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The CORLAT Handbook
Draft Version 1.1

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January 1991

International Soil Reference and Information Centre
Wageningen, The Netherlands

ADDENDUM

to the Corlat Handbook

Draft version 1.1, January 1991

Please, cut the following sections along the ====== line and past the strips on the indicated pages of the above MS.

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Cut, and past on page 4.

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 with their own, more or less well defined physical environment of formation.

Pedology studies the impact of the environment - the physical and the biological - on the upper layers of the earth, i.e. the formation of soils and their improvement/deterrioration as substrate for the growing of food (directly and indirectly).

In the past, and at various times, large surfaces of the earth crust have been exposed to the atmosphere, which must have let to the formation of reaction products comparable with present day soils. Some of these have been fossilized and are still discernable in the rock record of the earth crust: among them laterites and saprolites.

Table I - Characterization of rock forming processes related to environmental control at the time of formation - gives a overview of the most common of these rocks/soils, with a short description (in horizontal direction) of the series starting material ⇒ processes at work ⇒ resulting rocks with rock name, while vertically the succession in time of the processes and resulting rocks are marked. The basis of the chart represents the solid rock at the time the environmental actions/reactions start, i.e. magmatcic, sedimentary or metamprphic rocks.

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

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Please add on page 12, line 14: add 'o' to make the word "pedogenetic".

Please add on page 15, line 6: 'lateritic' before the word "bauxite";

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Cut, and past on page 15, below line 13, the following extension to section 2.2:

Karst bauxites, or bauxite deposits on carbonate rocks, or enclosed by carbonate rocks, are extensively discussed by Bardossy (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.

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Page 17: please remove the two paragraphs above 'Origin of plinthite'.

Page 25: Please add to the section heading 3.2: **The typical profile development: '- see Fig. 2A & B.'**

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Cut, and past on page 27:

The most conspicuous feature of the laterite horizon, best seen in its lower part, is the retension of the original rock structures and textures, although most 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 resulting constancy of volume has been used to compute chemical loss and gain firgures (Millot & Bonifas, 1955).

This replacement must have been an exchange of matter on a molecular scale, as the finest details of fine-grained besalts 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 blocks of the parent rock, where most of the original mineral grains are still present.

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Cut and paste in the Glossary, page 7, above 'Residual' the following item:

'*Pseudomorphism:* the phenomenon that a mineral or mineral aggregate - formed by alteration - has the outward shape proper to another mineral species or aggregate that it has replaced through alteration, e.g. limonite with the shape of pyrite, i.e. a limonite pseudomorph after pyrite. Hence 'pseudomorphic' - the state of showing pseudomorphosis (Geol.Nom.).

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ADDENDUM

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- Page 25: Please add to the section heading 3.2: The typical profile development: '- see Fig. 2A & B.'

- Page 29, second line from bottom, please insert after 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 color Plate II.

This feature proves that the alteration can take place without change in the 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 laterite/bauxite with parent rock pseudomorphs, gives an indication of the amount of matter that has been removed from the horizon in question during the lateritization process.'

- Glossary, page 7, please insert above 'Residual' the following:

'*Pseudomorphism:* the phenomenon that a mineral or mineral aggregate - formed by alteration - has the outward shape proper to another mineral species or aggregate that it has replaced through alteration, e.g. limonite with the shape of pyrite, i.e. a limonite pseudomorph after pyrite. Hence 'pseudomorphic' - the state of showing pseudomorphosis (Geol. Nom.).

The

CORLAT

Handbook

Draft version 1.1
January 1991

Prologue

Laterites are curious rocks.

They were recognized as representing something different by the medical doctor Buchanan; he suggested the name laterite = brick.

Later, laterites were studied by geologists, e.g. Lacroix, Fox, Fermor, Harrison, by soil scientists e.g. Alexander & Cady, and by geographers/geomorphologists, e.g. Walther, McFarlane.

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 terms, there exists some confusion in terminology. This can be solved, I think.

