generally banded coatings* — with a total thickness in the order of a few millimetres — of lateritic composition that occur on the walls of near-surface cracks in major laterite deposits and of the, often banded, veins of lateritic composition found in the near-surface horizons of major laterite deposits. It looks, as if such precipitates, seemingly derived from circulating solutions, are formed under fairly recent or present climatic conditions in the (near) surface horizons of already existing laterite horizons.

The soils, covering the laterite in such areas, are thin — a maximum of a few decimetres — and the vegetation may be of a grassy or forest nature. The local present day climate may vary from the tropical monsoon type in Suriname (N. coast of South America, at 5° S. Lat.) to the humid climate of the Natal highlands, South Africa (between 28° and 31° S. Lat.) and the mediterranean climate of the Australian West coast (Darling Ranges, between 31° and 33° S. Lat.). McFarlane (1976, Plate 3) provides an example from the Buganda topography, where the lateritic coating directly overlies the fresh parent rock (circa 0° - 1° N. Lat., over 3000 m high); the figure caption reads: pedogenetic laterite on fresh rock.

In summary, true laterites are — at the time of their formation — bound to the surface or near-surface environment, where the atmospheric influences causing weathering of the local substratum are strongest; they are of an *in situ* residual nature. In this context the weathering process may be considered as the re-equilibration of the locally present mineral phases to the P and T conditions of the surface environment. This re-equilibration proceeds fastest under conditions of high temperature and abundant precipitation (rain) — to maintain a high rate of leaching — and in the presence of organic acids, which promote the chemical attack of the silicates.

Table II provides a summary of a number of characteristics as they can be observed in the field. The high variability of most characteristics is worthy of note; it certainly contributes to the confusion around the term laterite and around the correct recognition of that entity in the field.

False laterites — to be distinguished from the true laterites discussed above — are all (near-surface) materials that look similar but are not the residual weathering products of the local bedrock. The most common examples are transported erosion products of true laterites — i.e. exolaterites, see Annex II — cemented by mainly ferruginous material and found on lower topographical levels than the true laterite bed, (Grandin, 1976) and often indicated as ferricretes.

Table II

TABLE II — Macroscopic characteristics of laterites for field use

Laterites are formed, and generally occur, near the earth surface, mostly just below the soil horizon. After their formation they are either denuded by erosion, or covered below younger deposits. They may be covered with a (heavy) forest, with the tree roots deeply penetrating into and through the laterite.

Hardness is highly variable, both within and between laterite deposits: plastic, brittle, breakable between the fingers to difficult to break with the hammer.

Colours are highly variable, although mostly reddish, reddish brown, brownish to yellow brown in hue, but white, black, greyish or purplish blue also may occur.

Grain size is often difficult to state, e.g. where laterite forms a massive, hard or microcrystalline mass, or where it is plastic or doughy. In crystalline laterites the grain-size varies between <0.1 and 2 mm.

Structures/textures are highly variable, from massive to even grained and layered, but also with vermiform, scoriaceous, columnar and root-like structures; if spherical bodies (pisoliths, or preferably pisoids) occur, they may represent between 1 and 90 % of the volume of the laterite. Locally, concretionary forms occur with pseudomorphic shapes after root stocks, in the shape of former voids (grouting structures) and as platelets, representing joint fillings.

Chemically the composition is highly variable, with Fe_2O_3 content varying between 1 and 65%, and Al_2O_3 content varying between > 60% (bauxite) and < 10%.

Mineralogically, they are mainly composed of newly formed weathering minerals, such as hematite, goethite, kaolinite, gibbsite, etc.; they may contain abundant quartz of a relict nature.

LOI (bound water) is variable with up to 34% in pure bauxite to circa 25% in goethitic, kaolinitic laterite.

Clay minerals may occur but are not an essential component; kandites (kaolinite, halloysite) predominate but smectites (montmorillonite) do occur as well.

Unweathered rock forming silicates (feldspars, feldspathoids, hornblende, pyroxene, biotite, garnet, etc.) may occur as relict minerals of the original parent rock. Muscovite may occur even in larger scales.

Accessory minerals, as relicts of the parent rock, may include ilmenite, staurolite, tourmaline, etc.

Pedologically, laterites may be considered to be zonal* soils — at the time of their formation — restricted to climates of high surface temperature and high humidity and/or precipitation. They were — at the time of their formation — also intrazonal*, as the chemical composition and structure/texture of the parent rock determine the ultimate chemical composition of the laterite formed.

As surficial products, laterites are liable to fall prey to erosion, the more so where they occupy topographically high positions in the landscape — which is commonly the case as that position is promoting the necessary high rate of rain water drainage. Most present day laterites have survived the erosional attack as result of their hard to very hard capping by an iron-rich accumulation zone (cuirass), while a few deposits were buried by younger sediments shortly after their formation, and so protected against erosion and against weathering processes conducive to lateritization of later periods.

The topographically high laterites will follow in their composition the changes in climate with successive mineral and structural/textural re-equilibrations. Hence many — if not all — exposed laterites are polyphase in origin, causing high complexity in structures and textures. Boulangé (1984) relates the frequent occurrence of pisoids* in the Ivory Coast bauxites to this re-equilibration of an already existing laterite horizon during more recent climatic conditions.

The simplest laterites are those that were only once exposed to the climatic conditions favourable for lateritization, i.e. the young Cainozoic laterites of e.g. South East Asia (be it that the conditions or the available time were presumably insufficient to produce thick and massive laterites). The other group of 'monophase' laterites are those that were covered by sediments shortly after their formation, e.g. those in the Coastal Plane of the Guyanas (Bárdossy & Aleva, 1990).

The age of formation of laterite deposits is generally difficult to establish. Absolute age determinations have not yet been possible, although several attempts have been made or are in the process of development, e.g. by using oxygen isotopes.

Stratigraphic methods have been successful in the Coastal Plain of northern South America, where Van der Hammen & Wymstra (1964) were able to date several lateritic bauxite deposits through palynological methods (Palaeocene-Eocene pollen were found in grey to black, earthy to clayey intercalations in and below the arkosic sedimentary parent rocks). See also Bárdossy & Aleva (1990).

Finally a point of language: the suffix '-itic' forms an adjective of nouns ending in -ite, hence laterite —> lateritic. The suffix '-itious' forms adjectives with the meaning 'related to', or 'having the nature of', hence a rock looking similar to laterite but missing one or more of its essential characteristics is a 'lateritious' rock, and not a laterite, nor a lateritic rock. The suffix '-oid' forms adjectives with the sense of 'having the form of' or 'resembling', hence again refers to a rock that is not a proper laterite. In many other languages this distinction can and, hence, must be made as well.

2.2 Bauxite*

Bárdossy & Aleva (1990) characterize lateritic bauxite as a member of the family of normal lateritic rocks with a particular enrichment of free aluminium hydroxide minerals, such as gibbsite, boehmite and, less commonly, diaspore. The name 'bauxite' derives from the 'Collines des Beaux', Southern France, the place from where the sample derived that Bertier (1821)

analyzed, thinking that the red brown material could be a good iron ore. However, he found the composition to be 52.0% Al_2O_3, 27.6% Fe_2O_3, 20,4% loss on ignition, and a trace of Cr_2O_3.

Karst bauxites, i.e, bauxite deposits on carbonate rocks, or enclosed by carbonate rocks, are extensively discussed by Bárdossy (1982); they form a separate type of weathering residue of silicate rocks, resulting from extreme leaching by circulating water with contemporaneous enlargement of the carbonate rock receptacle.

2.3 Special laterites

The common laterites are formed from common quartz-feldspar rocks with a relatively low content of Fe-Al silicates, such as granites, gneisses, etc. More specialized parent rocks, such as peridotites or manganese-rich carbonate and silicate rocks produce upon intensive (tropical) weathering rocks rich in nickel and manganese oxides. Because of the deviating parent rocks the processes and the weathering products formed may be much different from those resulting from 'normal' lateritization. E.g. nickel laterites usually have a phase of newly formed SiO_2, that may provide a skeleton for the rock as a whole.

2.4 Laterite *sensu lato**

The suffix 'sensu lato' indicates the less strictly defined uses of the term, where the emphasis is more on the process of intense weathering under humid tropical climatic conditions. In this sense it will be used e.g. in Chapter 3 – The Laterite Formation. In such contexts, the term laterite is used – as a type of shorthand – to indicate the group of processes that, over a sufficiently long period of time, result in the genesis of a Laterite Formation. Detailed study of such laterite occurrences may establish that it should be named e.g. a ferriferous bauxite, or a bauxitic or aluminous laterite – see also the ternary diagram of Fig. 1, A & B. In other contexts the 'sensu lato' might be used to include the exo-laterites – see Annex II.

2.5 Nomenclature, terminology and descriptive terms

During the first IGCP Symposium at Trivandrum, India, 1979, it became abundantly clear that one of the priorities should be to establish a modern, systematic and well defined nomenclature for all the facets of laterites and their geological, petrological, textural and structural, and chemical varieties.

Suggestions for such a nomenclature have been incorporated in the Summary of the IGCP 129 Project (Banerji, 1986). These terms were adopted, and approved upon, by Bárdossy & Aleva (1990). Later, suggestions were published for the description of voids – one of the most essential textural/structural entities in laterite – by Aleva (1987). Since the publication of these terms no serious objections have been raised against these suggestions, and no further improvements have been suggested, hence, they may now be considered as having been accepted by the community of laterite geologists and other interested scientists.

The complete set of suggestions is presented in a number of diagrams and tables, assembled in two annexes.

Annex II deals with the differentiation between the true, residual *laterite** and the allochtonous lateritic deposits, which after transport and hardening are often difficult to distinguish from the *true** laterites; they are not in the original place where the weathering process produced this more or less lateritic material, hence the name *exolaterite**. The chart does not require further elaboration.

In the past, some of these materials have been described under the name *ferricrete**, which could be an appropriate name only in case that the original lateritic material has been transported by fluvial action — to form a gravel of lateritic composition — followed by cementation in their new environment by circulating iron solutions. The resulting rock is not anymore a laterite but might be called an *impregnated lateritoid**, a name that tells the reader something about the rock's origin, which is not the case with the term ferricrete, as it is now commonly used.

Annex III provides all the terms required for a complete structural and (rock) description of true lateritic material.

Annex III-a provides a systematic summary of terms available for the description of structures and (rock) textures, including terms to describe voids (in contrasting type face) and what could be called concretions, nodules and other larger particles, enclosed in a finer grained 'groundmass'.

Annex III-b illustrates the terms available in the geological literature to describe the shape of particles of any size, and the names used for particles of certain grain size classes.

Annex III-c provides a diagram showing the observed variations in nucleus-cortex relationship in pisoids. Pisoid is defined as any spherical body with a relatively smooth surface, independent of its internal structure, in diameter varying from 2 - 60 mm.

Annex III-d gives a list of semi-quantitative relative abundance terms, based on a more or less logarithmic scale, with a one letter code. These abundancy terms and codes have proved to be in particular useful to report on semi-quantitative chemical and mineralogical analyses.

Annex III-e gives a classification and nomenclature for voids. Many laterites are for over 50% composed of voids which generally are described with one word: "vuggy*". A more detailed description is possible with the terms proposed, which will lead to a better understanding of various types of voids present and their genetic implications.

Annex III-f contains the terms to be used to describe the consistency of the consolidated and unconsolidated parts of a laterite-bauxite profile. The table gives the one word term usually employed with as explanation the response obtained by applying a certain force on the lateritic material. These response terms might be used as modifiers to the first term, e.g. dense and brittle, or hard but sectile.

2.6 Plinthite*

This relatively recent term is the result of an uneasiness among soil scientists with the (former) use of the term laterite. This may be illustrated by the following quotes:

(i) The Soil Survey Manual (Soil Survey Staff, Agriculture Handbook No. 18, 1951, p.184) states: "Laterite is found in many soils and is a distinguishing feature of Ground-Water Laterite soil. In the profile of a Ground-Water Laterite soil one may designate the horizons as A1, A2, A3, and B1, down into the B2 or perhaps into the B3. The same material may continue

practically without change for another 25 feet or so with no definite place for dividing the solum from the material underneath it. It would be unreasonable to exclude the upper part of the laterite from the solum; and it seems unreasonable to include the lower part, far removed from the influence of organisms."

(ii) The Agricultural Handbook No.436, p.50 (Soil Survey Staff, 1975) states under the heading *Plinthite*: "Plinthite (Gr. *plinthos*, brick) is an iron-rich, humus-poor mixture of clay with quartz and other diluents. It commonly occurs as dark red mottles, which usually are in platy, polygonal, or reticulate patterns. Plinthite changes irreversibly to an ironstone hardpan or to irregular aggregates on exposure to repeated wetting and drying, especially if it is exposed also to the heat from the sun. The lower boundary of a zone in which plinthite occurs usually is diffuse or gradual, but it may be abrupt at a lithological discontinuity." And further down "Much that has been called laterite [by soil scientists] is included in the meaning of plinthite. Doughy and concretionary laterite that has not hardened are examples. Hardened laterite, whether it is vesicular or pisolitic, is not included in the definition of plinthite."

(iii) The May 1981 draft Soil Survey Manual, Soil Survey Staff, p.4-77: "*Plinthite* consists of reddish bodies enriched in iron, that are low in organic matter and are coherent enough to be separated readily from the surrounding soil. The bodies are commonly about 5 to 20 mm across their smallest dimension. Plinthite bodies are firm or very firm when moist and hard or very hard when dry, but they can be broken by hand, They are roughly spherical, nodular, or plate-like; if plate-like, the bodies are oriented horizontally. Soils that contain plinthite rarely dry out in the natural setting". . . . "Plinthite that is exposed to the atmosphere and repeated wetting and drying hardens irreversibly to ironstone. Iron-enriched mottles that do not harden irreversibly on exposure to the atmosphere are not plinthite. *Plinthite is defined by its hardening characteristics, not by its degree of cementation.*" [italics by GJJA] . . . . "Plinthite commonly is associated with reticulated mottled horizons. The nodular form is a discrete body in the soil above the reticulated mottled horizon." . . . . "Plinthite does not stain the fingers when moist or wet".

2.7 Hardened versions of plinthite

These hardened versions of plinthite, etc. have caused, and still cause, much confusion with laterite, etc. Here follow three quotes to illustrate the more recent opinions on these materials.

(i) Petroplinthite*, a term proposed by Sys (1969): "Individualizations of iron oxides which are irreversibly hardened. In the humid stage petroplinthite cannot be cut by a spade. They are hard concretions within a clayey matrix, or occur as a carapace. The petroplinthite corresponds to the laterite definition by Alexander & Cady (1962)". The term seems to be superseded by "petroferric phase"; see the Revised Legend, Soil Map of the World (FAO-Unesco, 1988) — see below.

(ii) Petroferric phase*: refers to the occurrence of a continuous layer of indurated material, in which iron is an important cement and in which organic matter is absent, or present only in traces. The indurated layer must either be continuous or, when it is fractured, the average lateral distance between fractures must be 10 cm or more. The petroferric layer differs from a thin iron pan and from an indurated spodic B horizon in containing little or no organic matter. (FAO-Unesco, Soil Map of the World, Revised Legend, 1988).

(iii) Skeletic phase*: refers to soil materials which consist of 40 percent or more, by volume, of coarse fragments of oxidic concretions or of hardened plinthite, ironstone or other hard materials, with a thickness of at least 25 cm, the upper part of which occurs within 50 cm of the surface. The difference with the petroferric phase is that the concretionary layer of the skeletic phase is not continuously cemented (FAO-Unesco, 1988).

As a geologist, the compiler of this Handbook would say that the plinthites belong to the more or less recent weathering phenomena, while laterites are presumed to be formed in a former climate which is distinctly different from the present, e.g. dating before the Pleistocene and probably not much later than the Lower Tertiary.

In summary, it can be stated that laterites and plinthites are closely related in their origin and genesis; in particular this counts for:

— the required intensive weathering of surface or near surface layers, causing the precipitation of sesquioxides and the removal of alkalies and silica (which requires transport in solution in moving groundwater);
— this intensive weathering is caused by high ambient temperature and sufficient process water (for flushing out silica, etc. and to prevent local reprecipitation) and organic acids, hence a soil type of environment at the surface;
— extended time, which is essential for a noteworthy thickness of the soil or rock composed of the residues and precipitates;
— ground water fluctuations have a bearing on both the formation of plinthites and laterites; such fluctuations are common events in the earth's history;
— the series plinthite — petroplinthite — skeletic phase — laterite seems to be a genetic series of increasing age, where it should be remembered that the length of time during which the active, genetic processes were at work, seems to increase when going back into time. Or in other words, the details we see in e.g. recent and young plinthite deposits get lost in the course of time through superposition of successive phases of the formative processes; there is a type of homogenization in composition and texture as the soils or rocks become older. Also, the climate in recent times has been different — less favourable and more variable — from that in earlier periods of intensive weathering.

These observations explain the scarcity of Al-plinthites against the more abundant occurrence of aluminous laterites or bauxites. However, more or less recent, surficial Al accumulations do occur in areas with an extremely wet climates: soils high up on the slopes of the Hawaii volcanoes, or in the Columbian Andes, e.g. in the Cauca & Valle District, with 1600-1700 m altitude and a precipitation of 2000 mm per annum; here Al hydroxide seeps out of the walls of road cuts. Or at a much lower topographic level: the Kerikeri bauxite(!) deposits in the Northern Island of New Zealand, at an elevation of about 200 m and with 1250 mm rain per annum (Bárdossy & Aleva, 1990).

2.8 Ferrallite/ferralite*

The study of the weathering processes in humid and warm climates revealed already in an early stage, that weathering results in a relatively quick removal — through hydrolysis of most silicate silica, alkali and earth-alkali elements, with only aluminium — as $Al(OH)_3$ = gibbsite — and/or iron — as $\alpha FeO.OH$ = goethite remaining. Harrassowitz (1926) gave the name allite* or allitic to the soils and horizons mainly composed of these sesquioxides, and contrasted these with the horizons mainly composed of the Al-silicate kaolinite: the siallitic* horizons. As the sesquioxide horizon is generally a mixture of Al and Fe (hydr)oxides, Robinson (1949) suggested to name these *ferrallite*, which is also the common term used by the French workers in West Africa. Robinson uses the molecular ratio silica : sesquioxide to separate the siallitic clays from the (ferr)allitic clays, with the ratio 2 as borderline. See Chart I, after Pedro & Melfi (1983).

2.9 Soil*

Soil is the collection of natural earthy material on the Earth's surface, in places modified or even made by man, containing living matter, and supporting or capable of supporting plants out-of-doors. The lower limit is normally the lower limit of biological activity, which generally coincides with the common rooting of native perennial plants (Glossary of Geology, 2nd ed., Bates & Jackson, 1980). A large number of soil units have been identified, based on the presence or absence of *diagnostic horizons** and *diagnostic properties** — each quantitatively defined — produced by soil forming processes.

> Driessen & Dudal, eds. (1989) give the following description:
> "Soils are formed through the impact of *climate, vegetation & fauna* (including Man) and *topography* on the soil's *parent material*, over a variable *time* span. The relative importance of each of these five 'soil forming factors' in soil formation ('pedogenesis') varies among sites; this explains why there is such a great variety of soils."
> "With few exceptions, soils are still in a process of change; they show in their 'soil profile' signs of differentiation or alteration of the soil material, indicative of a particular pedogenetic history".

Since the end of the last century, soil scientists — mainly in USSR, Europe and the USA — have been engaged in the development of various systems of soil nomenclature which were intended to be world-wide applicable. A soil nomenclature was developed by the Soil Survey Staff of USDA and published under the name *Soil Taxonomy* (Soil Survey Staff, 1975 and 1990).

Concurrently, FAO-Unesco — in cooperation with the ISSS (International Society of Soil Science) — developed a nomenclature for the *Legend* of the *FAO Soil Map of the World*, 1:5 000 000. For the legend many of the soil properties and concepts already defined by the US Soil Survey staff for *Soil Taxonomy*, were adapted after modification to better serve the purpose of the Map (FAO-Unesco 1947 and revised 1988).

Classification in these systems is based on strict taxonomic rules. Both *Soil Taxonomy* and the *Legend of the Soil Map of the World* are multicategoric systems of classification, with one or more diagnostic horizons and properties at each categoric level dividing soils into mutually exclusive classes. *Soil Taxonomy* has six levels whereas the *Legend of the Soil* Map *of the World* has two, with a third level which is currently (1991) under discussion.

The classes are defined in terms of measurable and observable properties of the soil itself. Common combinations of specific properties which are generally accepted to have resulted from soil forming processes, define the *diagnostic horizons*. These diagnostic horizons are the basic identifiers in soil classification.

For example: a *ferralic B Horizon* is a highly weathered horizon which is at least 30 cm thick. Evidence of the advanced stage of weathering is the low cation exchange capacity* of the clay fraction, which — by definition — should not be more than 16 cmol(+)/kg clay. In addition, the fine sand fraction must have less than 10% weatherable minerals. The full definition includes some more requirements. The presence of a ferralitic B horizon places the soil in the major soil grouping: *Ferralsols* (FAO-Unesco, 1988).