Weathering, for the geologist, is the re-equilibration of the mineral essemblage (paragenesis) of a rock, mostly representing high temperature and pressure domains (igneous rocks and gneisses), to the chemical and physical circumstances that reign at the surface of the earth, e.g. 1 atmosphere = 101 325 Nm^{-2} and 0°-30° C, variable humidity going up to ~100% relative humidity. In addition, at the surface organisms are present; they die and their remains rot, producing organic acids.

Pedogenesis is the term used by soil scientists to indicate the process of soil formation, which is the weathering of the local rock under the influence of the atmosphere and living organisms.

In other words, weathering *sensu lato* = pedogenesis *sensu lato*, with the main difference that weathering is studied in a centrifugal way (from the earth's core outward to the surface) and pedogenesis in a centripedal way (from the surface downward).

Additional confusion resulted from the influence of the Pleistocene glaciations with their severe influence on the world's climates: temperature and humidity, the two main factors controling 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 and skeletic phases.

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

C O N T E N T S

CORLAT Technical Publication No. 1

There are a number of proposed titles:

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 sity weathering products in humid tropical climates (laterite, ferralite, plinthite, etc.), an interdisciplinary effort.

Lateritization, ferralitization, bauxitization and plinthisation.

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

Ammended first sketch for the proposed 'Handbook'

CORLAT
Techn.
Paper 1

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

1: Introduction

At the 2nd International Seminar on Lateritization Processes, Saõ Paulo, Brazil, 1989, 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 material and guidance for classification of laterites, using a rational descriptive terminology. The potential users of the collection include geologists, mineralogists, soil scientists/agronomists, geomorphologists, and civil engeneers.

By far the most ubiquitous laterites are of an iron/aluminium composition, resulting from the weathering of acid to fairly basic igneous and metamorphic rocks. If not specifically mentioned otherwise, this are the laterites discussed in this paper. 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 thus * an explanation or definition is given in the Glossary at the end of this paper.

1.1: Interdisciplinary use

This text has in its title the qualification "for interdisciplinary use". It is all but impossible to use - throughout these guidelines - only terms that in all related disciplines have exactly the same meaning. 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 vocubulary.

When perusing e.g. the Handbook for Soil Thin Section Description (Bullock et al., 1985, published under the auspicies of the Int. Soc. of Soil Sciences), it appears that there is only one term that is in its meaning clearly deviating from its use in the petrology branch of geology, and that is the term 'texture".

The Glossary of Geology (Bates & Jackson, 2nd edition, 1980) explains the difference with the following entries (in 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 revers of the English usage."

"**Texture (soil)** The physical nature of the soil according to the relative proportions of sand, clay and silt."

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' is 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' is described as to deal with "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 (1990, final draft), under the heading 2.3.1 Texture of fine earth, the ISO particle size classes of fine earth, i.e. < 2mm, are given, followed by the names and codes of the soil texture classes, which coincide with those of the (U.S.) Soil Survey Manual (1951).

The following **convention** will be used to handle this distinct difference in the meaning of 'texture' between Geology and the Soil Sciences (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 ment, e.g. in Chart I, the group C is marked as *rock textures*, i.e.

the geological meaning of texture, see above under 'texture (petrology)'. Where the soil sciences 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.

2. Some definitions and discriptions

2.1: Laterite'

Origin of the name: Dr Buchanan, M.D. (1807), writes in volume II, pages 440-441 of his Indian travel journal, dated 20-21 December 1800, when visiting 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* 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 *Lateritis*, the appelation that may be given to it in science". [quoted] by C.S. Fox, 1936, p. 393/4].

j also

And in Vol. III, pages 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 felspar. 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 felspar has crumbled to powder, leaving the quartz in angular masses".

This description by Buchanan is a feable 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, some of which are quoted here to illustrate the properties of laterite and the - partly still existing - confusions. Quoted also the paper by C.S. Fox (1932).