A further differentiation of the classes of soils is based on the presence or absence of *diagnostic properties*. For example: plinthite is an iron-rich, humus poor mixture of clay and quartz that hardens irreversibly on drying. Ferralsols which have plinthite within 125 cm of the surface are placed in the soil unit: *Plinthic Ferralsols.*

Both systems are provided with keys to identify the class name of the soil. Keys are provided for all categoric levels, starting from the highest level and step by step descending to the lower levels. The key must be followed strictly from the beginning — at the highest level — checking by comparison the properties of the soil to be classified against the properties stated in the key. If the properties of the soil do not meet the requirements as stated in the first section of the key for the highest level, the user must continue checking with the next sections in this key until — in one of the following sections — all the requirements are met and the highest level name of the soil is identified; the user is then referred to the key of the next lower level to identify the name of the subclass.

It should be emphasized that an entry in a key is *not* an exhaustive description of the soil class, but a listing of the properties which separate the soil class in question from all other soils, belonging to any other class.

The description of a soil consists mainly of descriptions of its several horizons* and their vertical succession in the profile. Conventionally, horizons are designated by a horizon symbol consisting of capital letters, and letter and figure suffixes. However, there is considerable divergence of opinion amongst soil scientists about the use of these symbols and many countries have their own system of horizon designation (Bridges, 1990). A system widely used throughout the world is the one published by FAO (1990). In the FAO system, the symbol for the principal (master) horizons consists of one or two capital letters. Lower case letter suffixes are used for subordinate distinctions, with or without a figure suffix. For details of the FAO horizon designation, see Annex IV.

2.10 The ternary compositional diagram*

The common essential minerals in laterites and related rocks are the iron minerals hematite [HMT] and goethite [GTT], the aluminium minerals gibbsite [GBS] and boehmite [BMT], and the clay mineral kaolinite [KLT].

This simple three element composition of laterite (Fe, Al and Si) is well suited to be represented in a triangular diagram (Thoenen et al., 1945; Doeve, 1955; Konta, 1958; Valeton, 1972; Bárdossy & Aleva, 1990).

Figure 1A illustrates the tetrahedron with the four participating oxides Al_2O_3, Fe_2O_3, SiO_2, and H_2O in the apices, and the position therein of the common laterite minerals gibbsite, kaolinite, hematite and goethite. Transforming the triangle formed by connecting the points for hematite, gibbsite and kaolinite into an isosceles triangle, produces the compositional ternary diagram of Fig. 1B; for practical purposes goethite is considered to reside in the hematite apex.

This ternary diagram illustrates the recommended rock names for aluminous and ferriferous laterites, bauxites and kaolin, including their mixtures. Note that an admixture of gibbsite to kaolinite makes it a bauxititious (or aluminous) kaolin and not a bauxitic one!

2.11 Chemical rock analysis for laterites

Quartz is considered to be a 'refractory' mineral in the laterite context; it is not — or at least relatively little — reactive in the laterite forming environment. Therefore, it is not represented in the ternary compositional diagram.

Fig 1

H₂O

GIBBSITE

GOETHITE
Fe₂O₃
HEMATITE

Al₂O₃

KAOLINITE

SiO₂

Fig. 1A

HEMATITE
GOETHITE
100%

10% KLN

FRT
FERRITE

80% FRT

50% FRT

ALUMINOUS
FERRITE

SILICIOUS
FERRITE

FERRITIC

50% KLN

FERRIFEROUS
BAUXITE

LTR
LATERITE

FERRIFEROUS
KAOLIN

BAUXITIC

KAOLINITIC

80% KLN

10% FRT

BXT
BAUXITE

SILICEOUS
BAUXITE

BAUXITITIOUS
KAOLIN

KLN
KAOLIN

100%
GIBBSITE
BOEHMITE
DIASPORE
(CORUNDUM)

80% BXT

50% BXT

10% BXT

100%
KAOLINITE
AND OTHER
CLAY
MINERALS

Fig.1b

Fig. 1A — Compositional tetrahedron with Al₂O₃, SiO₂, and H₂O at the apices. The positions of gibbsite, goethite and kaolinite are indicated. The ternary compositional triangle is marked with heavy lines, broken where behind the front faces of the three-dimensional body.

Fig. 1B — Ternary compositional diagram, illustrating the preferred nomenclature of the lateritic weathering products. In addition quartz and unweathered parent rock minerals may be present; the presence can be indicated by placing e.g. "quartz-bearing" in front of the rock name derived from the diagram.

20

Chemical analyses of lateritic rocks must therefore use an analytical method that separates the SiO_2 contained in quartz, or in unweathered (relict) rock forming silicates such as garnet, staurolite, mica, etc., from the silica contained in kaolinite (= reactive* silica*). This can be achieved by using a mild digestion process to bring the powdered rock sample into solution. The bauxite industry uses for this purpose a tri-acid mixture of H_2SO_4, HCl and HNO_3 (see Annex I), which allows to determine the amount of 'reactive silica' present besides the content of total* silica. When using commercial chemical laboratories to analyze lateritic rocks, the requirement of a double silica determination must be specifically stated, otherwise the reactive silica will not be determined (as is usual with common geological rock analyses).

2.12 Glossary

The preferred definitions for the various rocks and soils discussed are given in the Glossary at the end of this book; all terms in the text marked with an asterisk are also included in this Glossary. It is suggested to adhere to these definitions as much as possible. In case deviating or additional definitions are required, it would assist the reader if the non-adherence to a definition is stated, and a clearly worded *ad hoc* or additional definition is given.

3. The Laterite Formation and its typical profile development

3.1 Formation

A formation* may be defined as a persistent body of rock* with a common genetic background, having easily recognizable boundaries and being separated from other rocks by different lithology, geomorphological or lithostratigraphical composition, etc.

Fermor (1911) already mentioned the use of the term laterite to identify the laterite rock formation. Bocquier et al. (1983) suggested to restrict the use of the term laterite to the mappable unit, composed of a series of successive layers that together form the typical laterite profile development.

In the following text the conventional split in a lower saprolite* (or lithomarge*) layer and an overlying laterite layer is made. Recently, French researchers have proposed to indicate all *in situ* weathered material as alterite*. This term would include the saprolite and the accumulation layer.

3.2 The typical profile development

This profile, overlying the unweathered parent rock, is composed of three main layers: saprolite, laterite and soil — Fig. 2A. The unweathered parent rock warrants a closer look as well, as its composition and (rock) texture are important factors in the ultimate weathering products.

(i) The *unweathered parent* rock underlies the weathering profile; the contact with the overlying layer is often gradational in character with a transition zone often indicated as *rotten* rock, composed of crumbly parent rock with some kaolinite in between the silicate minerals; this material is wedged in between the fresh parent rock and the fully weathered saprolite* or lithomarge*. However, *rotten rock* is a confusing term, as 'saprolite' is the translation in Greek of 'rotten rock'. The term *'proto-saprolite** would more correctly describe the material in question; it also has been called *saprock**

(ii) The *saprolite* layer* is the zone of fully decomposed parent rock, partly still showing the original rock structures, while the mineral composition is essentially quartz, of a residual nature, and weathering derived kaolinite, without other newly formed minerals.

This layer may vary in thickness from zero to over one hundred metres — see Fig. 2B. Within this layer, *in situ* unweathered or incompletely weathered masses of the parent rock — core* boulders or core stones — may occur, either of a rounded shape or bounded by two or three sets of now invisible joints, which can mostly still be discerned in the underlying parent rock. The core stones or core boulders can be a nuisance during the industrial use of these materials; core stones may even occur in the lower part of the accumulation horizon.

The core boulder/saprolite contact relations may vary from abrupt to gradational over a distance of up to several decimeters. In many cases there is a still visible (rock) textural* difference between the main mass of saprolite and the core boulder: mostly the core boulder is finer in grain size than the relict texture of the surrounding saprolite.

Fig 2

TRUNCATED   COMPLETE   P R O F I L E

metre thickness

0-2

0-5

1-30

1 - 100

SOIL

ZONE OF ACCUMULATION

DURICRUST

BAUXITE

LATERITE

unstructured

ZONE OF LEACHING

SAPROLITE

structured

CORE BOULDERS
PROTO-SAPROLITE

PARENT ROCK

Fig. 2a

ATMOSPHERE

Interface I: Earth's surface

SOIL

Interface II: top laterite

ferruginous

LATERITE/BAUXITE

aluminous
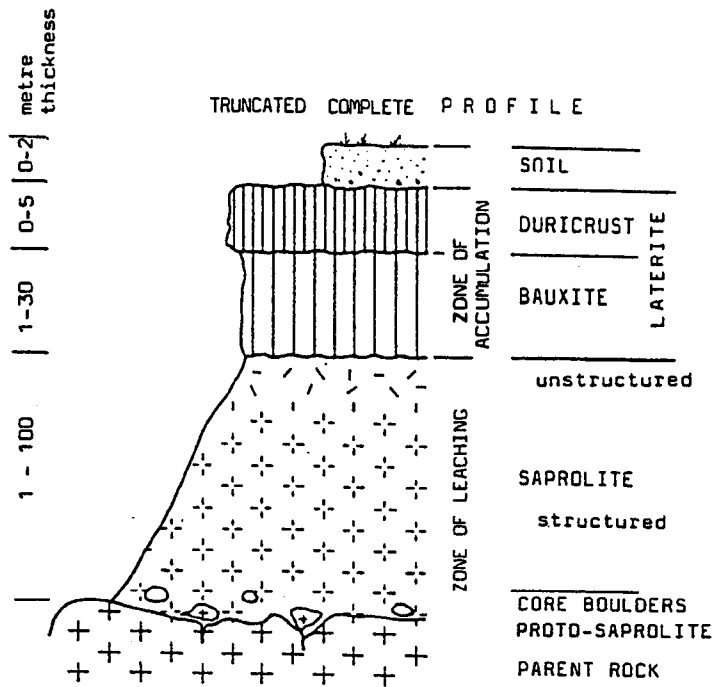
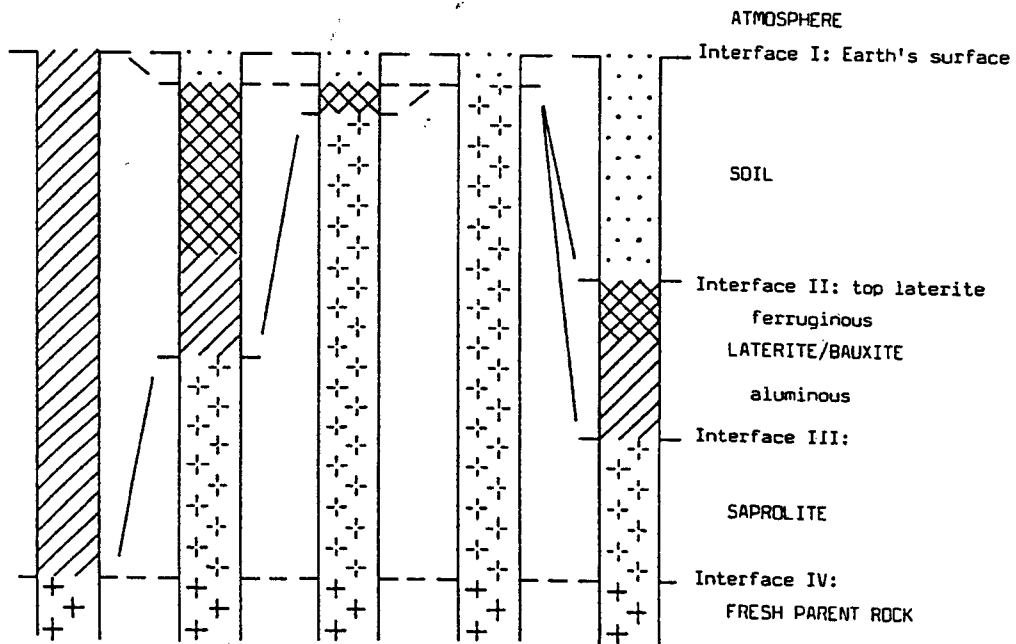Interface III:

SAPROLITE

Interface IV:

FRESH PARENT ROCK

Fig.2b

Fig. 2A - Sketch of the typical laterite-saprolite weathering
profile.

Fig. 2B - Example of reduced or truncated weathering profiles,
illustrating the absence of one or more typical layers.

Two sub-layers can generally be recognized within the saprolite horizon:

(ii. a) a lower *structured** sub-layer with all the primary structures* and textures* of the parent rock still discernable: hard — but sometimes broken up — quartz grains in their original position in space, in a matrix* of fully decomposed (weathered) parent rock minerals, still showing their original shape and size through slight variations in colour within the newly formed kaolinitic mass;

(ii. b) an upper *unstructured** or *massive* sub-layer, in which no primary structures and textures are discernable: the original quartz grains have fallen apart in smaller grains, the kaolinitic mass has become homogeneous in texture* and colour, or the colours present are displayed as Liesegang* rings: secondary, nested rings or bands of reddish colour in the pale yellow main mass — the rings show no geometric relation to the layer as a whole, or the colours are segregated in irregularly shaped spots and mottles; hence the older and imprecise term "mottled zone"*.

The contacts between saprolite and laterite are generally amazingly sharp and often independent of the original parent rock structures and textures.

A little distance below this upper contact, or reaching downward from this contact, the saprolite layer may contain hard bodies of lateritic/bauxitic matter of highly variable shape and size. Generally there is a relation between the shape of these bodies and the original structures of the parent rock: bedding planes, more or less vertical joints, plant roots or root systems, etc. These structural elements give the impression of original voids filled up by lateritic-bauxitic matter of a finely crystalline to dense mature, hence they have been named *grouting structures** (Bárdossy & Aleva, 1990).

In particular in older publications, the layers below the laterite are described in other terms, giving e.g. the following profile:

— laterite, as defined above, mostly with a deep reddish colour;
— mottled clay, the mottles being yellow, red, red brown in colour and up to 10 cm in diameter;
— pallid zone, a whitish, kaolinitic clay;
— fresh rock or 'unleached saprolite' (whatever that may be, sounds as a *contradictio in terminis*).

Others use an adaption or extension of the letter designation as used in successive suggestions for soil profile descriptions, with e.g.:

A or α for the recent soil, with or without residual pebbles, and including 'yellow soil';
B or β for the mineral horizon/layer showing illuvial clay or residual sesquioxide concentrations, and alteration of original parent material;
C or γ for the mineral horizon/layer of unconsolidated material, presumed to be the parent material of the soil;
δ for the layer of weathering rock;
C or R for the continuous, indurated rock.

The following listing provides an overview of the nomenclature used in this Handbook as compared with an older method (Eswaran et al., 1978) and a recent one (Valeton et al., 1991).

It is essential to always clearly indicate or (re)define the terms used, as confusion is easily created.

COMPARISON OF TERMINOLOGIES USED FOR DESCRIBING THE LATERITIC WEATHERING PROFILE

This handbook	Valeton et al., 1991	Eswaran et al., 1978
Residual soil (if present)	Recent soil Residual pebble or mineral layer	α: Pedological soil profile with A-B-C nomenclature
Accumulation zone = laterite-bauxite layer with an upper hard layer or cuirass	B_{ox} - in situ residual breccia - in situ bauxite, mainly with relict textures	β: accumulation zone with sesquioxide enrichment
Saprolite - unstructured - structured	B_{tr} - saprolite (0-x m thick)	γ_m: mottled zone γ_p: palid zone
Protosaprolite	B/C transition zone	δ: incipiently weathered rock
Fresh parent rock	C Fresh parent rock	R: cohesive rock

It is not recommended to employ these profile layer terms, as the existence of the mottling in the mottled zone is probably directly related to relatively recent ground water action. Also other colours have been observed, e.g. in Suriname the saprolite of sedimentary origin can be greyish blue to greyish purple to even vivid purple. It has been suggested that the oxidation state of iron, or the presence of finely divided crystalline hematite, or both, may cause these violet colours.

(iii) The *laterite (bauxite) layer* (Fig. 2A, p. ....). This is the characteristic accumulation* zone (in French often named carapace'*, in English often confusingly called a 'duricrust'*), which is in sharp contrast — chemically, texturally, and structurally — with the underlying saprolite. It is

enriched in iron or aluminium, or both, or in nickel, iron or manganese in the lateritic nickel, iron and manganese ores.

It contains the most conspicuous feature of the laterite layer, best seen in its lower part: the retention of the original rock structures and textures, although most or all of the original minerals have been replaced. Only part of the original quartz is still present as such, but pyroxene, hornblende and in particular feldspar have been replaced by newly formed minerals, mainly gibbsite, and voids. The resultant constancy of volume has been used to compute chemical loss and gain figures (Millot & Bonifas, 1955).

This replacement must have been an exchange of matter on a molecular scale, as the finest details of fine-grained basalts or dolerites are retained in the ultimate weathering product, composed of gibbsite and iron oxides. In coarser grained rocks, e.g. leucocratic rocks of gabbroic composition, gibbsite crystals mimic the cleavage planes of the original Na-Ca-feldspar; the boundaries of groups of parallel-oriented gibbsite crystals mark the original grain size of the parent rock. Proof can locally be found in the only partly weathered rims of large core blocks of the parent rock, where most of the original mineral grains are still present.

Generally, the accumulation layer exhibits two sub-layers:

(iiia) a lower, medium to barely indurated layer with generally a relatively low iron content, but in bauxites a considerable aluminium content.

(iiib) an upper, strongly indurated and generally iron rich and/or aluminium rich layer, best called *cuirass** or duricrust* — the latter is a more generally used term for hard surface layers.

The top part of the accumulation zone — the cuirass — may contain several types of deviating textures and structures, presumably resulting from periods in the laterite's history in which a different climate existed (i.e. lower temperature, drier climate) that caused degrading (i.e. mineral and textural equilibration at lower temperature and lower humidity) changes in the already existing laterite, e.g. brecciation, pisoid formation, etc. Later changes (again warmer and more humid) in the climate caused these degradation products to be incorporated again in the solid cuirass, through cementing by redeposited iron oxides (hence the term ferricrete, but see below).

The accumulation layer is harder — or at least more weathering resistant under present conditions — than the underlying saprolite layer, hence its French name. It is responsible for the typical relief development in the landscape, and as such it is of geographic or landscape morphogenetic importance.

In the English language there are no generally accepted terms for these different features, and the terms used are not always in agreement with their original definitions. E.g. 'ferricrete'*, which was coined by Lamplugh (1902) for iron oxide-cemented conglomerates along the Irish coast, hence rocks of originally detrital and transported origin (Aleva, 1991). Still, the French often translate, in abstracts of their papers, their term 'cuirasse' into 'ferricrete', while 'cuirass' is a good equivalent term in the English language.

In order to arrive at a generally acceptable terminology, the following is suggested: the hardened, massive accumulation layer is divided into:

— an upper, well hardened layer — of variable thickness — called *cuirass** (French: cuirasse), and

— a lower, less hardened main part called the accumulation layer, for which in French the term carapace* is frequently used.

The more or less recent detrital products of the cuirass, transported over the present surface over varying and often large distances, are discussed in section 3.3: Degradation.

(iv) The *soil** — if present at all. Many Laterite Formations do not posses a soil layer of any signature. The cuirass* is directly in contact with the atmosphere, the sun heats the generally iron-rich top layer of the profile. Such Laterite Formations are all but barren, only ornamented by a few single, hardy plants, far apart.

Other lateritic and bauxitic plateaux are covered with a residual* soil, composed of detritus derived from the locally broken down cuirass. There is good reason to believe that in many places the surficial part of the Laterite Formation is in disequilibrium with its surrounding, i.e. the present day — drier — climate (Leprun 1979, Millot 1983 — see section 3.3). This process of destruction and diminution will ultimately lead to a complete surficial disintegration and the formation of a soil, and revegetation of the original outcrop of the Laterite Formation. Or, depending on climate, the completely disintegrated matter will be removed by rain wash or wind action (Millot 1983).

Some laterite deposits grade upwards, over a distance varying from half a metre to several metres, into gravelly, sandy and clayey layers, at the top covered with a plant-bearing soil or even a full tropical forest, e.g. the Bakhuis Mountains, Suriname.

There also exist Laterite Formations which still posses their complete, original soil horizon: an example is the Groundwater* laterite, as described from Brazil by Sombroek (1966). The difference between a residual soil and an unconsolidated layer, later deposited on top of a truncated laterite profile, can be expressed in the notation of the soil sciences as follows:

in situ: A, E, (B_{concr}), B_{pl}, B-$C_{(pl)}$, C_{sapr} , R

ex situ: A, $B_{(soil)}$, II C_{concr}...

The absolute and relative thicknesses of the successive layers are highly varying, so much so that the upper, strongly indurated duricrust* may directly overly barely weathered parent rock with almost clear feldspar crystals.

In such instances it is not uncommon to find complete pseudomorphosis* of some of the parent rock minerals. e.g. feldspar into gibbsite, or Fe-Mg silicate minerals into hematite/goethite aggregates, with more or less complete retention of the original structural and (rock) textural features, even down to the submicroscopic scale — see the coloured Plate II.