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1/ The term laterite is used in two ways, namely, *stratigraphically* as the name of a geological Formation, and *petrographically* as the name of 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 duscussed 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 or 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 per cent.) 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 per cent. 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 the rocks intermediate between laterite and lithomarge the terms *lithomargic laterite* and *lateritic lithomarge* are available, the former being applied to forms containing 50-90 per cent. of lateritic constituents, and the latter to forms containing only 25 to 50 per cent. of lateritic constituents.

5/ The presence of any considerable amount of quartz, either residual or secondary (this form has not, so far as I am aware, yet been noticed 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 per cent., 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 (>25 per cent.) or without (<25 per cent. of lateritic constituents) the attributive *lateritic.*

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/ 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 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.

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 excepted 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 ore 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. True laterite itself interferes with land use in Africa, India and elsewhere in the Troipics. The soil materials 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".

Their publication contains a comprehensive discussion, covering a large amount of field observations and related technical data, which this time have been collected by soil scientists. They 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 recognize four geomorphological categories:

(i) High-level or peneplain, ferruginous crusts, occuring as a capping on high ridges and on peneplain fragments;

(ii) Foot-slope, or colluvial, seep-cemented ferruginous crusts, formed by cementation of colluvial material 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 more recent age than 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. Fe may be brought in by the groundwater, 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.

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 & 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 earthalkali elements, and part of the silicate silica, are transported out of the environment through groundwater 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 may be of a grassy or forest nature. The present day local 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, laterites are - at the time of their formation - bound to the surface or near-surface environment, where the atmospheric influence causing weathering is strongest. In this context the weathering process may be considered as the re-equilibration of the 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), and in the presence of organic acids.

Pedologically, laterites may be considered as zonal* soils restricted to climates of high surface temperature and high humidity and/or precipitation. They are 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 insifficient 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 laterite deposits are generally difficult to establish. Absoliute age determinations have not yet been possible, although several attempts have been made or are in the process of development, e.g. by using oxigen isotopes.

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

2.2: Bauxite•

Bárdossy & Aleva (1990) characterize 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 common, diaspore. The name 'bauxite' derives from the 'Collines des Beaux', Southern France, the place from where the sample derived that Bertier (1821) analysed, thinking that the redbrown 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.

2.3: Special laterites

The common laterites are formed from common quartz-feldspar rocks with a relatively low contend of Fe-Al silicates, such as granites, gneisses, etc. More specialistic 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*°

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. ferriferous bauxite, or bauxitic laterite - see also the ternary diagram of Fig.

2.5: Plinthite*

"Plinthite is 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 aggregates on exposure to repeated wetting and drying. In a moist soil, plinthite is usually firm but it can be cut with a spade. When irreversibly hardened the material is no longer considered plinthite. Such hardened material is shown [on the map or soil inventory] as a petroferric or a skeletic phase". From the 'Revised Legend of the Soil map of the world', pages 33, FAO-Unesco, 1988.

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In particular in older descriptions this hardened material has been designated as laterite (e.g. Soil Survey Manuel #18, 1951). This resulted in the ambiguous statement: "the same material [as found in soil horizons A and B] may continue practically without change for another 7-8 m (25 ft) [and in Central India to a depth of 50 m] 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".

However, in 1975 (U.S. Dept. Agr., Handbook 436) it is stated: "Much that has been called laterite is included in the meaning 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."

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Origin of plinthite

Sombroek (1966) distinguished in his book on Amazonian soils three groups of soils:

(i) Latosols': a thoroughly weathered soil, mainly composed of sesquioxides, silicate clay minerals having a 1:1 lattice (kaolinite group), quartz and other minerals highly resistant to weathering.

(ii) Soft plinthite' (also named mottled clay, Fleckenzone, argile tacheté, horizon bariolé), which can be cut with a knife: it is a dense, usually cleyey, humus-poor mineral material with many coarse and prominent mottles. The mottles are red or purple (usually 'weak red' in the Munsell notation) and often with admixture of some yellow, and occur in a white or light grey matrix. In case of predominance of the reddish, the situation may be described as the occurrence of white and some yellow mottles in a red or purple matrix.