This feature proves that alteration can take place without change in total volume of the original rock, The difference in weight (generally a loss) between a certain volume of the parent rock and a similar volume of structured saprolite — or of the laterite/bauxite layer — with rock pseudomorphs, gives an indication of the amount of matter that has been removed from the layer in question during the laterization process (Millot & Bonifas 1955). In other places several tens of metres of saprolite may be directly overlain by a cuirass of half a metre to one metre thick.

In SE Asia atypical profiles are of common occurrence: the accumulation horizon is usually rich in aluminium, which is expressed as gibbsite nodules in size ranging from millimetres to over one metre in diameter, embedded in a kaolinitic clay. These weathering profiles could well be of Pleistocene age, as they are related to the most recent, de-glaciation related landscape features. The parent rocks are Late Mesozoic — or younger — granites and basalts, that could be as young as Plio-Pleistocene.

3.3 Degradation and dispersion of the lateritic accumulation layer

The formation of laterites — as shown above — is essentially a re-equilibration of the mineral phases at particular atmospheric conditions: high ambient temperature and high humidity. The change back to a lower temperature or lower humidity, or both, produces again a re-equilibration in the mineral phases, resulting in chemical and mechanical changes in, and destruction of, existing laterite cuirasses.

The geological literature provides a number of excellent studies that contain details on the 'negative' re-equilibration processes, that best can be described in one word as degradation*.

Maignien (1966) described numerous cases of the physical and chemical attack on existing laterite cuirasses, and the subsequent deposition of in particular the iron component, which may travel in solution over long distances in the ground water, The resulting iron-rich deposits are

frequently confused with laterite deposits; they are in reality the reprecipitation of iron — derived from laterite deposits more or less far away — from circulating groundwater. The term 'ferricrete'* has also often been used — erroneously — for these precipitates.

Grandin (1976) studied in detail the history of the destruction of a bauxitic cuirass in the boundary area of the Ivory Coast, Burkina Fasso and Ghana.

The uppermost, bauxite-bearing plateau level, at 450-550 m elevation (and 300-400 m above the local base level) presumably is of Eocene age; it is still present in small caps on the highest hills, covering about 0.2% of the total surface ares of the region. The compact cuirass remnants, 10-15 m thick, are mainly composed of gibbsite, goethite and hematite, with pisolitic, granular and brecciated textures and some ferruginous deposits.

The lonely bauxite-capped summits are surrounded by a succession of piedmont levels, the highest covered with an iron-kaolinite crust without any quartz; the three lower levels are covered by crusts composed of iron oxide, kaolinite and quartz (33 % in the lowest level). Table III gives a summary of the results of Grandin's study (which contains several lucid geomorphological block diagrams and sections). It is interesting to observe, how already in the Intermediate level the original aluminium concentration has disappeared, while the iron content shows a maximum in this level. The crusts covering the successive piedmont levels illustrate the gradual decrease, level by level and hence in time, in their content in iron and kaolinite and the increase in quartz.

Several other workers studied the decay, or second re-equilibration phase, of the lateritic accumulation layer. Leprun (1979) provides extensive chemical data (using a tri-acid treatment to dissolve the sample matter). Boulangé (1984) used micromorphological methods, borrowed from the soil sciences, to study the processes that formed and transformed the cuirass. Numerous clear drawings illustrate this study.

More recently, a geochemical approach to pedogenesis and lateritization has been used by several scientists. Brimhall *et al.* (1991) is a recent example, which gives a wide-ranging overview, in which the behaviour of gold mineralization in the bedrock provides interesting clues.

Smith & Anand (1991) gave an overview of the work by the CSIRO Division of Exploration Geosciences in West Australia; they also announced the development of a laterite atlas (largely paid for by the mining industry and hence — as yet — not in the public domain). The arid and semi-arid climates of much of Australia provide numerous examples of the degradation processes in laterites and their results as seen in the terrain. They introduced the term "lateritic residuum"* for reworked and rounded, iron-rich "gravel" that covers the surfaces of the successive planation stages.

Comparable work is in progress in SE Australia by Bourman (1991), in an area with somewhat different geological history. He stated: "As surface weathering and erosion proceeded, the iron segregation, largely as hematitic mottles, were progressively exposed at the surface, where they hardened, disintegrated, and formed lags*". See also a forthcoming volume of the Handbook of Exploration Geochemistry by Butt & Zeegers (in press).

3.4 Some remarks

Parent rocks do not necessarily have to be consolidated rocks (in Geology even a soil is a 'rock'). The bauxites in Guyana and Suriname had as parent material unconsolidated sediments,

composed of arkose*, interlayered with clayey sediments. The stratified, very fine-grained kaolinitic saprolite below the present day bauxite deposits is — at least partly — deposited as a much coarser sediment, as is testified by the coarse, weathering-resistant minerals enclosed, such as quartz, staurolite and opaque minerals. Also the grain size of these sediments has been of influence on the process of 'bauxitization' (i.e. the formation of an aluminium-rich accumulation layer): at some depth (varying from 0.2 to 4 metres) below the main bauxite layer there may occur 5-80 cm thick bauxite layers interbedded in the kaolinitic saprolite. These bauxite beds can be followed horizontally for many tens of metres; eventually they either pinch out or become part of the main bauxite layer (Aleva, 1965). The opposite does also occur: a kaolinitic layer of 1-3 dm thickness pinches out in the bauxite layer. The last tens of metres of the clay bed form a boudinage structure within the bauxite. Only the very last kaolinitic lens (circa 10x30 cm in size) is fully converted into a dense, porcelaineous and very pure bauxite (composition: in the order of 63% Al_2O_3, 2% SiO_2 and 1% Fe_2O_3).

The possible complexity of the formation of bauxite, i.e. a particular version of the formation of an accumulation layer in the lateritization process *sensu lato*, is illustrated in Plate B, photograph 1, where a banked or layered bauxite (arkose derived) is transected by a cross cutting — or epigenetic — 'vein' of dense, colour-banded bauxite (Bárdossy & Aleva, 1990, Fig. 3-5).

Table III

TABLE III – Synopsis of the landscape development in the Blafo-Guéto area, Ivory Coast, after G. Grandin, 1976

Level name type age	Hight:(m) absolute Relative % total surface area	Thickness soil (m) Crust (m) Structure	Chemical comp. % Al_2O_3 % Fe_2O_3 % SiO_2 % average/ range	Mineral comp. % Fe-min's Kaolinite Quartz	Duricrust facies Main types
BAUXITE Plateau level Al-Fe crust Eocene	450-550m R300-400m 0.2 %	0-0.3 m 10-15 m compact	Al 51 36-62 Fe 26 1-40 Si 2 0.2-5	Fe 17.6 KLT 4.2 QRZ 0.0	Pisolitic Granular Breccia Encrusta- tions
INTERMEDIATE level Older piedmont level Pliocene	200-340m R100-150m 0.1 %	20-30 m 4-6m fractured	Al 15 4-18 Fe 60 50-79 Si 13 4-19	Fe 59.6 KLT 27.6 QRZ 0.0	Concretio- nary Pseudo- gravel Massive Reworking
HIGH PIEDMONT level Early Quaternary	80-260m R 20-70m 10-15%	<1m 1-4m spotty	Al 17 14-23 Fe 42 31-54 Si 26 17-38	Fe 41.6 KLT 41.3 QRZ 6.8	Gravel Alveolar Platy
MIDDLE PIEDMONT level Middle Quaternary	– R 2-30m	No soil <1.5m –	Al 16 8-24 Fe 30 17-49 Si 40 21-58	Fe 33.6 KLT 31.9 QRZ 24.1	Gravel Locally: alvolar platy
LOW PIEDMONT level Subrecent	– R 0-2m	some dm Locally –	Al 12 7-19 Fe 29 12-55 Si 47 26-63	Fe 29.1 KLT 29.2 QRZ 32.9	NOT well developed ferrugi- nous con- cretions.

4. The cyclic nature of the processes of laterite formation

In essence the processes consist of *in situ* subaerial weathering (an intentional pleonasm) of a rock, which then becomes a parent* rock; effectively it is the equilibration of the parent rock mineral association to the temperature, pressure and humidity of the earth surface environment.

A humid tropical climate provides the most favourable process circumstances for this re-equilibration, i.e. high process temperature (remember the Van 't Hoff [1852-1911] theorem: reaction speed increases 2-3 times for every degree Celsius temperature increase, e.g. from 18°C to 28°C around 2000 - 180 000 times!), abundant fresh process water (high rain fall as well as good drainage), and abundant organic matter and (micro-)organisms to provide organic acids to accelerate the weathering process. In addition the seasonal variations in pluviosity result in seasonally varying groundwater levels, hence a wide zone with alternating supply or lack of oxygen.

The processes at work are in principal similar to those required for the formation of soils, hence the vague boundaries between laterite, plinthite and soil. Products of weathering — be it in highly metamorphosed state — have been recorded from Archaean times onward. Abundant lateritic products, in essentially un-metamorphosed state, have been recorded from the Carboniferous, from Upper Cretaceous-Eocene times, from the Middle Miocene to the Upper Pliocene, and from the Quaternary period.

Lateritization is a process at the interface earth-atmosphere, hence — as a result of erosion and denudation — at different times different rock levels of the earth crust were in contact with the atmosphere, depending on local erosion and denudation (or deposition!). In addition, crustal plate movements transported certain plates, or parts of these, in a SE ——> NW direction completely through the most favourable latitudes for weathering and lateritization. Finally, certain periods had a more favourable climate for lateritic weathering than other periods — see Fig. 3 (after Frakes 1979 and Haq et al. 1987).

Tectonic plate movements must be taken into account when considering the time span required for the formation of certain laterite/bauxite profiles. The intensity and the duration of the formation processes will be mirrored in the thickness of the profile formed, taking into account the different susceptibilities of the various parent rocks. Using the stratigraphic column with the estimated ages of the successive periods and epochs — e.g. the one by Van Eysinga (1975) — leads to the time spans for the lateritic weathering processes in the northern part of South America as shown in Table IV (the Guyana Shield, partly after Aleva, 1984).

Kronenberg et al. (1979, 1982) estimate the time required for the development of a deep laterite-bauxite profile to be in the order of 10 to 100 Ma, an estimate based an research on the Paragominas bauxite deposits in the Eastern Amazon region.

Lucas (1989), working in the central Amazon area near Manaus, arrives at a required time range from > 80 Ma for the oldest ferruginous cuirass on a quartz-rich sediment, to approximately 30 Ma for the gibbsitic accumulation (3-8 m thickness of the bauxite),

It should be realized, that any period of increased weathering activity not only attacks fresh rocks but also continues to work on already existing weathering crusts and their degradation* products formed during the intervening periods of lower temperatures, dryer climate, or both. This could explain why so many laterite profiles show in their upper horizons such a multiplicity of different textures and structures.

Fig 3
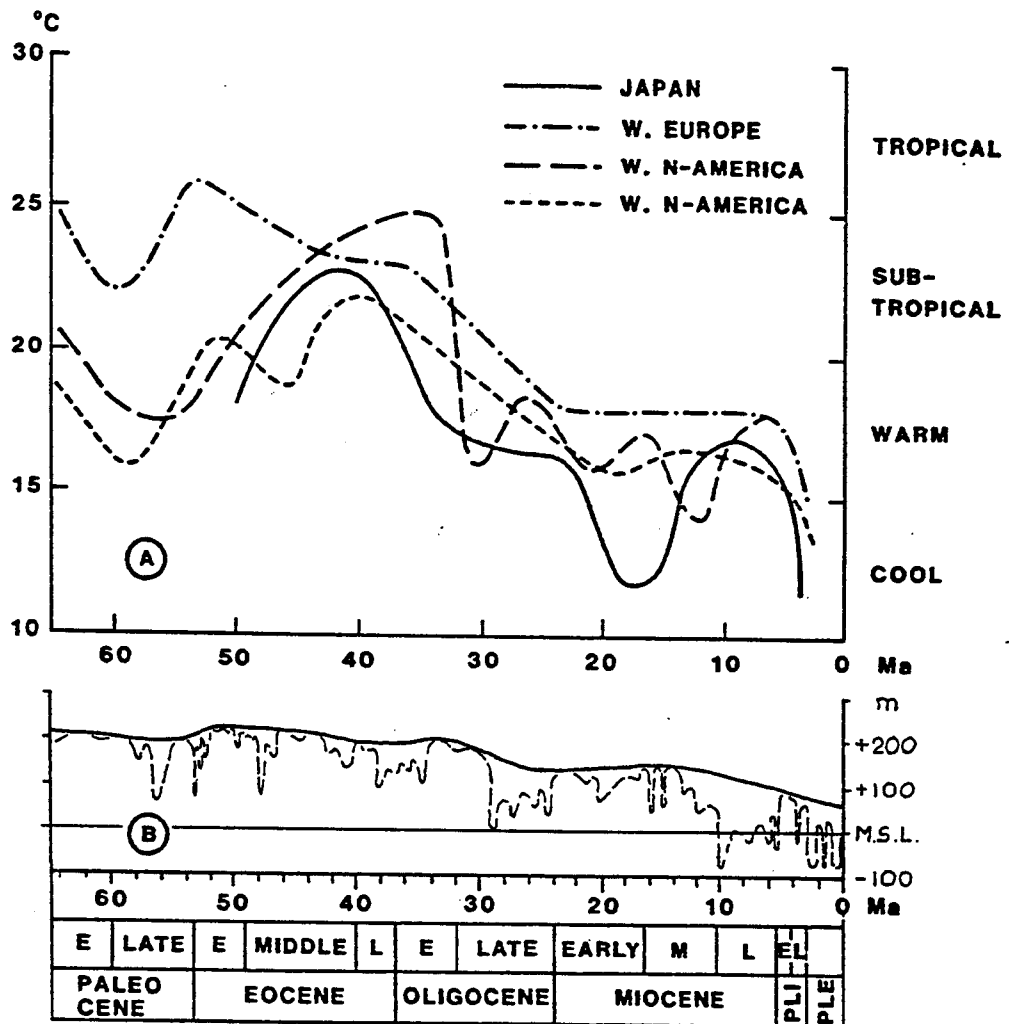
Fig. 3 - Charts illustrating the world-wide fluctuations during the Cainozoic of two features that contribute to the prevailing climate.
A - Changes in the mean ambient surface temperature in °C, after Frakes, 1979.
B - Changes in the average sea-level: the heavy line is the long term fluctuation, the broken line is the short term variation; after Haq et al., 1987.

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Parent rock composition and texture are important factors in the lateritization process: feldspathoids weather more easily than feldspars, while very fine-grained igneous rocks and very coarse-grained pegmatitic rocks resist weathering in relation to fine to medium grained rocks. At similar grain sizes, it can be stated that lateritization is realized fastest in alkaline rocks and arkoses, through basalts, dolerites and anorthosites to the slower reacting granites and feldspathic sandstones.

Table IV — Laterite deposits and their thickness versus planation levels and their ages in the northern part of the Guiana Shield (After Aleva, 1984)

Period	Age of lower boundary (Ma)	Observed average thickness (m) of laterite/bauxite	Name of topographic surface	Duration of favourable weathering period
Quaternary	1.8	< 2m	present surface with plinthite	< 1 Ma
Pliocene	5	~ 2m	Pediplane level with laterite	~ 2 Ma
Miocene	22.5	< 5m	Foothill level with laterite	~ 10 Ma
Eocene/Cretaceous	100	5-15 m	Main laterite-bauxite level	~ 25-30 Ma

5. The uses for and the description of laterites

The complete description of a Laterite Formation is a difficult and time consuming task. The interest in – and the uses of – laterite are highly varying, and hence it is common practice that a description is made to include in particular those facets that are of prime importance for a specific, potential user – or the person threatened by the presence of laterite, e.g. the local farmer.

Aleva (1986) gave a list of interested professions, and their particular interests, which is reproduced here in a little different version:
– Farmer: how to prevent hardening of the soil;
– Civil engineer: where to find sufficient road metal or railway ballast; how to construct a durable dam or road;
– Geomorphologist: laterites as markers of stages in the landscape development;
– Survey geologist: the nature of the parent rock below the laterite;
– Economic geologist: the chemical and mineral composition of the total available volume;
– Mining engineer: hardness and moisture content of the laterite, the presence of core boulders;
– Ore trader & process engineer: the chemical and mineralogical composition in view of potential users (e.i. TiO_2)

There are three stages in the description:
– In *the field* where the basic data for al the further work are collected; an error or omission made here, can only be repaired by returning to the spot, which may be prohibitively expensive.
– In the *laboratory* there is mostly an enormously broad choice of different tests and examinations; it is economically important to select the minimum number of analyses to be made, but they should cover all the essential aspects required for the particular assignment and the terms of reference in force.
– In *the office*, finally, the essential data and the outcome of the investigation must be summarized in a concise and clear final report. This should preferably contain some photographs of the area and of the outcrops sampled, and a good map of the investigated area (with an index map to show where in the country the fieldwork has been done).

There exist a few manuals for the effective description of field observations. For soils the FAO Guidelines for Soil Description (FAO, 1990) is a good manual. It also may assist in the description of 'geological layers' by following selected methodologies and some of the measurable characteristics. Otherwise, standard geological texts in sedimentary and igneous petrology should be followed.

5.1 In the field

The description starts with defining the object.

– Give X, Y, and Z of the outcrop studied, in the national geographical coordinates.
– State the name on the map or the name by which the spot is known by the local population.
– Give a short description of the local landscape, the major relief features, if any, the vegetation, and the climate. See e.g. the "Guidelines for Soil Description" (FAO, 1990) for

descriptive terms for the landscape and the lay of the land. State the representativeness of the survey site for the larger surroundings.
- Describe macroscopically the Laterite Formation, starting with an overview and proceed stepwise to more details, e.g.
  - the profile as a whole;
  - number, thickness and character of the discernable layers, if any; the presumed (weathered) parent rock to be considered as a layer as well;
  - description of each separate layer with colour(s), structures, textures including voids (use hand-lens!), mineralogy as far as possible with the hand-lens only, nature of contact with the underlying layer, samples taken (for each with position within the layer and analytical work proposed), horizontal changes within the layer.
- Take photographs e.g. from the total vertical profile and from each of the layers separately; prepare the face of the outcrop for photography by placing a measuring staff (graduated in cm, dm and m) for scale, and place numbered cards or boards at the spots where samples have been taken. If colour photography is being used, place also a standard colour reference chart or colour-striped tape to guarantee correctly coloured prints later.
- Collect monolith, if so desired and planned.
- Make a bore hole, or excavate/dig a pit or channel, in places where the lower layers are not exposed, either from the top of the Formation, or from a position at the foot of the outcrop slope.

The macroscopic description of the laterite profile and its successive layers should make use of standardized terms and nomenclature, without terms such as 'fist-sized', etc.
Recently several papers have been published in international journals and conference proceedings that may assist in providing systematic descriptions in clearly defined terms (Aleva, 1983, 1986, 1987; Bárdossy & Aleva, 1990; Guidelines for Soil Description - FAO, 1990; see also Annex III). All measurements should be given in the official International System of Measures (SI), correctly using capital and lower case letters as well as dots and commas!

There is one structural/textural unit that warrants specific mention: the *pisoid** (or pisolith) which, when occurring in great abundance, forms the rock called *pisolite**. It is suggested to use in the laterite context the term pisoid, in order to prevent confusion from the calcite pisoliths found in many limestones.

Pisoids may range in size from say 3 to 30 mm; they are generally well rounded, and contain a massive core or *nucleus*, surrounded by a cortex composed of many, thin concentric and colour-banded layers. Cortex and nucleus range in colour from white to black, with in between all shades of yellow, pink, red and brown.

Some pisoids have a more complex structure, with a core composed of a number of small pisoids or pisoid fragments, which are enveloped by the outer cortex.

Diameter of core and thickness of cortex vary greatly: some pisoids are mostly nucleus, with a cortex not much thicker than a coat of paint, while other pisoids are almost without core (See e.g. Bárdossy & Aleva, 1990, from which Annex II-c is borrowed).

The frequency of occurrence of pisoids is also highly variable: there are large deposits without even one pisoid (Onverdacht, Suriname, South America, a bauxite deposit — Aleva, 1965, and the deposits of the Eastern Ghats, India) and there are also huge deposits that consist completely of pisoids (Weipa, Queensland, Australia, also bauxite).

The chemical/mineralogical composition of pisoids is highly variable, from mainly gibbsite to mainly hematite/goethite. In some deposits the majority of pisoids have a nucleus with a septarian type of cracks, generally filled with gibbsite.

5.2 In the chemical/mineralogical laboratory (see Annex V)

The following remarks may seem superfluous, but . . .

— Assure that sufficiently large reference samples are taken and safely stored directly after the samples have been received in the laboratory. These reference samples must be stored on a permanent basis, e.g. in closed (and sealed?) plastic or glass containers with a label mentioning number, name of sample location and country, and the name of the scientist who took — or was responsible for taking — the sample, and the date and year of the sampling.
— Arrange for the permanent filing of all available information, including maps and literature references, with respect to the sampling site and its surrounding.
— Decide on a comprehensive plan for chemical, mineralogical, petrographical and/or physical characterization of the samples, according to one or more of the following conventions:
- soil sciences, inclusive of micromorphology based on soil thin section descriptions (cf. Handbook for soil thin section description, Bullock et al., 1985);
- scanning electron microscopy (SEM): study of microfabric of laterite, morphology of minerals present and their spatial relationships;
- mineralogical/geological descriptions and specific chemical analyses as used in the investigations of mineral deposits;
- physical and mechanical investigations as used in soil and civil engineering and foundation practices.

Chemical analysis used during exploration activities for mineral deposits (bauxite) should adhere to the specific requirements and conventions of the relevant industry. For all lateritic rocks this includes careful drying at a temperature not higher than 105 °C — and not longer than necessary — in order not to destroy the OH-group containing Al and Fe minerals (gibbsite and goethite).
In case of bauxite, this includes mainly the necessity of a double silica determination, i.e. separate determinations of the silica contained in kaolinite (= reactive silica), and that present as quartz and unweathered or only partly weathered silicates, e.g. staurolite. This is generally realized by using a tri-acid solution to digest the sample aliquot (instead of using a melting procedure with aggressive agents such as Na_2O_2, caustic soda or Na-K-pyrosulphate); in the resulting solution the kaolinite mineral is decomposed while quartz and remaining rock silicate minerals are not attacked. The quartz SiO_2 is determined afterwards through weighing before and after an HF treatment of the precipitate to remove the quartz present; or total silica is determined by physical analytical methods and the reactive silica is subtracted.
A completely different approach may be used in bauxite exploration, where a representative sample is treated in a laboratory-scale alumina plant. One gram of the ground sample is placed in a nickel-steel bomb (autoclave) of 15 ml volume, 10 ml of the plant-type caustic soda solution is added and the bomb is heated — while rotating — to the temperature at which the alumina plant is (proposed to) operate, e.g. 150-250 °C. After a standard lapse of time, the bomb is opened and the various required analyses are made on the highly charged liquid. This involves

determination of dissolved Al_2O_3, Fe_2O_3, and (reactive) SiO_2. Generally used operating temperatures are approx. 150 °C and approx. 250 °C.

A source of information for alumina-related analyses, etc., is the Light Metals Yearbook of AIME, USA.

Geochemical investigations, i.e. the determination of trace elements and their spatial distribution, may provide interesting information on the lateritization processes of the parent rock.

Truckenbrodt et al. (1991) studied in detail the laterite/bauxite deposits of the Lower Amazon area in Brazil, trying to establish once and for all the origin of the 5-10 m thick clay layer covering the accumulation zone. They did not succeed in arriving at a definite answer to this question, but they established that the parent rock, the laterite/bauxite accumulation layer and the overlying Belterra clay are geochemically clearly related.

Geographical trends in the geochemical composition of the parent rocks recur in the geochemical composition of the accumulation layer and in particular in the covering Belterra clay. This correlation is so close that the authors suggest that geochemical analysis of the top layer can be used for the prospecting of (metallic) mineral deposits in the saprolite and in the parent rock. Hence, they suggest that the above relation could be employed as a mineral exploration method to look through the laterite cover.

Valeton et al. (1991) discuss in extenso the use of chemical analyses of main and trace elements to characterize the lateritic weathering processes. They show how certain elements may get lost during the lateritization processes (e.g. Ba, Ce, Zn), while others are clearly accumulated (Cr, V, Zr) in the course of the intense chemical 'reworking' during weathering.

Mineralogical analyses are essential in many instances, as they may allow to determine e.g. substitution of Fe by Al in minerals such as goethite and hematite, and the hematite/goethite ratio itself.

Mineralogical analyses can in many instances — e.g. when a translation of the chemical composition into the mineral compostion would facilitate the understanding of the rock forming process — be substituted by petrochemical computations (norm* computation), provided that good chemical analyses are available and a differentiation has been made between total silica and free silica (=quartz) (Van der Plas & Van Schuylenborgh, 1970, Bárdossy & Aleva, 1990)

DTA analysis is useful for a quick determination of the gibbsite content, as DTA instrumentation is present in most soil laboratories. For field determination of the gibbsite content a portable differential thermal gravity instrument is well suited ("Gibbsite analyzer", Van Essen et al., 1971).

Density determinations are more difficult and time consuming than most operators realize. Most rocks have a larger inhomogeneity than is realized at first observation, and laterites are notorious in this respect. Hence relatively large samples — at least 10 to 25 kg each — are required, and the sample must be packed and stored — until analysis — in an air-tight container, as the natural moisture content must be determined as well. Hence, also collect the moisture condensed against the walls of the containers used.

When average values of the laterite profile are required, the most efficient sampling method is to make narrow, vertical sampling slits from the upper to the lower boundary of the laterite profile. Take a number of similar sized samples along the slit, and combine these to one final sample to be analyzed.

When more detailed information, e.g. layer by layer, is required, the sampling should employ one sample for each layer, and where layers are thicker then 1 metre, a sample should be taken for each successive metre (the last sample will generally be a fraction of a metre!). The sampling slits preferably have a rectangular isosceles triangular cross section (with the 90° angle digging into the laterite wall; use a metal or plywood template to check the cross-section on shape and size). The in situ density figure of each sample must be accompanied by its moisture content! The (dry) density may vary between 1 (Fe-poor bauxite) and 3 (for iron-rich laterite), average values (dry) will vary between 1.3 and 1.8.

In addition to pitting, drilling and sampling of natural talus, there is the possibility to drive a tunnel; this will be an exercise of last resort, as tunneling requires experienced staff, and the more of less horizontal tunnel will only provide samples of one depth level.

5.3 In the office

Prepare a summary report on the observations made and the analyses executed, giving also the analytical methods employed. It should contain all the essential data obtained in a summary way. Be sure to include a topographic map of the area, the key words by which the detailed data can be reclaimed from the files, and the location — with box or drawer number — of the duplicate samples stored in the storeroom.

6. Artificial outcrops or pitting and drilling (see also Annex VI)

The highly variable nature of the Laterite Formation is such, that closely spaced sites of observation and data collection are needed when considering mineral exploration, planning excavations, or civil engineering work.

Depending on the purpose, this will often require drilling, pitting or trenching to produce artificial outcrops. There are many successful methods available for creating artificial outcrops, but the selection of the most appropriate method for each situation is far from simple because of the many, often conflicting technical requirements, and financial, infrastructural and time restrictions, all of them related to the local situations. Four examples follow.

6.1 Pitting

This is possible in almost any situation and it produces the best artificial outcrops for geological and engineering studies. The sampling required can be guided by detailed geological observations. It is also the slowest method available, but in remote areas generally the cheapest!

A good example is furnished by the exploration for bauxite in the central Amazonian forest, the Trombetas area.

— *Amazon tropical forest — well drained:* originally pitting was used to create artificial outcrops through the 5-10 m thick bauxite formation and the overlying 8-12 m kaolinic clay. Pit depth varied between 8 and 12 m, the diameter of the circular pits was 0.8 m (no ropes required for entering and climbing out!). The pits were dug by three men: one at the bottom with pickaxe or shovel, one at the surface to hoist the broken up soil and laterite, and one man for safety if something would happen at the pit bottom. The deeper pits (over 8-12 m) required artificial ventilation, realized with a small, hand-operated blacksmith's air blast operated from time to time by the third man at the surface. Average time required for an average hole (12-15 m deep) was 14 days, inclusive of the daily walk to the camp. Sampling was by cutting vertical channels from the pit wall, after the field geologist had marked (with 10 cm long nails) the (sub)layer boundaries; one sample for each (sub)layer or maximum 1 m plus a sample for the remainder of the (sub)layer.

6.2 Drilling

Mostly a fast method, and depending on the method used and on the local situation, it may be very cheap or very expensive. The quality of the samples obtained is highly variable with the drilling method used, which is determined by the technical/geological requirements of the sample to be obtained, and the local hydrological situation, i.e. the level of the water-table and the moisture content of the material to be sampled. A few examples with contrasting parameters follow:.

— *Suriname Coastal Plain:* partly swampy — up to 2 m deep — and completely waterlogged. Banka* drilling with 5 cm ⌀ casing, unconsolidated overburden (when detailed sampling is not required) blown out by water jet (5 cm ⌀ centrifugal pump with small gasoline engine). Sampling starts from the top of the hard duricrust/accumulation layer; samples taken over every

successive one metre penetration separately. Profile description based on macroscopic study of the sludge and the hardness, i,e. penetration resistance. The best drilling bit for the laterite/bauxite layers is preferably of the fish tail type with two narrow, pointed tungsten carbide tipped teeth. Drilling bit directly connected to a core barrel to collect the drilling sludge at the bottom of the hole; core barrel closed at the bottom with a ball valve.

—*Amazon tropical forest* —*well drained,* same location in the Trombetas area as example a: core drilling producing 15 cm diameter cores; compressed air to flush the cuttings out of the hole; cores directly collected into 15 cm ø plastic tubes. Drilling crown with large chunks of tungsten carbide as teeth with a good amount of space between them to prevent clogging.
Average 3 holes per working day (a little less in the rainy season); distance to camp 10-45 minutes by truck. Description and sampling of the core in the central camp (after removal from the plastic pipe) layer by layer. With three drills operating round the clock, the cost per hole was still a little higher than the hand-dug pits — but the required time for a drilling campaign of say 500 pits/holes was considerably less — which may be a decisive factor in an area with a long and heavy rainy season.

— *Australia, Darling Range* —*well drained*: drilling with a rotary type vacuum drill mounted on an agricultural tractor. The simple, 2-pronged drill bit is connected to a hollow rod, which is connected with rubber tubing to a type of dust collector with an air suction pump. There is a fast depth progress as long as the drilling pulp is dry; the drilling pulp is automatically collected — without losses — in the dust collector, which is emptied every one metre or so drilling progress. At the bottom of the hole, where the underlying saprolite hinders draining of the bottom 0.5 - 1 m of the laterite profile, moisture problems may locally occur, i.e. clay plugs may hinder the air flow and no sample reaches the surface.

In general, it must be realized that the great horizontal and vertical variability of laterite deposits requires a large number of sampling points, i.e. number of holes or pits per surface unit. Bauxite ore reserve drilling will often start at a 200 x 200 m grid, later to be reduced for quality control purposes locally to as little as a 10 x 10 m.

6.3 Trenching

This is a superior method as continuous geological observations — horizontally and vertically — can be made over distances of up to several tens of metres. Usually heavy earthmoving equipment (depending on thickness and consistency of the overburden or cover) is required, which restricts trenching generally to the last stages of a feasibility study — when dealing with possibly commercial laterite deposits. For foundation and road construction engineering the trenching method is particularly useful — and often adequate equipment can be obtained near the site.
Trenching by hand is used in e,g. Gujarat, N.W. India, for the exploration (and mining) of refractory grade bauxite (small tonnages can already be economically interesting); the bauxite occurs as rounded to irregular shaped boulders and larger pebbles in a kaolinitic clay. Trenching and breaking up the top 1-2 m of the ground is done by male labourers, handpicking and cobbing the bauxite for quality control is done by female labourers (who also do the transportation of ore within the mine — on their heads).

6.4 Shaft sinking and tunneling

These artificial outcrops require sound technical advice and supervision from a mining engineer during the full period of creating the open space in the ground and the period of study and sampling. The mining regulations with respect to marking the hole at the surface, and closing the hole after the work is finished, should be adhered to closely .

Shafts are — with respect to sampling — very similar to pits, in particular when the sampling can be done in between the drilling, blasting and mucking shifts of the mining crew. Hence, when the wall to be sampled can be reached by short ladder from the shaft bottom.

Otherwise, the sampling has to be done at a later stage by a geologist to mark the sample sites and by — preferably at least two — samplers. These men have then to be lowered from the surface, sitting on a boatswain's chair, by a competent hoisting crew. The sampling of an existing shaft is a notoriously difficult job and prone to accidents!

6.5 Geotechnical aspects of laterite (Contribution by A.M.Kruse — Delft Geotechnics, Delft)

In soil and rock engineering laterite is commonly referred to as reddish to brownish hard encrustations, or more or less homogeneous reddish to brownish earthy material. It is generally considered to be a "residual soil", and as such it is recognized to behave differently from common soils. In this section, reference is made to the weathered material laterite in the sense used in this "Corlat Handbook". The Engineering Group Working Party of the Geological Society has published in 1990 a report on Tropical residual soils (EGWP, 1990) containing an extensive review of sources. Several conferences on the mechanical aspects of residual soil in tropical terrain have been held (see references Proc. Honolulu 1982, Brazilia, 1985, and Singapore, 1988).

In general, the geotechnical aspects of laterite can be differentiated after behaviour of the materials in situ, behaviour of the excavated material used in earth works or brick work, and the physical and physico-chemical background of the mechanical behaviour of the material.

Prominent in situ characteristics concern:
— bearing capacity
— stability of sloping or otherwise loaded terrain
— compressibility under surface load
— bulk density
— erodibility
— permeability
— excavation characteristics
— long term changes
— vertical and lateral variation in properties

Characteristics for the excavated material are many; notable characteristics are:
— bulk density
— compaction and densification behaviour
— abrasion and erosion behaviour
— permeability of reworked material

– lateral and vertical variation of properties at the borrow site.

The engineering properties of laterite can be determined using the common soil and rock testing procedures, the latter for hard material, both in situ and in the laboratory. Care must be taken for changes in properties as ambient conditions change. Due attention must be paid to dispersion characteristics, erosion behaviour and what is called collapse in laterite.

The engineering properties of laterites are generally understood to be determined to a large extent by cementation within and between aggregates and particles by various agents, and by the pore-system in the material. For the strongly deformed and excavated material, the properties are also determined by the properties of the individual particles and aggregates. The properties of the mineral phases present in laterites are notably those of iron and aluminium oxides and hydroxides.

The relevance of cementation is evident in a lack of general relevant correlation between mechanical properties and various classification parameters commonly used to identify granular and cohesive soils (i.e. Atterberg limits, grain size distribution, bulk mineralogical composition, bulk density, etc., see Gidigasu, 1976). Correlation may of course well be evident for individual occurrences.

The porosity of laterites in some location in India ranges from 10 to 40 % = V_{voids}/V_{total} (Mallikarjuna et al., 1981). The natural moisture content of those laterites varied from 5 to 20 % (m/m), but is of course highly dependent on site conditions. The dry bulk weight of laterites is highly variable, and ranges from about 14 to over 20 kN/m^3 [1.43 to 2.04 t/m^3]. Laterites generally have significant portions of larger pores in the in situ material, resulting in relatively high permeability (field tests suggest about $10^{-5} - 10^{-6}$ m/s). The permeability of the underlying saprolite is usually much lower.

The compressive strength of the in situ laterites is high, from about one to several tens of MPa [1 to several tens of kg/cm^2], and is higher in the uppermost layers with a relatively low water content and relatively much ferruginous material. The strength of laterite is reduced upon weathering of cementing material or upon frequent changes in water content such as due to exposure in road cuts.

The excavated material is used for e.g. road construction. The quality of the material as base in a road construction is debated (Sahasrabudhe & Vaidyanath, 1981), as a result of degradation of the material upon compaction and exposure to wetting condition (hindered drainage). Addition of 6 % lime appears to result in a suitable base material for a Nigerian laterite (Akinlambiola, 1977).

The vertical variation found in a laterite profile requires detailed sampling to establish mechanical properties. This is the more so in polycyclic landscape environments. The properties of laterites will change as ambient conditions change since water content changes and mineralogical changes will occur. These short and long term changes will have to be considered in designing constructions on and with laterite. Also the use of excavated material will have to pay due attention to the variability at the borrow site and to changes upon excavation.

See also Charman (1988).

6.6 Knowledgeable volunteers requested for field and laboratory criteria to distinguish monocyclic from polycyclic profiles!

6.7 ???.

GLOSSARY

Definitions or explanations are given for terms marked in the text with an asterisk (*). In addition, all terms occurring in the appendices and figures are presented, as well as several other related terms.

The derivation or author of the term is given between brackets. GG marks that the term's explanation is taken from the 'Glossary of Geology', by Bates & Jackson (1980); GN refers to Visser (1980): Geological Nomenclator; most of the unmarked terms are derived from Bárdossy & Aleva (1990): Lateritic bauxites.

If terms are used in several subdisciplines, the name of the relevant discipline is added in brackets.

Accumulation zone: (weathering) that part of the lateritic weathering profile which is characterized by the accumulation of one or more of the elements Al, Fe, Mn, Ni, etc.; the material is generally harder than the underlying saprolite, whence indicated in French as 'carapace'.

Acicular: needle-like in shape.

Allite: weathering products (through hydrolysis) mainly composed of $Al(OH)_3$ = gibbsite, and α FeO.OH = goethite (Harrossowitz 1926). See also ferrallite.

Alterite: (weathering) a surface or near surface rock characterized by its complete mineral re-equilibration to the physical-chemical environment of the reigning or fossil (e.g. humid and tropical) climate. The main components are kaolinite or gibbsite, or both, with Fe compounds and weathering resistant minerals such as quartz.

Alveole: the smallest of the interstices* distinguished (<16 mm), usually equant to tri-axial in shape. Their shape, frequency and distribution pattern is highly variable, from the occasional opening to making up >50% of the rock surface or volume, in which case they determine the rock texture (alveolar, spongy*); see Annex III.

Aphanitic: rock texture in which the components are <0.06 mm in diameter and hence not distinguishable with the unaided eye (GN).

Arkose: a sedimentary rock largely composed of feldspar grains; a feldspar sandstone.

Armour: a possible translation of the French term cuirasse; when rich in iron: iron crust.

Auger: a screw-like boring tool to make shallow sampling holes in unconsolidated sediments or weathered rocks. See Annex VI.

Azonal soils: soils that are too young to reflect the influence of site-specific conditions in their profile characteristics; see also zonal and intrazonal soils (Driessen & Dudal, 1989).

Banded: said of a vein, sediment or other deposit having alternating layers of matter that differ in colour or texture* and that may or may not differ in mineral composition. Also an outcrop feature developed in igneous and metamorphic rocks and the weathering profile as a result of alternation of layers, stripes, flat lenses, or streaks differing conspicuously in mineral composition, texture or colour.

Banka drilling: a drilling method for unconsolidated material (sediments or weathering products) in which a steel tube is lowered (by rotating under verticaly downward pressure) while the mineral matter rising inside the tubing is removed - and may serve as sample - with a 'spoon' or 'mud pump'. Also named 'Empire drill'. See Annex VI.

Bauxite: a lateritic rock enriched in free aluminium hydroxide minerals, such as gibbsite, boehmite, diaspore, etc.; a laterite rich in gibbsite and other Al hydroxides, and a possible aluminium ore.

Bedded/bedding: formed, arranged or deposited in layers or beds; also applied to non-sedimentary material such as lava or structures in igneous or metamorphic rocks and weathering materials.

Blocky (geology): structure resulting from three or more sets of intersecting joint planes; the enclosed rock mass is still in situ, although the joints may leave a few millimetres space between the blocks; this space is open or filled with kaolinite or with gibbsite; size of blocks >64 mm.

Botryoidal: texture consisting of groups of globular forms resembling clusters of grapes - of any size; the globular form consists generally of acicular crystals in radiating clusters.

Bouldery: unconsolidated deposit of coarse, generally subrounded, clastic* particles >256 mm in diameter; the interstices are usually filled with clastic matter of smaller grain size; also applied to *in situ* weathering products with a similar structure or texture.

Blocky (soil): soil aggregates having the shape of blocks or polyhedrons, nearly equidimensional, with flat or slightly rounded surfaces which are casts of the faces of the surrounding soil aggregates

Boudinage or Roll-shaped: structure produced by the stretching of a competent layer, resulting in a series of bodies resembling boudins or sausages, enveloped by the surrounding incompetent material.

Boxwork: in the laterite context: a construction of angular shaped interstices* or chambers, resulting from thin, plane sheets of hard, lateritic matter intersecting in three or more directions in space (usually two sets of these walls are more or less vertical), the whole enclosed in lateritic rock or saprolite*. See Annex III.

Breccia: a rock composed of, or rich in, broken rock fragments, >2 mm in size, in an aphanitic* cement or fine-grained matrix*. Also the (rock) texture resembling this rock.

Buchanan Type texture: a (rock) texture or structure as exhibited in the topotype laterite*, composed of a knotty mass of bent, sinuous and contorted* and vermiform* features, up to 1 cm in diameter, enclosing granular* to aphanitic* masses (with concentrically arranged vivid colours in orange, red, purple and brown) that form the main mass of the rock; the tubular* features and other interstices* are in many places lined with cream-coloured coatings*.

Burrow: a tubular* or cylindrical hole or opening, made in originally soft or loose sediment, by a mud-eating worm or other invertebrate, extending along a bedding plane or penetrating a rock, and often later filled with clay or sand preserved as a filling; it may be straight or sinuous, and vertical, horizontal or inclined.

Carapace: (weathering) a French term used for the accumulation zone, the generally hard upper layer of the laterite profile. See also 'duricrust'.

Cation exchange capacity (CEC): a measure for the amount of cations adsorbed in exchangeable form by particles (organic and inorganic) as a result of the negative electric charge. Expressed formerly in meq/100g, at present in cmol(+)/kg.

Cave: an interstice* in size between a cavity* and a cavern*, or varying between 1/4 to several metres in diameter; see also Annex III.

Cavity: an interstice* in size between an alveole* and a cave*, or varying between 16 and 256 mm in size; see Annex III.