The pattern of mottling is varying. It may be reticulate (polygonal, prismatic (vesicular) or platy (laminar). The centres of the red or purple parts are often indurated.

(iii) Hard plinthite° (also named concretions, iron crusts, laterite, cuirass, ferriferous quartzite, canga, piçarra) is a slag-like (i.e. breakable with the hammer), humus-poor mineral material, apparently largely consisting of indurated iron oxide; as well as the earth between this material, if present. The indurated elements vary in coulour (red to black), size (from gravel to enormous boulders and crusts), shape (pisolithic, platy, prismatic, massive, vesicular), grainage (fine to very coarse elements, usually of quartz, around which the sesquioxides are cemented), and arrangement (vertical, horizontal, irregular). This is the end product of soil wathering. Following the Revised Legend (FAO, 1988) this material is no longer considered plinthite, but is a petroferric or skeletic phase.

Sombroek makes then a further distinction between a/ plinthite below or in the lowest part of the solum against b/ plinthite formed within the solum.

(a) Plinthite formed in the lower part of the solum and below it, is exemplified by field description 185A: kaolinitic Yellow Latosol, with

$A_1 + A_2$: sandy loam (0-70 cm)

$B_1 + B_2$: (light) sandy clay loam (70-150 cm)

C_{1g} : light sandy clay loam with medium sized distinct white and red mottles (210-260 cm)

C_{2g} : light sandy clay with many coarse prominent red and some yellow mottles (260-350 cm).

Follows the interesting comment: "the plinthite formation is more a geological than a pedological process. Most probable, there is no transport of sesquioxides and/or clay sized particles from the upper 200 cm to the horizon of plinthite formation".

(b) Plinthite formed within the solum: it produces the ground water laterite, observed in many places in Amazônia. The formation is bound to terrain with imperfect drainage and a shallow zone of fluctuating ground water (arbitrarily set at less than 2 m deep), restricting the activity of roots and soil fauna, and resulting in incomplete homogenization. Clay-sized particles and sesquioxides are carried downward to the horizon of plinthite formation, i.e the B horizon of the pedological profile.

Variations in the soil profiles are caused by the following three factors:

1 - the character of the fluctuations of the ground water level, which may vary in depth and frequency;

2 - the texture of the parent material;

3 - the degree of 'pre-weathering' of the parent material.

(c) Fossil plinthites', wich are layers of hard or soft plinthite in well drained sites, with the phreatic or groundwater level at many metres depth, and where a shallow pseudo ground water level does not occur. These deposits are considered to be fossil; they formed at times when there existed, in situ or in the surrounding, a land surface with a fluctuating water level at shallow depth. Fossil plinthites do occur both within the present solum and below the present solum.

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;
- this intensive weathering is caused by high ambient temperature and sufficient process water (precipitation) and organic acids, hence a soil type of environment;
- extended time, which is essential for an increased thickness of the soil or rock composed of the 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 - skeletic phase - laterite seems to be a genetic series of increasing age, where it should be remembered that the duration during which the active, genetic processes were at work, seem 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: there is a type of homogenization in composition and texture as the soils/rocks become older. Also, the climate in recent times has been different - less favourable - 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 Hawai 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 a hight of ca 200 m and with 1250 mm rain per annum (Bárdossy & Aleva, 1990).

In retrospect, the misunderstandings between geologists and soil scientists (and possibly geographers/geomorphologists) with respect to laterite, plinthite, etc., are largely due to the fact that the geologist studies a profile from the bottom (= the parent rock) upward. He can study the parent rock in detail, hence the intrazonal aspect of the laterite genesis. The climatic aspects of their formation can only be deduced in a cumbersome and inprecise way, while the factor time is almost completely outside his grasp. Only in a few - lucky - instances isotope and palynological dating, with the close cooperations of specialists in these disciplines, have let to interesting results.