Cavern: an interstice* larger than a cave*, exceeding a few metres in size; see Annex III.

Cellular: a rock texture or structure composed of a construction of interstices or cells with convex-concave, double convex or double concave walls, enclosed in a lateritic* rock or in saprolite*; the size of the cells varies widely, from the size of a large alveole* to a small cavity.

Clay (geol): (i) rock fragment, mineral fragment, detrital particle or crystal of any composition < 1/256 mm (or < 0.004 mm = < 4μm); (ii) loose, earthy, extremely fine-grained natural particles, or a soft rock composed primarily of clay-sized or colloidal particles and characterized by high plasticity and by a considerable content of minerals from the group of clay minerals (GG).

Clay (soil): a rock or mineral particle in the soil less than 0.002 mm (2 μm) in diameter (GG).

Coated grain: in the laterite context: a rock or mineral particle of any composition or size, that is epigenetically surrounded by a layer of any thickness and composed of lateritic* matter.

Coating: (field mapping) a deposit of lateritic composition on the walls of open cracks and voids*, covering all primary textures of that wall; there are three varieties:

(i) paint or scale coating, composed of dense lateritic matter, often with colour banding in cross-section, and following the void wall as a coat of paint or plaster; the surface of the coating is generally smooth but may be knobby or wavy; the thickness may vary between a coat of paint to almost closing the void;

(ii) dust coating, a dull, earthy coating, often whitish or reddish in colour and strongly adhering to the walls of the void;

(iii) (micromorphology) pedofeatures that coat the surfaces of voids, grains and aggregates; coated grains and aggregates can be embedded in the groundmass (Bullock et al., 1985).

Colloform: a texture composed of rounded, finely banded* kidney-shaped mineral matter, formed by ultra-fine grained rhythmic precipitation and once thought to denote deposition from colloids.

Colour banding: rhythmically arranged layers of different colours that impart a banded* appearance in cross-section.

Columnar (geol): a structure composed of solid prisms or cylindrical elements that are close together in parallel position, usually with the long axes in vertical position; the space between the columns may be void* or filled with mineral matter of any texture and of syngenetic or epigenetic origin.

Columnar (soil): prismatic-shaped soil aggregates with rounded tops.

Concretion: a hard, compact mass or aggregate of mineral matter, spherical to oblate, dish-shaped or irregular in shape and usually with odd or fantastic outlines, supposedly formed by precipitation from an aquous solution, and generally of a different composition than that of the rock in which it is formed.

Concretionary: characterized by, consisting of, or producing concretions, or a zonal "concretionary texture" (if an ore) characterized by concentric shells of slightly varying properties due to variation during growth (GG).

Conglomerate: the consolidated equivalent of gravel, both in size range and in the essential roundness and sorting of its constituting particles.

Consolidated: in the laterite context: the primary or epigenetic property of firmness and coherence, that obligates the use of a hammer or knife to take a hand specimen; see Annex III.

Contorted: texture or structure in which the elements are strongly and irregularly bent, knotted and intertwined, in particular found by tubular* and vermiform* elements.

Core boulder, core stone: the rounded, ellipsoidal or broadly rectangular and hard blocks, composed of virtually fresh parent rock, locally occurring in the saprolite layer - or even in the

accumulation zone - of the lateritic weathering profile; the residual unweathered remnant of a joint block, originating from any massive type of parent rock, e.g. granite, gabbro, dolerite, etc.

Cortex: the outer, concentric shell or envelop of a pisoid* or ooid; it may be of highly varying thickness, expressed as the ratio between pisoid diameter and cortex thickness; see Annex III.

Crackled: a texture of small to minute cracks formed after the crackled body came into being, generally developed by shrinkage during crystallization or aging of colloidal matter or gels (syneresis or septarian cracks); the originally open cracks are usually subsequently filled with gibbsite or kaolinite.

Crystalline: texture wholly composed of crystals or crystal fragments of a size larger than can be resolved by the unaided eye (>0.6 mm ∅); opposite of aphanitic*, dense* or amorphous.

Crystal mesh: texture composed of an open construction of mostly facetted crystals (e.g. of gibbsite) up to 2 mm in size, forming the iregular and indistinct, fuzzy walls of larger, shapeless and partly coalescing interstices*; the total amount of (lateritic) matter may be as low as 10-25% of the total volume.

Cuirass: (weathering) the hard, upper layer of the accumulation layer in the laterite profile, particularly enriched in iron oxide minerals; a type of duricrust*.

Degradation: changes in the (mineral) compsition and structure/texture, resulting from the equilibration of the mineral association to a lower pressure and/or temperature regime, and - in the laterite context - a drier and/or cooler climate. It may include the influence of vegetation and groundwater fluctuations.

Dense: a not recommended synonym for aphanitic* because it might imply high density.

Density: the mass of a unit volume of matter (in the laterite-bauxite context: tonnes or kN per cubic metre); the *in situ density* of a bauxite/laterite is the density in the ground before mining (specify if dried or with the natural moisture content).

Detritus: fragmental material, such as gravel, sand, silt and clay, derived from older rocks and moved from its place of origin.

Diagnostic horizon: (pedology) a soil horizon that combines a set of properties which are used for identifying a soil unit. These properties are expressed in terms of quantitatively defined soil morphological properties (FAO-Unesco, Revised Legend. Tech. Paper 20, ISRIC 1989).

Diagnostic properties: soil characteristics which do not constitute distinct horizons but which are of importance for classification purposes (FAO-Unesco, Soil map of the world, Revised Legend, 1988; ISRIC, Wageningen, 1989).

Diapiric: structure resulting from rupturing and piercing of a relatively brittle rock layer by underlying plastic or mobile material, through the effect of geostatic loading.

Dike: a tabular* mass of rock, igneous or sedimentary, that cuts across the bedding, structure or foliation of a pre-existing rock.

Duricrust: a product of terrestrial processes within the zone of weathering in which either Fe and Al sesquioxides (in the case of laterites) or calcium carbonate (in the case of calcrete) or other compounds (in the case of magnesicrete) and the like have dominantly accumulated in and/or replaced a pre-existing soil, rock or weathered material, to form a substance which may ultimately develop into an indurated rock (after A. Goudie, 1973).

Exolaterite: a rock of lateritic composition and of allochthonous origin with respect to its parent rock, formed by absolute accumulation (in ionic, colloidal or particulate form) in a geomorphological position below the place of actual weathering; see Annex II.

False laterite: surface or near-surface materials that are not the residual weathering products of the local parent rock (or bedrock). They are mostly transported erosion products of laterites

occurring in the neighbourhood, cemented by mainly ferruginous matter derived from circulating (ground)water.

Fenestra: gaps in rock framework larger than a grain-supported* void* (Tebbutt et al., 1965); in the laterite context: a small interstice* in an aphanitic* to finely crystalline* and otherwise homogeneous laterite, and with an irregularly shaped and gradual or fuzzy wall; also called 'shrinkage cavity' by Tebbutt et al.

Ferrallite/ferralite: (weathering) a humid tropical soil, or *in situ* weathering product, formed by the leaching of silica and bases, and characterized by a large content of iron or aluminium oxides, or both - see also allite (Robinson, 1949).

Ferral(l)itic alteration: a particular case of weathering, distinguished from other weathering processes (ferruginous, podzolic, etc.) by the hydrolysis of the primary minerals, which leads to
1/ the individualization of all chemical elements of these minerals;
2/ the total leaching of alkali and earthalkali elements;
3/ partial or total leaching of silica;
4/ the remaining in place of the other elements, such as Fe, Al and Ti, as hydroxides and oxides. Remaining silica is present as unaltered, residual quartz or as newly formed kaolinite (Delvigne, 1965).

Ferricrete: a conglomerate composed of iron oxide cemented gravel (G.W.Lamplugh, 1902); hence an allochthonous rock, incompatable with the laterite scene.

Ferrite: a lateritic rock in which the iron oxide and hydroxide minerals represent ≥80% of the lateritic weathering minerals; see Fig. 1B.

Filling: epigenetic fill of an earlier void*.

Fill-in structure: structure suggestive of a tubular* void* that has been gradually filled from one end, with distinct layering of the fill perpendicular to the length direction of the tube and usually flatly concave as seen from the direction the fill presumably entered. Cf. 'Stopfgefüge' of Valeton, 1971.

Fissure: fracture or crack in a rock along which there is a distinct separation, i.e. a displacement normal to the fracture surface; in the laterite context: an interstice* with a shape having one axis much shorter than both other axes; the short axis may vary in length from place to place and both long axes may be straight, curved or sinuous; fissures may be epigenetically coated* along their walls or completely filled in with lateritic matter.

Formation: (geology) a persistent body of igneous, sedimentary or metamorphic rocks, having easily recognizable boundaries and that can be traced in the field without recourse to detailed palaeontological or petrographical analysis (GG).

Fossil plinthite: layers of hard or soft plinthite in well drained sites far above the ground water level and without shallow pseudo water-level.

Geode: in the laterite context: a hollow or partly hollow globular or subspherical body of lateritic composition, generally over 2 cm in diameter and with a relatively smooth outer surface; the internal void* is lined with minute gibbsite crystals or may contain gibbsite rods, threads or irregularly shaped plates. In other (bauxite) geodes the central part is filled with soft kaolinitic or gibbsitic clay. The geode may have (relict?) colour banding parallel to the colour banding of the surrounding bauxite/laterite.

Grain: more or less equidimensional mineral or rock particle, smaller than a few millimetre in diameter and generally lacking well developed crystal faces.

Grain or pebble-supported: unconsolidated or consolidated rock in which the composing grains or pebbles touch each other and form the framework of the rock, which would not collapse through removal of the finer grained matrix* - if such were possible (Dunham, 1962).

Granular: rock texture in which the crystalline components may be distinguished by the unaided eye, i.e. >0.06 mm in diameter.

Gravel: an unconsolidated natural accumulation of rounded rock fragments resulting from erosion, consisting predominantly of particles* larger than sand (>2 mm diameter) such as boulders, cobbles, pebbles, gravels, or any combination of these fragments (GG).

Ground-water laterite: (i) a tropical, imperfectly drained soil profile composed of a leached A horizon and a slowly permeable B horizon with soft plinthite formed by accumulation of sesquioxides derived from overlying horizon(s) (Sombroek, 1966).

(ii) a laterite in which the (sesquioxide) precipitations are formed in zonal soils within the zone of fluctuation of the ground-water table (McFarlane, 1976).

Ground-water lateritic soil: a thick, bleached and very sandy A horizon, grading sharply into a thick, relatively heavy-textures, dense, slowly permeable B horizon of soft plinthite. At the transition zone of the two horizons, some plinthitic material may occur that has been hardened already (Sombroek, 1966).

Grouting structures: structures formed by a natural process much similar to the grouting techniques used in mining: the process of injecting a watery cement slurry into fissures, joints and pores of a rock to reduce its porosity.

Heterogranular: structure of a granular rock with a grain-size distribution with two or more widely separated modes.

Heterolithic: structure of a more or less massive rock composed of two or more components with distinctly different lithologies or textures.

Horizon (geol.): the plane that seperates two beds, hence without thickness - or in practice a very thin distinctive bed; see Layer.

Horizon (soil): a pedogenetic layer of soil approximately parallel to the soil surface (U.S. Soil Conservation Service, 1951) - and differing from adjacent genetically related layers in physical, chemical and/or biological characteristics, or in colour, structure, texture, consistence, etc. (GN).

Impregnated lateritoid: lateritoid* rock composed of epigenetically and pervasively deposited lateritic matter in a permeable, mostly not lateritic host rock below the topographical level of residual weathering.

Internal hollow: interstice* of any shape or size completely inside a clearly defined lateritic body or a lateritic rock, e.g. in a concretion*, pisoid* or other, apparently accretionary body, or in a (sub)angular block of laterite bounded by joint planes.

Interstice: a rock-supported void*, i.e. a void with walls composed of rock or soil; the shape and size of interstices vary unlimited and are not directly related to the grain size of the rock forming the walls; see Annex III.

Intrazonal soils: see zonality of soils.

Iron crust: a substantial concentration of an iron compound in a relatively thin layer, covering an already existing substrate, and hence harder than underlaying layers.

Invaded lateritoid: lateritoid rock composed of epigenetically deposited lateritic matter in distinct veins and dikes in a bedded or fractured, mostly not lateritic host rock below the topographical level of residual lateritic weathering.

Irregular: rock texture in which the textural elements are seemingly distributed without any orderly arrangement.

Kaolin: an unconsolidated rock in which the minerals of the kaolinite group represent ≥80% of the weathering minerals; see Fig. 1B.

Karst bauxite: aluminous weathering residue collected and formed in a carbonate environment, where circulating water can move relatively freely in self-made and self-enlarging conduits.

Lag (laterite): iron segragations, originating largely as hematitic mottles, that as result of ongoing weathering and erosion became progressively exposed at the surface, where they hardened, disintegrated and formed 'gravel-like' lag deposits (Bourman, 1991).

Laterite: a term coined by Buchanan, 1807, for the weathering material from which blocks are cut, that after drying are used as building bricks; local names at the time: 'itch-stone' (in reference to the look of the rock surface as that of a seriously affected skin) or brickstone. Redefined many times, e.g. by Alexander & Cady (1962): Laterite is a highly weathered material rich in secondary oxides of iron, aluminium, or both. It is nearly void of bases and primary silicates, but it may contain large amounts of quartz and kaolinite. It is either hard or capable of hardening on exposure to wetting and drying. Or by W. Schellmann (1982): Laterites are products of intense rock weathering. They consist predominantly of mineral assemblages of goethite, hematite, aluminium hydroxides, kaolinite minerals and quartz. The SiO_2 :(Al_2O_3 + Fe_2O_3) ratio of a laterite must be lower than that of the kaolinized parent rock in which all the alumina of the parent rock is present in the form of kaolinite, all the iron in the form of iron oxides, and which contains no more silica than is fixed in the kaolinite plus the primary quartz.

Laterite *sensu lato* is used when the term laterite appears in a more general connotation, e.g. where the emphasis is more on the process of intense weathering under tropical climatic conditions.

Lateritic: the adjective for a true laterite; it should not be used in the sense of "somewhat similar to a laterite". In that case the suffix "-itious" (= related to) should be used.

Lateritic constituants: the oxides and hydroxides of Fe, Al, Ti, Mn and Ni as they occur in the various laterites (after Fermor, 1911).

Lateritic residuum: the assembly of a lateritic duricrust and its derived unconsolidated layer of lateritic nodules and other clastic weathering products (Smith & Anand, 1991). See "lag".

Lateritite: an alternative for **detrital** laterite: rocks formed by the accumulation of detritus from masses of chemically formed laterite, either alone or mixed with extraneous materials (Fermor, 1911).

Lateritization: the process of transformation of a (near) surface layer into a rock of lateritic composition and structure.

Lateritoid: an exolaterite formed through precipitation of lateritic matter from solutions; see Annex II.

Latosol: a zonal soil characterized by deep weathering and abundant hydrous oxide material, developed under forested humid tropical conditions. A now obsolate term (GG).

Layer (geol): a tabular unit of igneous, sedimentary or metamorphic origin, of comparatively homogeneous composition, and separated from the material above and below by well defined boundary planes. More or less synonymous with stratum (stratigr.): . . . , a bed or stratum of rock, with . . . no limitation as to thickness (GG).

Liesegang rings: (weathering) secondary nested rings or bands caused by rhythmic precipitation within a fluid-saturated rock (GG).

Lithomarge: the amorphous compound of composition $2H_2O.Al_2O_3.2SiO_2$, i.e. kaolinite (Fermor, 1911); a smooth, indurated variety of common kaolin, consisting at least in part of a mixture of kaolinite and halloysite (GG); an older, not well defined term; see saprolite.

Massive: being or appearing to be without internal structural or rock textural features.

Matrix or groundmass: the finer-grained material enclosing, or filling the interstices between, the larger grains or particles of a sediment or sedimentary rock. The term refers to the relative size and disposition of the particles, and no particular particle size is implied (GG).

Matrix-supported: texture in a heterogranular* rock in which the larger particles are loosely distributed, generally without touching each other, in an abundant matrix*; removal of the matrix — if that were possible — would result in a loose pile of the larger particles.

Microtubular: a void* texture consisting of sinuous tubes of more or less circular cross-section and a diameter of <0.5 mm, occurring in otherwise more or less massive* and aphanitic* rock or soil.

Mottled zone: said of a zone or layer marked with spots and patches of different colours, usually as result of oxidation of iron compounds, poor aeration or seasonal wetness (GG).

Nodule: irregularly shaped rounded knot, mass or lump, or a mineral or mineral aggregate, normally having a warty or knobby surface and no internal structure, and essentially exhibiting a contrasting composition from the surrounding matrix* or rock in which it is embedded; generally they can be separated as discrete masses from the host material. Hence **Nodular:** the texture of a rock composed of a relatively structureless matrix* enclosing numerous nodules.

Norm$_{(1)}$: the theoretical mineral composition that might be expected had all chemical components crystallized under equilibrium conditions according to certain rules (Stockes & Varnes, 1955) (GG).

Norm$_{(2)}$: the theoretical mineral composition of a rock in terms of *normative mineral* molecules, that have been determined by specific chemical analyses for the purpose of classification and comparison. GG.

Normative mineral: a mineral whose presence in a rock is theoretically possible on the basis of certain analyses. A normative mineral may or may not be actually present in the rock (GG).

Nucleus: the spherical, rounded or angular core of a pisoid*; it may be of similar or contrasting chemical and mineralogical composition with respect to the cortex*.

Ooid: spheroid body, generally with concentric or radial internal structure, with a diameter ≤ 2 mm. Hence ooidal: the texture of a rock composed of ooids.

Ophitic: rock texture, characteristic for intrusive dike rocks of basaltic composition, in which lath-shaped plagioclase crystals are partially or completely included in pyroxene crystals.

Parent material, -rock: the rock from which sediments or other rocks, or a soil's parent material is derived (GG).

Patchy: having patches; smaller areas of irregular size and occurrence and uneven in colour or composition.

Pedogenetic laterite: see chapter 2.1

Pedofeature: discrete fabric units present in soil materials recognisable from adjacent material by a difference in concentration in one or more components, e.g. a granulometric fraction, organic matter, crystals, chemical components or an internal fabric (Bullock et al., 1985).

Pelitomorphic: pertaining to or composed of clay-sized particles of any mineralogical composition; preferred synonym: aphanitic.

Petroferric or skeletic phase: see text, chapter 2.7 (FAO-Unesco Revised Legend, 1988).

Petroplinthite: iron [and/or aluminium] oxide individualizations, which have hardened irreversible. When moist it can not be cut with a spade. It appears as hard concretions in a clayey matrix, or as a hard crust or sheet (Sys, 1969). This term has been superceded by the 'petroferric phase', see text, chapter 2.7.

Pillow structure: structure observed mainly in submarine basaltic extrusive rocks, which is characterized by pillow-shaped rock masses in size ranging from a few centimetres to over one metre in their greatest dimension. The little space between the pillows is filled with material of the same composition as the pillows, with clastic sediments or with scoraceous material. It is a wide-spread relict texture in laterite and bauxite.

Pipe: tube* with a diameter larger than 1/4 metre (256 mm).

Piping: subterranean erosion by percolating water forming tubular* underground conduits through which mainly solid particles are removed, ultimately leading to subterranean caving.

Pisoid: (weathering) non-generic term for a more or less sphaeroidal textural or structural element, between ~3 and ~30 mm in diameter, consisting mostly of a homogeneous core or 'nucleus' and an outer, concentrically layered rind or 'cortex', both composed of lateritic matter; see Annex III. Hence **pisoidal:** texture of a rock composed of pisoids. The more or less synonymous term pisolith (the rock composed of pisoliths is called pisolite) is not recommended.

Pisolith: (carbonate sedimentology) the small, pea-sized accretionary bodies that make up the rock called pisolite (after GG); see also Pisoid.

Platy: (i) shape of a particle with the short axis less than 1/3 of each of the other two axis - see Annex III.

(ii) Texture of a rock that splits easily into lamina having a thickness of not more than a few millimetres.

Plinthite: see text, chapter 2.6. The revised Legend of the FAO-UNESCO Soil Map of the World (1988) gives the following definition: an iron-rich, humus-poor mixture of clay with quartz and other diluents. It commonly occurs as red mottles, usually in platy, polygonal or reticulate patterns, and changes irreversibly to a hardpan or to irregular aggregations on exposure to repeated wetting and drying. In a moist soil, plinthite is usually firm but it can be cut by a spade. When irreversibly hardened the material is no longer considered plithite. Such hardened material is shown as a petroferric or a skeletic phase.

Pore: a particle- or grain-supported* or grain-surrounded small to minute void* (opening or passageway) in a rock, soil or mineral grain; see Annex III.

Porous: general term for a rock having numerous minute voids*, connected or isolated; see Annex III.

Proto-saprolite: intermediate stage of rock weathering between fresh rock and saprolite. In the literature the term 'rotten rock' is frequently - but erroneously - used; synonym: saprock.

Pseudomorphism, -morphosis: the phenomenon that a mineral or mineral aggregate - formed by alteration - has the outward shape proper to another mineral species or aggregate that has been replaced through alteration, e.g. limonite with the shape of pyrite. Hence 'pseudomorphic' - the state of showing pseudomorphosis (GN).

Rattle rock: a volume of rock with one or more voids* containing a freely moving grain or piece of rock; the voids vary in size from a small alveole* containing a single quartz grain with a solution-textured surface, to cavities* with a smaller free-moving stone inside, composed of lateritic matter' see Annex III.

Reactive silica: see under silica, below.

Relict: remnant of a mineral, structure*, texture* or other feature of an earlier rock that has persisted in a later rock in spite of processes such as metamorphism or weathering, tending to destroy it. Also used for the elements of an older landscape still present in a younger landscape.

Residual: in the context of weathering: that what is left behind in its original place (in x and y coordinates) after the weathering processes have done their work, e.g. residual soil, residual plateau, residual minerals.

Rhizoconcretion: a root-shaped, solid or hollow condretion*, cylindrical or conical in shape, usually branching or anastomosing; frequently occurring at the lower contact of a laterite/bauxite layer, where they may be abundant.

Rock: an aggregate - hardened or not - of one or more minerals, e.g. granite, shale, sand, marble; or a body of undifferentiated mineral matter, e.g. obsidian, clay or of organic material, e.g. peat, coal.

Rod-shaped: cylindrical solid particle (with a prolate shape) smaller than a column (up to ca 16 mm) and generally with the two smaller axes nearly similar in size; the long axis may have any orientation.

Roll-shaped: see Boudinage.

Root channel: tubular* void* of up to a few centimetres diameter and several decimetres or metres long, more or less vertical and fairly straight; in many places remnants of the original root may still be present, in other places these channels are filled in with lateritic matter in grains, small pisoids* or clay-sized matter.

Root-shaped: cylindrical to conical solid, generally with anastomosing branches or in parallel groups similar to the root pods of grass, reeds or palm trees; see also rhizoconcretion*.

Rotten rock: a frequently used but incorrect term to indicate the transitional material between fresh rock and its fully weathered state, called saprolite (see below); proto-saprolite is sugested as a better term.

Saprock: compact, slightly weathered rock with low porosity; less than 20% of the weatherable minerals altered. Weathering effects are present mainly at the microsites of contacts between minerals and intra-mineral fissures, along shears and fractures through the rock as a whole or affecting only a few individual mineral grains or mineral species (Butt & Zeegers, in press).

Saprolite: (Greek for 'rotten rock') a soft, earthy, typically clay-rich and thoroughly decomposed rock, formed in place by chemical weathering of igneous, sedimentary and metamorphic rocks, and mainly composed of kaolinite. It is characterized by preservation of structures that were present in the unweathered rock (after Becker, 1895). Frequently, the saprolite layer contains a lower sublayer with preserved structures (structured S), and an upper sublayer in which the parent rock structures have disappeared (unstructured or massive S).

Siallitic: a weathering product characterized by Al-silicate minerals, i.e. kaolinite.

Silica: dioxide of silicon or SiO_2. In the weathering context two varieties are commonly recognized, i.e. *reactive silica:* which in the laterite/bauxite context is the silica present in the clay minerals, in particular kaolinite, which is soluble in hot soda solutions; and *total silica:* all SiO_2 present, hence reactive silica together with quartz and silica contained in unweathered silicates from the parent rock (e.g. feldspar).

Skeletic phase: soil material which consists for 40% or more, by volume, of coarse fragments of oxidic concretions or of hardened plinthite, ironstone or other hard material, with a thickness of at least 25 cm, the upper part of which occurs within 50 cm of the surface; this phase is not continuously cemented; FAO-Unesco, Revised Legend of the Soil map of the World, 1988.

Slit: a more or less parallel-sided void* with a width, in a size range of millimetres, much smaller than the two other dimensions.

Soil: (i) material formed through the impact of climate, vegetation & fauna (including Man) and topography on the soil's parent material, over a variable time span. The relative importance of each of these five 'soil forming factors' in soil formation (or pedogenesis) varies among sites; this explains why there is such a great variety of soils (Driessen & Dudal, 1989).

(ii) Engineering: all unconsolidated material above bedrock.

(iii) The natural medium for growth of land plants;...the lower limit is normally the lower limit of biological activity, which generally coincides with the common rooting of native perennial plants (GG).

(iv) An independant natural body: a three dimensional body being composed of mineral and organic matter which has been formed by various environmental factors into a soil profile composed of a number of horizons (Bridges, 1990).

Spheroid: solid body shaped so as to approach a sphere; hence spheroidal.

Spongy: said of a rock with numerous, more or less evenly distributed voids*, interconnected or not, in size ranging from 2-16 mm.

Stone-line: layer in a generally non-lateritic weathering profile, composed of angular to subrounded fragments of weathering-resistent components of the underlying parent rock, and normally occurring at a depth between 0.3 to several metres below a gently sloping topographic surface. It marks the boundary between *in situ* weathered parent rock (saprolite*) and a originally residual soil layer gradually moving downslope. Synonym: carpedolith.

Structure/texture: see Chapter 1, § 1.

Structured: see saprolite.

Tabular: shape of a solid body in which the short axis is distinctly smaller than both other axes: less than 1/3rd for mineral particles, and less than 1/50th for sedimentary bodies or geomorphological forms.

Ternary compositional diagram: see Fig. 1 and Chapter 2.10

Texture: see Chapter 1, § 1. Also (petrology) a term applied to the smaller, megascopic features of a rock; the general appearance of a rock, including geometric aspects and the mutual relations among its component particles (after GG).

Total silica: see under silica above.

Tube: interstice* with a shape having one axis very much longer than both other axis; the long axis may be straight, curved, crooked or winding; the long axis can have any attitude in space. The ratio of the two shorter axes may vary along the length of the long axes; the cross-section of the tube is usually more or less circular; the diameter ranges from 2-256 mm or even more.

Tubular: structure composed of more or less closely packed tube-shaped and thin-walled voids*; the long axis of the tube may be straight, bent, or contorted*. The individual tubes may contain fill in* structures of secondary nature (Valeton, 1971).

Tubule: tube* with diameter <2 mm.

Unconsolidated: in the laterite/bauxite context: the in general primary property of looseness of the constituants, that allow it to be crumbled or deformed with the fingers; see Annex III.

Vein: tabular* or sheet-like body of rock or mineral, younger than the enclosing host rock and generally cutting accross its structures.

Vermicular, vermiform: solid mineral body having the size and the cylindrical and sinuous shape of a worm. Often erroneously used for hollow, void features (a worm is a solid and not an open space).

Void: volume of vacant space enclosed in solid matter; see Annex III.

Vuggy: (rock) texture characterized by numerous, irregularly distributed vugs, i.e. irregularly shaped voids* ≥ 4 mm.

Weathering: the adjustment of the mineral assemblage of a given rock to the conditions reigning at the surface of the earth. Hence, 'sub-aerial weathering' is a pleonasm.

Zonal: said of a soil that occurs predominantly in specific climate zones (Driessen & Dudal, 1989).

Zonality of soils: soils are characterized by their formative environment; three types are distinguished:

(i) azonal: soils that are too young to reflect site-specific conditions; generally very young soils;

(ii) intrazonal: soils whose characteristics result from strong local dominance of soil forming factors, *other* than climate;

(iii) zonal: soils mainly occuring in specific climatic zones (Driessen & Dudal, 1989).

Zone: (geology) a belt, band or strip of earth materials, however disposed, characterized as distinct from surrounding parts by some particular property or content (GG).

Zoned, zoning: (soil) structure characterized by a succession of lithostratigraphic zones or horizons, parallel to the earth surface and differing from overlying and underlying horizons in one or more features such as mineralogy, chemistry, texture, colour, etc.;

(geol) any regular pattern in the spatial distribution of minerals or elements in the Earth's crust (GG).

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CHART I

CHART I

PRINCIPAL GEOCHEMICAL TYPES OF SURFICIAL ALTERATION
Place of ferrallitization°
After G. Pedro & A.J. Melfi, 1983

	Degree of hydrolisis	Total hydrolysis	Partial hydrolyses
Evolution of alumino-silicates	Silicate chemistry	Total desilicification	Partial desilicification
	Minerals of neoformation	Al hydroxides	Clay silicates
	Characteristics	ALLITES	SIALLITES
	Mineralogical type	Gibbsite Al(OH) Boehmite γAlO.OH	Kaolinite (1/1) = KLT / Smectite (2/1)
	Geochemical processes	ALLITIZATION	MONO-ALLITIZATION / BI-ALLITIZATION
	Geochemistry of alkaline & earth-alkaline cations	Total Desalkalinization	Partial desalkalini-zation
Evolution of Fe & Mg minerals	Mineralogical types	Ferric Hydrates amorphous & crystallized compounds αFe_2O_3 = HMT & $\alpha FeOOH$ = GTT	Ferric smectite (Nontronite)
General evolution of rocks	Geochemical processes	FERRALLITIZATION — Sensu stricto (Ultraferral-litization)	Sensu lato / Sialferriti-zation
	Characteristic paragenesis	GBS + Ferric hydrates (oxidic type)	KLT + ferric hydrates (kaolinitic type) / Smectite (Al-Fe)

Codes: BMT = boehmite, GBS = gibbsite, GTT = goethite, HMT = haematite, KLT = kaolinite.

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CHART II

THE GREAT WAYS OF SUPERFICIAL EVOLUTION UNDER
FERRALLITIZING TROPICAL CONDITIONS
After G. Pedro & A. J. Melfi, 1983

CHART II

Ways of Evolution	Characteristic mechanisms	Corresponding phenomenon	Genetic conditions		Relations with the pedoclimate
I Homogeneous ways	Clay-iron association maintained skeleton-plasma bonding	Ferrallitic pedogenesis	Humid medium *permanently drained*		zonal evolution
II Heterogenous ways with segregation	Separation of clay versus iron and of skeleton *versus* plasma	Lateritisation *sensu lato*	Alternating pedo-climates	Alternation of humid and dry seasons	Seasonal evolution
				Alternation of humid drained periods and waterlogged periods (free groundwater)	

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CAPTIONS TO ANNEXES

Annex I

Analyses of Buchanan's Laterite from Malabar: The quote from Fox (1936).

Annex II

The classification of laterites: true laterites versus exo-laterites, or the allochthonous rocks of a near-lateritic composition.

Annex III

Suggestions for the descriptive terminology of lateritic materials, largely derived from Bárdossy & Aleva (1990).
a - Diagram illustrating the available terminology for the description of structures, rock textures and voids, and of structural and rock textural elements.
b - 1/ Diagram illustrating the terminology to describe thre-dimensional bodies and voids, mainly after Zingg (1935) and Krumbein (1941).
   2/ Grain size nomenclature based on the Wentworth scale. Size is indicated in micrometres, mm, and in phi ("fee"), i.e. the negative ^{2} log 2 of the grain size diameter in mm.
c - Diagram showing the observed variations in nucleus-cortex relationship in pisoids, based on the pisoid definition: any spherical body with a smooth surface, independent of the internal structure, and in diameter varying between 2 and 60 mm. Most pisoids, however, have a nucleus and a cortex.
d -Suggested terms for semi-quantitative (estimated, or the result of a rough analysis) relative abundances. These terms have proven to be very useful for use with semi-quantitative mineral and chemical analytical data.
e - Classification and nomenslature of voids, including terms for type, size, and shape.
f -Terminology for the description of consistency of lateritic materials.

Annex IV

Soil horizon designations: the master horizons according to the FAO (1988 & 1990).

Annex V

a - Some analytical methods available for the analysis of lateritic materials, with their usefullness and other qualifications for specific elements and minerals.
b - Epi-norm computation to transform chemical elemental analytical data into epi-norm mineralogical data. The chemical data must include a differentiation between reactive silica and total or free silica.

Annex VI

Overview of some methods for making artificial outcrops (i.e. pitting, trenching, drilling, etc.) to systematically sample the total (laterite, bauxite) profile. After Bárdossy & Aleva (1990).

Analyses of Malabar Laterite (Fox, 1936)

The section, from which the analyzed samples derive, is in the Cheruvannur quarry near Calicut and is described as follows:

"Top 5 ft chiefly of loose red (ferriferous) laterite soil
    which was discarded as useless by the quarrymen.
No. 1 - 5 ft, ferruginous vermicular laterite somewhat
    friable, but suitable as building stone and quarried
    blocks.
No. 2 - 5 ft, normal looking vermicular laterite, easily cut
    into blocks and considered as yielding good building
    stone.
No. 3 - 5 ft, normal looking vermicular laterite, perhaps
    paler than No. 2 but also easily cut and regarded equal
    to No. 2 for building purposes.
No. 4 - 5 ft, light coloured friable laterite, vermicular
    texture not always clear, base not seen, but said to pass
    down into kaolinised gneiss or laterite with gneissose
    structure. Poor building stone judging by blocks."

Fragments or grains of quartz are seen in all the samples but appear to be more conspicuous in No. 4 than in the others and least in No. 1. The following are the analyses made by Mon. F. Raoult through the kindness of Prof. A. Lacroix." (see Table A to this Annex).

Mr Raoult used a gentle agent to take up the sample in solution, in order to be able to distinguish between quartz and silica bound to kaolinite. In the analytical procedures for the alumina/bauxite industry a tri-acid mix of the following composition has been used for this purpose:
    485.1 ml H_2O 242.2 ml Conc. H_2SO_4
    181.8 ml Conc. HCL   90.0 ml Conc. HNO_3
N.B.: Be aware of strong heet development during the mixing process!

The following norm* computation (see Table A and B) is based on the hypothesis that the parent rock has been fully weathered, resulting in a mineral paragenesis composed of only laterite* minerals plus quartz. All unsoluble material, remaining after the tri-acid treatment, is counted as free silica (quartz), but could contain unweathered parent rock silicates.
    The computation starts with the distribution of L.O.I. (water loss on ignition; Fox states "Loss at red heat") among the oxides of silicium, aluminium and iron, to form the minerals kaolinite, gibbsite and/or boehmite and hematite and/or goethite. Three common, actually occurring parageneses are computed: gibbsite + hematite (a 'dry' combination), gibbsite + goethite (a 'wet' combination) and gibbsite + hematite + goethite. A paragenesis resulting in a negative mineral phase indicates a wrong hypothesis.
    The table shows that the gibbsite-hematite norm always produces negative amounts of certain minerals, hence this 'dry' hypothetical paragenesis is wrong and must be rejected.

Both the gibbsite + goethite and the gibbsite + hematite + goethite paragenesis appear to be valid for the samples 1, 2 (a -0.10 value can be disregarded, as being well within the margin of error) and 3; in sample 4 (see Table B) none of the parageneses are valid; the reason is not clear, but from Fox's description the rock is not a fully weathered, lateritic rock (note also the low L.O.I. value).

Attached is table A, which gives the original and the recomputed chemical analyses 1, 2 and 3, in de upper part, and a summary of the Norm composition for these samples as computed by the BASIC program used for the computation of the normative mineral parageneses.

Table B gives a complete print-out of the BASIC programme "Bauxite Norm Computation" (Bárdossy & Aleva, 1990). This print-out shows that for sample 4, none of the three norm hypotheses result in a realistic mineral composition. Hence the hypothesis of a lateritic mineral composition is for this sample invalid. The rock represented by sample 4 is either not a "lateritic" rock, or the analysis is in error (e.g. the low L.O.I. value looks suspecious).

References: Bárdossy & Aleva, 1990.
            Fox, 1936.

BAUXITE NORM COMPUTATION
———

sample identification number 1

Total Al2O3	21.42	Fe2O3	40.65
Reactive SiO2	17.56	Free SiO2	6.86
L.O.I.	11.36	TiO2	1.77
————

gibbsite-hematite norm		gibbsite-goethite norm		gibbsite-hmt/gtt norm	
gibbsite	21.36	gibbsite	1.64	gibbsite	9.95
boehmite	-8.82	boehmite	6.40	hematite	17.22
hematite	40.65	goethite	45.20	goethite	26.06
sum is	53.19	sum is	53.24	sum is	53.23
anatase		1.77			
quartz		6.86			
kaolinite		37.75			
total	99.57	total	99.62	total	99.62

sample identification number 2

Total Al2O3	18.64	Fe2O3	33.64
Reactive SiO2	20.90	Free SiO2	12.68
L.O.I.	10.19	TiO2	2.04
————

gibbsite-hematite norm		gibbsite-goethite norm		gibbsite-hmt/gtt norm	
gibbsite	16.22	gibbsite	-0.10	gibbsite	1.36
boehmite	-11.49	boehmite	1.11	hematite	3.13
hematite	33.64	goethite	37.41	goethite	33.94
sum is	38.38	sum is	38.42	sum is	38.43
anatase		2.04			
quartz		12.68			
kaolinite		44.94			
total	98.03	total	98.07	total	98.08

sample identification number 3

Total Al2O3	22.06	Fe2O3	26.78
Reactive SiO2	21.72	Free SiO2	14.06
L.O.I.	11.38	TiO2	2.51
————

gibbsite-hematite norm		gibbsite-goethite norm		gibbsite-hmt/gtt norm	
gibbsite	18.23	gibbsite	5.24	gibbsite	5.53
boehmite	-9.83	boehmite	0.20	hematite	0.70
hematite	26.78	goethite	29.78	goethite	29.01
sum is	35.19	sum is	35.22	sum is	35.24
anatase		2.51			
quartz		14.06			
kaolinite		46.70			
total	98.46	total	98.49	total	98.50

sample identification number 4

Total Al2O3	16.89	Fe2O3	18.71
Reactive SiO2	27.08	Free SiO2	26.16
L.O.I.	8.61	TiO2	2.55
————

gibbsite-hematite norm		gibbsite-goethite norm		gibbsite-hmt/gtt norm	
gibbsite	6.66	gibbsite	-2.42	gibbsite	-9.34
boehmite	-12.37	boehmite	-5.37	hematite	-14.14
hematite	18.71	goethite	20.81	goethite	36.54
sum is	13.00	sum is	13.02	sum is	13.06
anatase		2.55			
quartz		26.16			
kaolinite		58.22			
total	99.93	total	99.95	total	99.99

PS: deviation from 100% is rounding-off error

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Some analyses of laterite samples from the Malabar Coast, Calicut, India, collected by
C.S. Fox in 1933 and analysed by F. Raoult, Paris (Fox, 1936)

Table A. Chemical analysis

Sample No	1		2		3	
	original	recomputed	original	recomputed	original	recomputed
Insol.	6.67	6.86	12.45	12.68	13.64	14.06
$R.SiO_2$	17.08	17.56	20.90	21.28	21.08	21.72
Al_2O_3	20.83	21.42	18.64	18.98	21.40	22.06
Fe_2O_3	39.09		33.23		26.30	
$\sum$ iron [+])		40.65		33.64		26.78
FeO	0.98		0.92		1.07	
CaO	0.30	0.31	0.28	0.29	0.56	0.57
P_2O_5	0.07	0.7	0.09	0.09	0.09	0.09
TiO_2	1.72	1.77	2.00	2.04	2.44	2.51
L.O.I.	11.05	11.36	10.19	10.38	11.04	11.38
Sum	97.25	100.00	98.19	100.00	97.03	100.00

Table B. Mineralogical norm composition[++])

	GBS+GTT	+HMT	GBS+GTT	+HMT	GBS+GTT	+HMT
Gibbsite	1.64	9.95	− 0.08	1.39	4.48	5.53
Boehmite	6.40	–	1.12	–	0.51	–
Hematite	–	17.22	–	3.16	–	1.53
Goethite	45.20	26.06	38.10	34.60	30.70	29.01
Anatase	1.77		2.04		2.51	
Quartz	6.86		12.68		14.06	
Kaolinite	37.75		45.75		46.70	
Sum	99.62		99.60		99.32	

[+]) Sum of % Fe_2O_3 + 2.2 × % FeO
[++]) Anatase, quartz and kaolinite are independent of the norm hypothesis used.

N.B. Deviations of the sum from 100.00% is rounding off error.
Mineral codes: GBS = gibbsite, GTT = goethite, HMT = hematite
Ref. Bárdossy & Aleva (1990) for the method of computation.

RANK \ ROCK TYPE	LATERITE sensu lato					
	I — Autochthonous	II — Allochthonous				
		A — In ionic and colloidal solution		B — In particulate form, derived from I and IIA		C — In particulate form onto a carbonate substratum
CLASS — Relation of laterite vs substratum	Autochthonous	Allochthonous				
SUBCLASS — Transport mechanism	LATERITE (s.s.) (residual l., true l.)	LATERITOID		LATERITOID and LATERITOID-CONTAINING SEDIMENTS		
	EXOLATERITE					In particulate form onto a carbonate substratum
ORDER	Based on parent rock	Based on depositional environment				
	1. Sediment- 2. Metamorphic- 3. Granitoid- .. .. n Ultramafitite- -DERIVED LATERITE	1 — ≥ 50% LATERITOID Sandstone-Conglomerate-Pyroclastic- etc. a/ If pervasive IMPREGNATED LATERITOID b/ If in veins INVADED LATERITOID	2 — < 50% LATERITOID LATERITOID INFILTRATED -sand(stone) -conglomerate -pyroclastic etc.	1 — ≥ 50% clastic matter LATERITOID SEDIMENT Talus, scree Colluvium Alluvium etc.	2 — < 50% clastic matter LATERITOID-CONTAINING -sandstone -conglomerate -argillite etc.	Related to karst depressions KARST BAUXITE LATERITE
EXAMPLES OF ROCK NAMES — See ternary diagram of Fe-Al-kaolin minerals	akose-derived ferriferous bauxite Gabbroid-derived aluminous ferrite	sandstone-impregnated kaolinitic lateritoid Anorthosite invaded ferritic lateritoid	aluminous lateritoid-infiltrated sandstone Ferritic lateritoid-infiltrated pyroclastic rock	bauxitic lateritoid talus kaolinitic lateritoid colluvium	ferritic lateritoid-containing gravel bauxitic lateritoid-containing sandstone	kaolinitic karst bauxite ferritic karst bauxite

Annex II

The classification of laterites: true laterites versus exo-laterites, or the allochthonous rocks of a near-lateritic composition.