The soil sientist starts in his studies from the earth's surface, within a geographical and hence climatological well defined area. For him the zonal aspects are the starting point of his research, as he can establish parameters such as depth (and fluctuations) of ground water, amount of precipitation, effectivity of drainage, etc.. The factor time can be studied in detail for the more recent soils, say for the latter 100 000 years (carbon isotopes). Older soils would require palynological study, which requires extensive, specialistic research. For the soil scientist the parent rock is mostly a hidden parameter at a depth too great to allow its study in detail.

The geographer and geomorphologist are in an intermediate position, trying to unravel the genesis of the present shape of a certain, confined area of the landscape, as it relates to both the geological and the climatological history.

2.6: 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 Afruca. Robinson uses the molecular ratio silica : sesquioxide to separate the siallitic clays from the (ferr)allitic clayes, with the ratio 2 as the borderline. See also Chart I, after Pedro & Melfi (1983).

2.7: Soil*

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., 1980). A large number of soil units have been identified, based on the presence of diagnostic* horizons, each with quantitatively defined diagnostic properties 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 varaible *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."

"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".

2.8: 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 kaolin and not a bauxitic one!

2.9: 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. Therefor, it is not represented in the ternary compositional diagram.

Chemical analyses of lateritic rocks must therefor 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 analyse 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).

2.10: Glossary

The preferred definitions for the various rocks and soils discussed are given in the Glossary at the end of this booklet; all terms in the text marked with a degree symbol (°) 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 definiton 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 horizons that together form the typical laterite profile development.

In the following text the conventional split in a lower saprolite° (or lithomarge°) horizon and an overlying laterite horizon 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 horizon.

3.2: The typical profile development

(i) The **unweathered parent° rock** underlies the weathering profile; the contact with the overlying horizon is mostly gradational in character with a transition zone of *rotten° rock*, composed of a mixture of crumbly parent rock in a kaolinitic matrix, between the fresh parent rock and the fully weathered saprolite° or lithomarge°.

(ii) The **saprolite° horizon** 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.

The horizon may vary in thickness from zero to over one hundred metres. Within this horizon, *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 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 abrubt to gradational over a distance of up to several decimetres. In many cases there is a still visible 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.

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

(ii.a) a lower *structured° sub-horizon* 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-horizon*, in which no primary structures and textures are descernable: 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 horizon as a whole.

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

A little distance below this upper contact, or reaching downward from this contact, the saprolite horizon may contain hard bodies of laterite/bauxite 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 nature, hence they were named *grouting° structures* (Bárdossy & Aleva, 1990).

(iii) The **laterite (bauxite) horizon**. This is the characteristic accumulation° zone (in French named 'carapace°', in English often 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.

Generally, the accumulation horizon exhibits two sub-horizons:

(iiia) a lower, medium to barely indurated horizon 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 horizon, best called *cuirass°*.

The top part of the accumulation zone may contain several types of deviating textures and structures, presumably resulting from periods in the laterite's history in which a different climate existed that caused degrading changes in the already existing laterite, e.g. brecciation, pisoid formation, etc. Later changes in the climate caused these degradation products to be incorporated again in the solid cuirass, through cementing by redeposited iron oxides.

The accumulation horizon is harder - or at least more weathering resistant under present conditions - than the underlying saprolite horizon, 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 used 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-cemented conglomerates along the Irish coast, hence rocks of originally detrital and transported origin. Still, the French often translate, in abstracts of their papers, their term 'curasse' into 'ferricrete', while 'cuirass' is the equivalent word in the English language.

To arrive at a duo of clear, generally acceptable terms in the English language, a choice could be made from the following two sets of three terms, each set placed in alphabetic order:

Accumulation horizon - armour
Carapace - cuirass
Duricrust - iron crust,

with this author's preferrence for the combination accumulation horizon and cuirass.

(iv) The **soil* horizon** - if present at all. Many Laterite Formations do not posses a soil horizon of any signature. The cuirass* is directly in contact with the atmosphere, the sun heats the generally iron-rich top horizon 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 surface horizon of the Laterite Formation is in desequilibrium with its surrounding, i.e. the present day - drier - climate (Leprun 1979). This process of destruction and diminution will ultimately lead to a complete surficial desintegration and revegetation of the original outcrop of the Laterite Formation.