Size Groups \ Shapes	Homogeneous	Inhomogeneous — Equi-dimensional	Cylindrical — Long dimension vertical	Cylindrical — Long dimension horizontal	Tabular — Short dimension vertical	Tabular — Short dimension horizontal
A STRUCTURES — Massive	Massive	Bouldery Blocky+ Sphaeroidal	Columnar+ Diapiric+	Roll- Boudinage- shaped	Banded Bedded+ Layered+ Stratiform+ Lens-shaped+ Zonal Pillow"	Dike+
A — Pore / Interstice	Pore Interstice	Cave Cavernous	Tube Tubular	Pipe	Fissure	Fissure
B SMALLER SCALE STRUCTURES / LARGER ROCK TEXTURES — Massive	Massive	As above plus Breccia-like Coated grains Concretionary Geode Pisoidal Matrix and grain-supported	Root-shaped Rod-shaped Columnar+	As above plus Rod-shaped	As above plus Platy+ Laminated Heavy mineral streaks"	Dike Fissure filling
B — Pore / Interstice	Pore Interstice	(as above)	Root channel Tubule Tubular	Pipe Root channel	Fissure Slit	Fissure Slit
B — (cont.)		Alveolar Boxwork+ Cavity Cellular Composite pore Fenestra Internal hollow Rattle rock	Bent, contorted, inclined, irregular, etc. — Filled-in borings + burrows, Fill-in structure, Buchanan topotype, Vermicular+		Vein-shaped+ Botryoidal + colloform coatings Filled-in fissures Boxwork + cellular walls	
C ROCK TEXTURES — Massive Crystalline Aphanitic	Massive Crystalline Aphanitic	Crystalline+ Granular+ Ophitic" Nodular Concretionary Pisoidal Ooidal				
C — Interstice / Pore	Interstice Pore	As above plus Crystal mesh Interstice Pore	Alveolar Cavity Contorted tubule Microtube Tubule/tubular		Boxwork Crystal mesh Cellular Fissure Internal hollow Slit	

+ Frequently as parent rock relict   " As parent rock relict only   'Void terms' in this type

Annex III

Suggestions for the descriptive terminology of lateritic materials, largely derived from Bárdossy & Aleva (1990). a – Diagram illustrating the available terminology for the description of structures, rock textures and voids, and of structural and rock textural elements.

GRAIN SIZE-TEXTURE SEDIMENTS AND SEDIMENTARY ROCKS		UNITS mm	UNITS phi	UNITS µm
BOULDER	RUDITE PSEPHITE	512	-9	
		256	-8	
COBBLE		128	-7	
		64	-6	
PEBBLE		32	-5	
		16	-4	
		8	-3	
		4	-2	
GRANULE		2	-1	2×10³
SAND very coarse	ARENITE PSAMMITE	1	0	1000
SAND coarse		½	1	500
SAND medium		¼	2	250
SAND fine		⅛	3	125
SAND very fine		1/16	4	64
SILT coarse	LUTITE PELITE		5	32
SILT medium			6	16
SILT fine			7	8
SILT very fine			8	4
CLAY			9	2

EQUANT

PROLATE

OBLATE

TRI-AXIAL

b:a 1.0 0.75 0.5 0.25 0

c:b 0.25 0.5 0.75 1.0

b - 1/ Diagram illustrating the terminology to describe three-
dimensional bodies and voids, mainly after Zingg (1935) and
Krumbein (1941).
2/ Grain size nomenclature based on the Wentworth scale.
Size is indicated in micrometres, mm, and in phi ("fee"), i.e.
the negative $^2\log 2$ of the grain size diameter in mm.

NUCLEUS	Composition of the nucleus				
	Foreign matter		Lateritic matter		
				Homogranular and massive	
CORTEX concentrically arranged and mostly colour-banded lateritic material	mineral grain	rock fragment	pisoid fragment	main mass of pisoid	main mass of pisoid with central void containing several spheroids of same material
THICK $\geq \frac{1}{2}$ radius of nucleus	normal or grain pisoid	rock pisoid	two phase pisoid	-	-
THIN $< \frac{1}{2}$ radius of nucleus	superficial pisoid to coated grain	superficial rock pisoid to coated rock fragment	superficial two phase pisoid to coated pisoid fragment	anuclear pisoid	compound anuclear pisoid
ABSENT	(clastic grain)	(rock fragment)	pisoid fragment	laterite spheroid	-

N.B. If size range of pisoids is large add: serate
   If pisoid is not well rounded add: subrounded or subangular
   Occurrence not recorded is marked with - .

c - Diagram showing the observed variations in nucleus-cortex relationship in pisoids, based on the pisoid definition: any spherical body with a smooth surface, independent of the internal structure, and in diameter varying between 2 and 60 mm. Most pisoids, however, have a nucleus and a cortex.

Semi-quantitative relative abundance terms

From %	To %	Code	Name
> 50	≤ 100	d	dominant
> 25	≤ 50	p	plentiful
> 10	≤ 25	c	common
> 5	≤ 10	m	minor
> 1	≤ 5	a	accessory
> 0.1	≤ 1	r	rare
> 0	≤ 0.1	t	trace
		o	looked for but not identified
		x	not looked for

d -Suggested terms for semi-quantitative (estimated, or the result of a rough analysis) relative abundances. These terms have proven to be very useful for use with semi-quantitative mineral and chemical analytical data.

A CLASSIFICATION AND NOMENCLATURE OF VOIDS

Dedinition: VOID – a volume of vacant space enclosed in solid matter (mineral, rock or soil)

CLASS	I – Grain-supported or surrounded void PORE – simple – composite	II – Rock-supported void INTERSTICE – simple – composite

ORDER	1 – Interparticle pore
	  a: INTERCRYSTALLINE PORE
	  b: INTERGRANULAR PORE
	
	2 – Intraparticle pore
	  a: INTRACRYSTALLINE PORE
	  b: INTRAGRANULAR PORE
		1 – With sharply defined walls
		  a: ALVEOLE-CAVITY-CAVE-CAVERN +)
		  b: TUBE-TUBULE-PIPE
		  c: FISSURE-SLIT
		  d: INTERNAL HOLLOW
		  e: BOXWORK
		  f: CELL
		  e: RATTLE ROCK
		
		2 – With diffuse, gradual walls
		  a: FENESTRA
		  b: CRYSTAL MESH

+) Size terminology

    <4 mm   small} alveole
    4 – <16 mm large}
    16 – <64 mm small} cavity
    64 – <256 mm large}
    0.26 – many m cave
           many m cavern

Shape terminology, based on ratio of three, mutually perpendicular axea a > b > c

    a ≈ b ≈ c : equant
    a > b > c : tri-axial
    a ≈ b > c : oblate, lensoid mold
    a ≈ b ≫ c : fissure
    a > b ≈ c : prolate, spindle-shaped mold
    a ≫ b ≈ c : tubular

e – Classification and nomenslature of voids, including terms for type, size, and shape.

Terms to describe the consistency of
consolidated and unconsolidated parts
of the laterite - bauxite profile, in
particular the bauxite horizon

Terms expressing the physical STATE of the rock or soil	Terms expressing the RESPONSE to deformation (pressure, shear) to be used as modifiers to the terms listed in column at left

Consolidated

Hard	Tough, brittle, splintery
Dense, medium hard	Conchoidal (fracture)
Soft	Brittle, sectile, doughy

Unconsolidated

Hard	Tough, sectile, doughy
Soft	Plastic, sectile, sticky
Earthy	Friable, crumbly
Dense	Tough, brittle, sectile
Granular	⎤
Powdery	⎬ by definition loose
Disintegrated	⎦

f -Terminology for the description of consistency of lateritic
materials.

Annex IV: Soil horizon designations: the master horizons according to FAO

The following are brief descriptions; for full definitions the reader is referred to FAO (1988 and 1990).

H   Horizon formed at the soil surface with high content of organic matter and saturated with water for long periods of the year; organic carbon content more than 12-18 percent, depending on clay content.

O   Horizon formed at the soil surface with high content of organic matter and <u>not</u> water saturated for more than a few days per year. Organic carbon content 20 percent or more.

A   Surficial mineral horizon showing:
      - accumulation of humified organic matter closely associated with the mineral fraction, or
      - a morphology acquired by soil formation, but lacking the properties of B and E horizons.

E   Mineral horizon showing a concentration of sand and silt fractions high in weathering resistant minerals, resulting from a loss of silicate clay, iron or aluminium or some combination of them.

B   Mineral horizon, faint or no rock structure, and one or more of the following:
      - illuvial concentration of one or several of: silicate clay, Fe, Al, organic matter.
      - residual concentration of sesquioxides.
      - alteration of the original parent material; soil structure rather than rock structure; formation of silicate clays, liberation of oxides.
      NB: accumulation of carbonates, gypsum or other more soluble salts do not necessarily indicate a B horizon.

C   Mineral horizon or layer of unconsolidated material, presumed to be the parent material of the soil, without properties diagnostic of any other master horizon; includes gravelly and stony materials allowing root development.

R   Layer of continuous indurated rock, too hard to dig by hand with a spade; insufficient cracks for significant root development.

Transitional horizons are indicated by a symbol consisting of two capital letters, viz. the symbol of the overlying and of the underlying horizon.

In addition, there exists an almost complete lower case alphabet to "qualify" the master horizons, e.g. g: mottling reflecting variations in oxidation and reduction, s: accumulation of sesquioxides.

Annex IV

Soil horizon designations: the master horizons according to
the FAO (1988 & 1990).

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Annex V: Chemical and mineralogical analysis

Table V gives a summary of the chemical composition of the
main minerals present in laterites. *'Restite'* indicates the
solution remnants of some more refractive (less reactive)
minerals that may be present. Haematite and goethite may
contain appreciable amounts of Al_2O_3, reaching several percent
points.

Drying of samples

Any analytical work must be preceded by drying the sample
in order that all moisture is removed. However, this moisture
must be driven out in a gentle way, as above 100°C the
crystal-bound water of gibbsite, kaolinite and goethite starts
to be expelled as well. Even the analytical standard drying
temperature of 105°C is already high. The procedures must be
standardized in order to obtain repeatable analytical results,
e.g. drying never longer than an experimentally determined
time at a specified temperature below 105°C. Cooling and
storing the samples before analysis must be done in a
dissicator with specified drying agents.

Chemical analysis

The complete chemical analysis is the most time-consuming
method available but - when executed correctly - it gives the
most accurate results. This high accuracy is in many practical
circumstances not required, hence faster and less labour
intensive methods are generally employed. Details on the
complete chemical analysis can be found in the relevant
chemical literature, and in such magazines as "Light Metals",
dealing with bauxite, alumina, etc.

Mineralogical analyses

A complete elemental analysis is seldom required.
Generally, the content in only one or a few minerals or
elements is wanted. A good example is the gibbsite analyser
(Van Essen et al. 1971) which, quickly and accurately,
determined the gibbsite content; it was designed to establish
the gibbsite content of the bottom layer in a drilling
programme, i.e. to establish the boundary between the
aluminous gibbsitic laterite and the underlying kaolinitic
saprolite, both whitish in colour.

Differential Thermal Analysis (DTA) can be performed in
almost any soil survey laboratory. The method can be used in
two essentially different ways:

1/ In the gibbsite analyser the sample is heated to past the
temperature at which dehydration is complete, and the total
weight loss during the heating process is determined (weigh
after cooling the sample to ambient temperature!). If only
gibbsite - and no kaolinite or goethite, or both - is present
there is a straight relation between weight loss and Al
content.

2/ A more detailed analysis can be made by recording the
weight loss in relation to the rise in temperature. Such a
procedure can establish the presence of a number of minerals,
as several minerals can be identified on the basis of the
temperature range within which they release their crystalline
water.

A frequent bottle neck in the routine determination with DTA instrumentation, is the necessity to start each determination with a sample container at ambient temperature. This cooling can be speeded up by placing the sample container in a refrigirator!

Total phase distribution

Sometimes it is essential to obtain the total mineral phase distribution of a laterite (bauxite). This requires a number of chemical analyses: total Al_2O_3, total SiO_2, reactive SiO_2, iron oxide, titanium oxide and loss in ignition. In addition, the bomb digest results must be known for the alumina digested at ca. 150°C (trihydrate or gibbsite Al) and that at ca. 250°C (trihydrate plus monohydrate Al, i.e. total Al) - see also Table V.

TABLE V: THE MINERAL & CHEMICAL CHARACTERISTICS
OF THE LATERITE-RELATED MINERALS

NAME [code]	FORMULA (comp. in %)	HARDNESS *DENSITY*	CLEAVAGE	COLOUR S=streak
GIBBSITE =Hydrargilite [GBS]	$Al(OH)_3$ Al_2O_3 65.4 H_2O 34.6	2½ – 3½ *2.3-2.4*	perfect	wh, gy, rd-yw
BOEHMITE [BMT]	$\gamma AlO(OH)$ Al_2O_3 85.0 H_2O 15.0	3½ – 4 *~3*	very good	wh, cl
KAOLINITE [KLT]	$Al_4(Si_4O_{10})\cdot(OH)_8$ SiO_2 46.5 H_2O 14.0	2 – 2½ *~2½*	perfect mostly earthy	wh, yw, rd, bn, pp
HAEMATITE [HMT] =Oligiste (Fr) =Eisenglanz (G)	Fe_2O_3 Fe 69.9	5 – 6 *4.8-5.3*	(1000) parting	bn – bk S: rd
GOETHITE [GTT]	$\alpha FeO.OH$ Fe_2O_3 89.9 H_2O 10.1	5 – 5½ *4.3*	(010) perfect	yw, rd dk bn S: bn-yw
QUARTZ [QRZ]	SiO_2 100.0	7 *2.6*	none	col.less wh-rd bn
RUTILE [RTL]	TiO_2 Ti 60.0	6-6½ *4.2-4.4*	(010) good	rd, rd-bn
ANATASE [ANS]	TiO_2 Ti 60.0	5½-6 *3.8-4.2*	perfect earthy	yw bn
RESTITE [RST]	Fe-Mg-Al as silicates ore-minerals oxides	*~6* *~3½*	variable	variable

Colour codes:
wh – white	yw – yellow	r – red	cl – colourless
gy – grey	bn – brown	pp – purple	S: – streak
dk – dark	bk – black		

Ref.: Mainly after DEER, HOWIE & ZUSSMAN, Introduction to the rock forming minerals, Longman, 9th reprint, 1976, 528 pp.

Analytical methods

Method Parameter	LOI	TG	BD	NA	XRF	DTA	WC	XRD
H₂O+	#	.	.	.	.	.	#	
ABEA/MEA	.	.	#	.	.	.	.	
SiO₂	.	.	#	.	.	.	.	
Al	.	.	.	#	–	.	#/	
Si	.	.	.	#	#	.	#	
Fe	.	.	.	#/	#	.	#	
Ti	.	.	.	#/	#	.	#	
Gibbsite	.	#	.	.	.	#	.	∗
Boehmite	.	.	.	.	.	#	.	∗
Quartz	.	.	.	.	.	.	#	∗
Hematite	.	.	.	.	.	#	.	∗
Goethite	.	.	.	.	.	#	.	∗
Kaolinite	.	.	.	.	.	#/	.	∗
Accuracy	x	xx	xx	xx	xx	x	xx	x
Speed: single determin.	xx	xx	x	=	x	x	=	x
same: in batches	x	xx	xx	xxx	xxx	xx	xx	xx
Sample preparation	x	x	x	xx	xxx	xx	x	xx
Analytical staff: time	x	x	xx	x	x	x	xxx	x
same: training	x	x	xx	xx	xx	xx	xx	xx
Automation	o	o	o	xx	xx	x	o	x
Instrument reliability	x	x	x	x	x	x	xx	x
Repair in field	xx	x	xx	o	o	o	xx	o
Operating cost	x	x	xx	x	xx	xx	xxx	xx
Capital cost	x	x	xx	xxx	xxxx	xx	xx	xx
Suitability remote areas	xx	xx	xx	x	x	x	xx	x
Cost of duplicate analysis				80$		100$		200$

Codes

LOI – Loss on ignition   XRF – X-ray fluorescent spectroscopy
TG – Thermogravimetry   DTA – Differential thermal analysis
BD – Bomb digest analysis   WC – Wet chemical analysis
NA – Neutron activation analysis   XRD – X-ray diffraction analysis

\# – possible method   x   – acceptable, low
– – possible but low accuracy   xx – good, medium
\#/ – possible with special arrangements   xxx – excellent, high
∗ – DTA peaks often overlap   =   – not well feasible
    partly or completely   o   – absent
. – not applicable $ – immaginary monitary unit

Annex V

a – Some analytical methods available for the analysis of
lateritic materials, with their usefullness and other
qualifications for specific elements and minerals.

Code	Mineral name	% A=	% H=	% S=	% Q=	% Fe=	% Ti=
		Al_2O_3	L.O.I.	$R.SiO_2$	$F.SiO_2$	Fe_2O_3	TiO_2
KLT	Kaolinite	39.5	14.0	46.5	.	.	.
GBS	Gibbsite	65.4	34.6	.	.	.	.
BMT	Boehmite	85.0	15.0	.	.	.	.
HMT	Hematite	.	.	.	.	100.0	.
GTT	Goethite	.	10.1	.	.	89.9	.
QRZ	Quartz	.	.	.	100.0	.	.
RTL	Rutile	.	.	.	.	.	100.0

After reactive silica (S) is combined with the required amount of alumina (A) to make kaolinite, there remain amounts of loss on ignition (H') and alumina (A') that have to be divided over gibbsite and boehmite; this gives two equations with two unknowns to solve. In the following equations a multiplication is indicated by *; all % signs have been left out, an oxide or mineral code means its amount.

$$KLT = 2.151 * R.SiO_2 \qquad \qquad 1/$$

This is a summation of three equations

$$H_{KLT} = 0.301 * R.SiO_2 \qquad \qquad 1a/$$

$$A_{KLT} = 0.850 * R.SiO_2 \qquad \qquad 1b/$$

$$S_{KLT} = 1.000 * R.SiO_2 \qquad \qquad 1c/$$

Remains for further assignment:

$$A' = A - A_{KLT} \qquad \qquad 2/$$

$$H' = H - H_{KLT} \qquad \qquad 3/$$

From the above mineral compositions it follows that

$$H' = 0.176 * A_{BMT} + 0.529 * A_{GBS} \qquad \qquad 4/$$

$$A' = A_{BMT} + A_{GBS}, \text{ or } A_{BMT} = A' - A_{GBS}$$

$$\text{and } A_{GBS} = A' - A_{BMT} \qquad \qquad 5/$$

The two equations are solved as follows:

$$H' = 0.176 * (A' - A_{GBS}) + 0.529 * A_{GBS}$$

$$= 0.176 * A' - 0.176 * A_{GBS} + 0.529 * A_{GBS}$$

$$= 0.176 A' + 0.353 * A_{GBS}$$

$$\text{or } A_{GBS} = (H' - 0.176 A') : 0.353 = 2.833 * (H' - 0.176 * A') \qquad 6/$$

in which $0.176 * A' = X$

and $A_{GBS} = Y$

b – Epi-norm computation to transform chemical elemental analytical data into epi-norm mineralogical data. The chemical data must include a differentiation between reactive silica and total or free silica.

Type of artificial outcrop	Size of outcrop	Type of sample	Transport of sample to surface	Influence of bauxite consistency on sample	Geological information	Contact relations visible	Remarks	Examples	Suitability of methods
EXCAVATIONS									
1. PIT, hand-dug	minimum 0.8x 1.2 m or 0.8 m circular	channel in pit wall or bulk sample	by bucket on string	free-standing walls required; hard beds may require blasting	very good	very good	efficient method in area with little infrastructure	Amazonas, BRA Bintan, IDN 15-30 m deep	geological observations in unaccessable terrain
2. TRENCH, BACKHOE or BULLDOZER	depending on width of machine; limited depth	channel in trench wall or bulk sample	by hand or truck	free-standing walls required; hard beds may require blasting	very good	very good	bringing in heavy equipment and fuel may be prohibitively expensive	Michell Plat. AUS, Amazonas, BRA	geological observations, providing bulk samples for pilot plant testing
CASED DRILLHOLE									
3. EMPIRE/BANKA DRILL, hand & motor driven	hole Ø usually 51, 102, 113 & 152 mm	pulp from chisel bit, pulp from auger	cylindrical spoon with valve or auger	hard beds may slow drilling progress to practically zero	limited	reasonable to absent	usefull to penetrate thick soil or overurden up to 80 m thick	Arkansas, USA Nassau, SME Onverdacht, SME with motor auger inside	most effective in unconsolidated rocks and/or remote unaccessable areas; can be mounted on swamp tractor
UNCASED DRILLHOLE									
4. AUGER, single or continuous flight; hand or engine driven	hole Ø usually 3-10 cm, but up to 25 cm possible	pulp	intermittent: lift auger and collect sample continuous: see remarks	almost any bauxite; hard aphanitic iron-oxide bands may prevent further progress	limited	limited	simple, fast and accurate when correctly used	Guinea, Piji-guaos, VEN	not for very hard bauxite; independent of moisture, even below water-table good recovery
5. GEMCO BAILER DRILL, engine driven	10 - 25 cm Ø	crumbs or loose nodules	lift out bailer at set intervals	only feasible in loose, granular to nodular bauxite	limited	limited	excellent for fragile pisoids	Aurukun, AUS	mainly for unconsolidated fragile nodules or pisoids
6. VACUUM or SUCTION DRILL, engine driven	5 cm Ø	crushed bauxite	by vacuum inside the hollow drill stem	little progress in sticky or tough clay; sampling only above water-table	limited	limited	efficient in well drained hilly terrain; even in hard bauxite	Mitchell Plat. AUS, Worsley, AUS	mounted on 4-weel drive tractor efficient for large areas in wooded terrain; very fast drilling and sampling
7. AIR/FOAM LIFT of cuttings; down-the-hole drill	variable, usually 5 - 10 cm Ø	chips of all sizes	by air or foam pressure through anulus around drill stem	best in hard and brittle bauxite; unsuitable below water-table	limited	limited	fast and efficient in massive, hard bauxite; accuracy locally uncertain		only above water-level; requires heavy air compressor which consumes much fuel
8. CORE DRILLING; dry, water or mud flushing or by compressed air	5 - 25 cm Ø	solid cylinder of bauxite in compact ore	hoisted out in core barrel	suitable in almost any circumstances, except loose, dry, small pisoids.	good	good	high degree of sampling accuracy; requires good roads	Amazonas ABMP, BRA, Lelydorp, SME, Mitchell Plateau, AUS	effective in almost any type of bauxite; below water-level use triple core barrel.

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Annex VI

Overview of some methods for making artificial outcrops (i.e. pitting, trenching, drilling, etc.) to systematically sample the total (laterite, bauxite) profile. After Bárdossy & Aleva (1990).

Annex VII

Engineering data.
a – Data to be collected from the material *in situ* by the
field crew.
b – Data to be derived from testing samples in the laboratory:
(1) Preferred methods for taking and storing the samples;
(2) Essential methods of testing
(3) References.

PLATES

Plate A:

1 - Laterite brick quarry, showing brick-grade laterite under ~80 cm thick loose, granular overburden. The laterite is cut into ~15 cm thick slabs, which are split into ~20 x 40 cm sized bricks. On the surface piles of bricks are drying before sale. The quarry is on the flat high plateau near Toussana, SW of Bobo Dioulasso, Burkina Fasso, West Africa.

2 - Mine front of the Saracá plateau bauxite deposit, Trombetas, Lower Amazon Basin, Brazil. The light-coloured, kaolinitic Belterra Clay - up to 10 metres - overlies the dark brown and highly porous laterite/bauxite. This accumulation layer contains numerous vertical structures reminicent of roots and joints. It is underlain by a sedimentary, kaolinitic saprolite of presumably Upper Cretaceous age.

3 - Nodular, refractory grade bauxite mined in the Naredi mine, Guajarat, India. The accumulation zone is composed of purely gibbsitic nodules in a gibbsitic-kaolinitic powdery matrix. Quality control is by hand cobbing and manual selection by the female miners.

4 - The lower boundary of the sediment-derived, highly gibbsitic bauxite of the Onverdacht mine, Coastal Plane of Suriname. The photograph shows from the top down - i.e. from the far distance towards the observer - the grey mine face composed of clay and sand overburden (up to 20 metres thick), the redbrown sediment-derived bauxite bed, then a step caused by the not mined underlying massive kaolinite (the bauxite-kaolinite interface is undulatory with a few protuberances of kaolinite into the bauxite at left). In front, just behind the camera box (20 cm high) and the pipe, is a vertical face in the underlying sediment-derived kaolinite. In this kaolinite face occur numerous, parallel, narrow dikes of porous bauxite with boxwork structures, formed at a later stage in vertical cracks in the kaolinite bed. These cracks are considered to be caused by drying out of the kaolinite and undercutting of the kaolinite-bauxite mass through a bend of the Suriname river.

Plate B:

1 - Epigenetic bauxite vein crosscutting stratified, highly aluminous laterite (sediment-derived bauxite); little or no kaolinite is present. Scale: the hammer handle is 28 cm long. From: St Helena Hill, Onoribo, Suriname.

2 - Detail of the photograph 1 (after removal of the hammer); this print is about 7.5 times enlarged in respect to fig. 1. The photograph represents a rectangle that touches with its upper left corner the original place of the chisel end of the hammer on photograph 1.

3 - Quartz-rich ferriferous bauxite, representing the upper part of the accumulation layer over a granite-derived laterite/bauxite. Ca 3.5 times enlarged. From: Alcoa Mine,

Darling Range, Western Australia.

4 – Same, with a distinct pisoidal texture. Note the variable relation between nucleus (variable composition, even within one pisoid) and cortex, The outer cortex may envelop more than one nucleus. Ca 3.5 times enlarged. From same locallity as photograph 3.

Plate C:

1 – Contact between fresh, dark green and quartz free foyalite (the parent rock) and its lateritic weathering rim (bauxite). Scale is in millimetre and centimetre. From: Poços de Caldas, Minas Gerais, Brazil.

2 – Relict texture in a purely gibbsitic weathering product of a leuco-gabbroid parent rock. The gibbsite blades mirror the cleavage of the original feldspar grains, which seem to have been 3 to 5 mm in diameter (the rounded groups of simmilarly directed gibbsite blades). Ca 3.5 times enlarged. From Northern part of the Bakhuis Mountains, Suriname.

3 – Grouting structure formed in a thinly bedded sedimentary rock. The block is solid, aphanitic aluminous laterite with a central vertical tube with irregularly shaped walls. Scale: the ball-point pen is 15 cm long. From: Paragominas bauxite district, Pará, Brazil.

4 – Fluvial gravel completely replaced by aphanitic laterite/bauxite (it is not certain wheather the gravel of Devonian shale and intruded diabase was bauxitized or that the gravel was formed after the bauxitization of these two different parent rocks). The scale is marked in cm and mm. From: Sangaredi bauxite mining area, Boké, NW Guinea, West Africa.
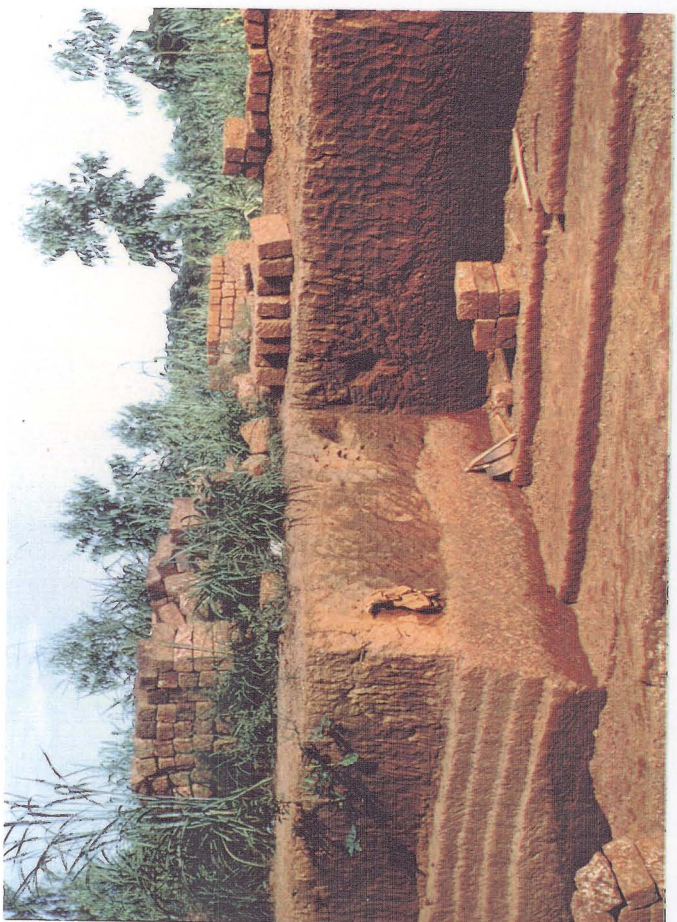
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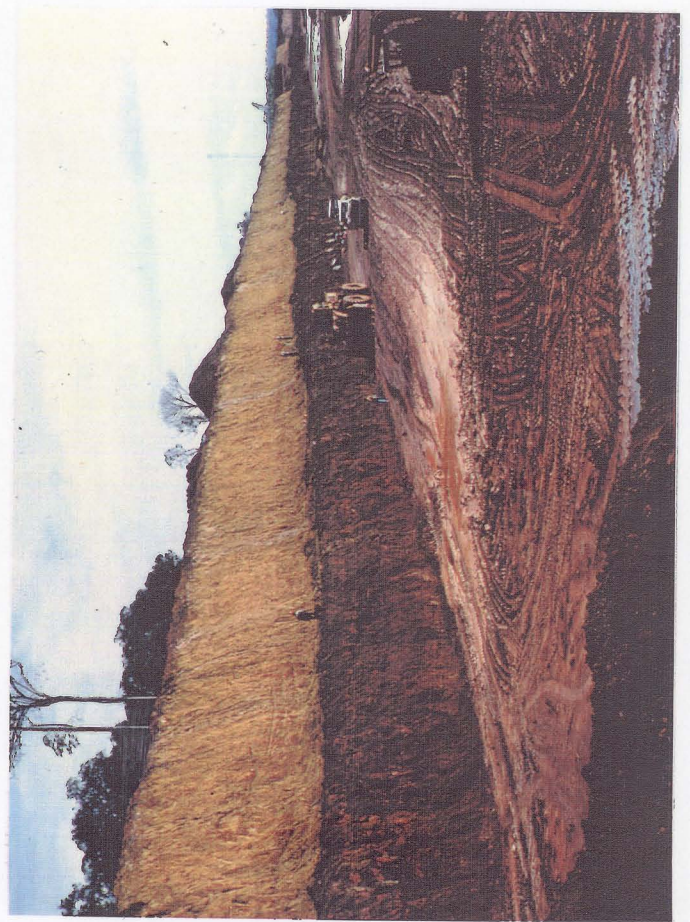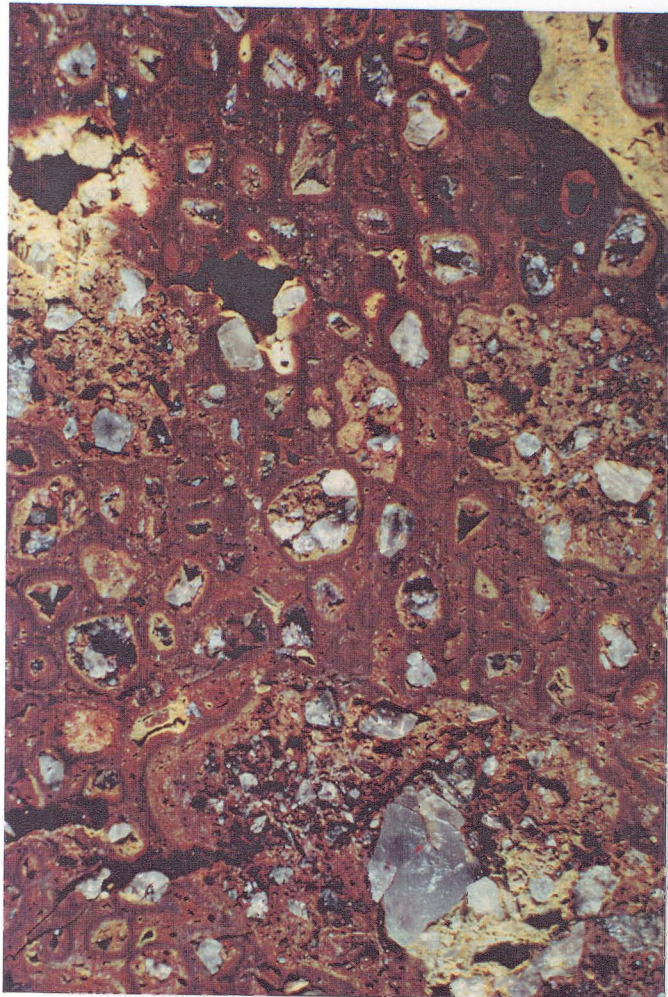
3

4

1

2

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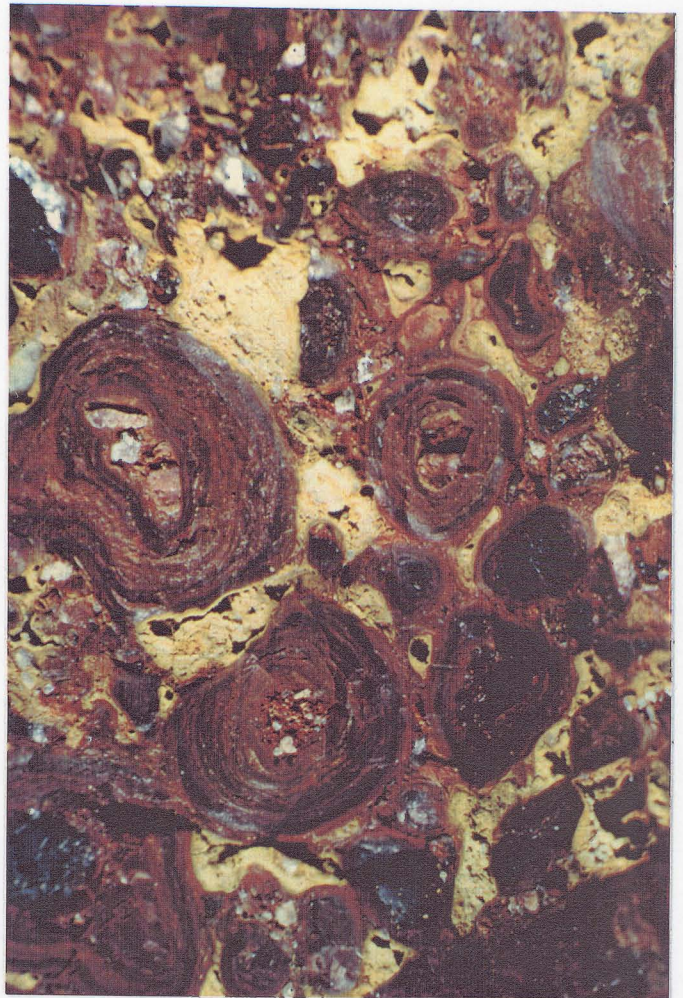
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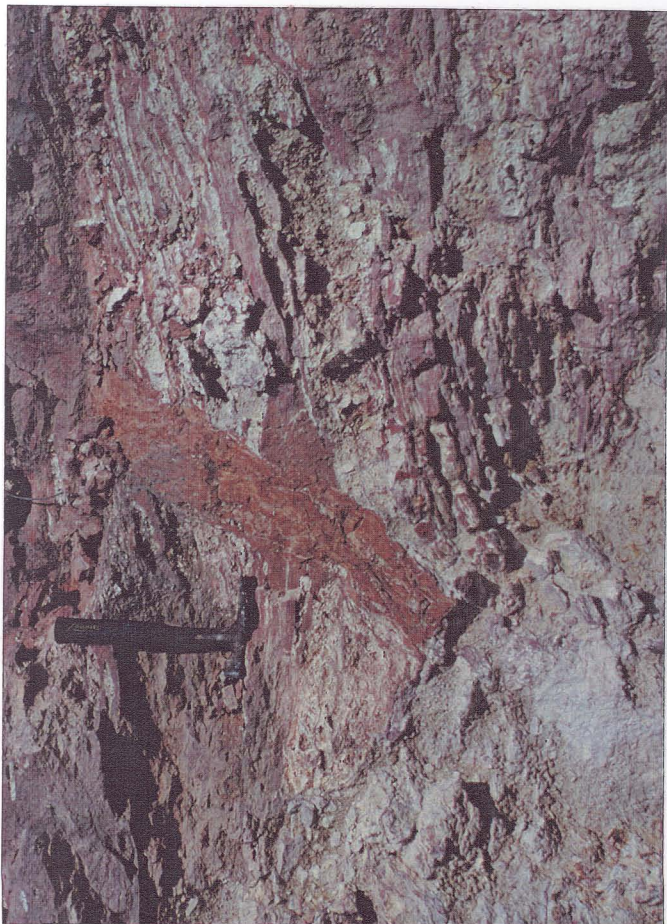
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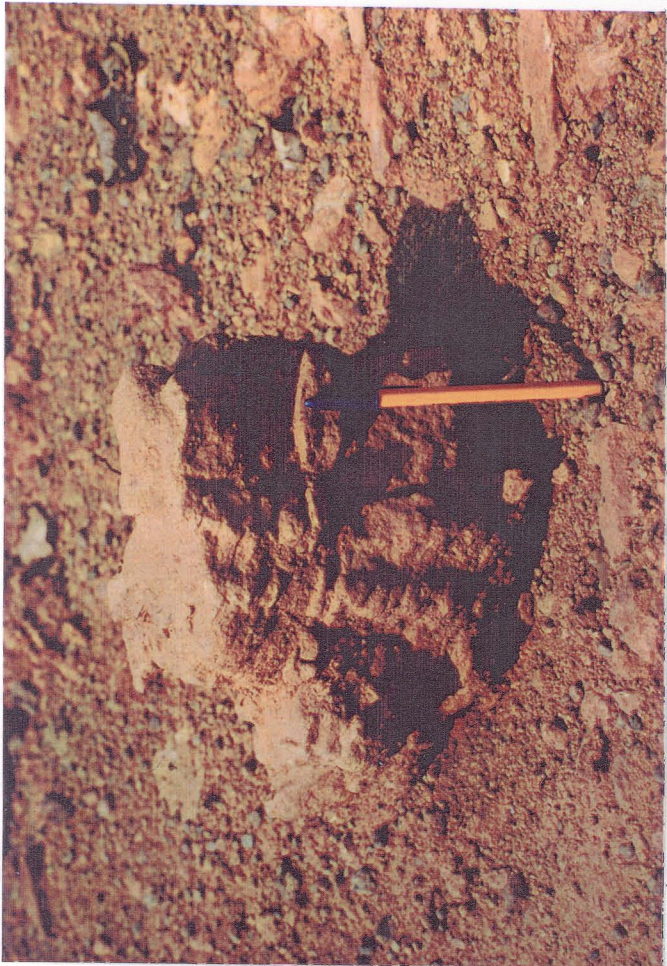
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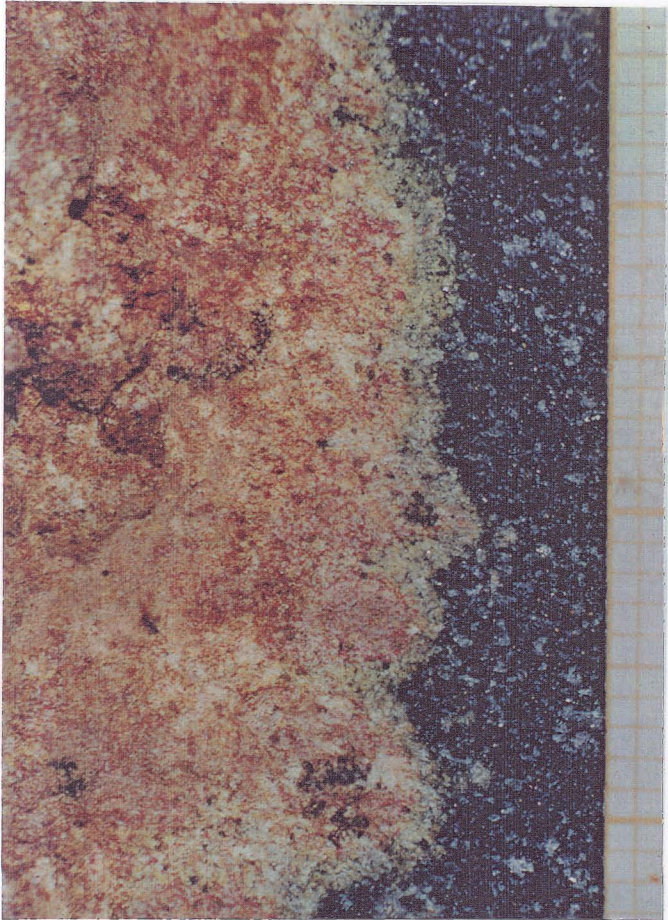
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PLATE C