Some laterite deposits grade upwards, over a distance of up to several metres, into gravelly, sandy and clayey horizons, at the top covered with a plant-bearing soil or even a full tropical forest, e.g. the Bakhuis Mts, 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 horizon and an unconsolidated horizon 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}, $B\text{-}C_{(pl)}$, C_{sapr}, R

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

The absolute and relative thicknesses of the successive horizons 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 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 granites and basalts, that could be as young as Plio-Pleistocene.

3.3: Some remarks

Parent rocks have not necessarily 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-resistent minerals enclosed, such as 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 zone): at some depth (varying from 0.2 to 4 metres) below the main bauxite horizon there 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 horizon (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 10×30 cm in size) is fully converted to a dense, porcellanous and very pure bauxite (composition: in the order of 63% Al_2O_3, 2% SiO_2 and 1% Al_2O_3).

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

4. The processes of formation and degradation of Laterite

In essence the processes consist of *in situ* subaerial weathering (an intentional pleonasm) of 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 precipitation result in seasonally varying groundwater levels, hence a wide zone with alternating supply or lack of oxigen.

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 unmetamorphosed 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 - due to 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.

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 process will be mirrored in the thickness of the profile formed. Using the stratigraphic column with the estimated ages of the successive periods and epochs - e.g. the one of van Eysinga, 1975 - leads to the following time spans for the lateritic weathering processes in the northern part of South America (the Guyana Shield, partly after Aleva, 1984)

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

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 on 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 ~ 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.

Parent rock composition and texture are also influencing lateritization directly: feldspatoïds weather more easily than feldspars, while very finely grained igneous rocks and very coarely 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 bazalts, dolerites and anorthosites to the slowest reacting granites and feldspatic sandstones.

5. The description of laterites

There are three stages in this description: in the field where the basic data for all 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. 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 few manuals for the effective description of field observations. Soil Horizon Designations, by E.H. Bridges, Technical Paper 19, ISRIC 1990, is a good manual for the description of soils. It also may assist in the description of 'geological' horizons by following selected methodologies and some of the measurable characteristics. Otherwise, standard geological texts in sediment and igneous petrology should be followed.

5.1: In the field

The desription 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 vegatation, and the climate. See the "Guidelines for

soil descriptions", FAO 1990, for descriptive terms for the landscape and the lay of the land. State the representativiness 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 horizons, if any; the presumed (weathered) parent rock to be considered as a horizon as well;

• description of each separate horizon with colour(s), structures, textures including voids (use handlens!), mineralogy as far as possible with the handlens only, nature of contact with underlying horizon, samples taken (for each with position within the horizon and analytical work proposed), horizontal changes within the horizon.

- Take photographs e.g. from the total vertical profile and from each of the horizons 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 garantee 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 horizons 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 horizons 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

; see also Annex II

providing systematic descriptions in clearly defined terms (Aleva, 1983, 1986, 1987; Bardossy & Aleva, 1990; Guidelines for soil descriptions - Final draft, FAO, 1990). All measures should always 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 with 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 are more complex in their 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).

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) and there are also huge deposits that consist completely of pisoids (Weipa, Queensland, Australia, also bauxite).

- Aleva, 1965

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

5.2: In the laboratory (see also Annex III)

- 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 containers with a lable 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 micromorphology based on soil thin section descriptions (cf. Handbook for soil thin section description, Bullock et al., International Society of Soil Sciences, 1985);

• 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 for use in the laterite/bauxite mining industry should adhere to its specific requirements and conventions. This includes mainly the necessity of a double silica determination, i.e. separate determinations of the silica contained in kaolinite, and that present as quartz and unweathered or only partly weathered silicates, e.g. staurolite. This is 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 the quartz is not attacked. The quartz SiO_2 is later on in the analytical procedure determined through weighing before and after an HF treatment to remove the quartz present.

A completely different approach may be used in bauxite exploration, where a representative sample is treated in a laboratory-scale aluminaplant. One gram of the ground sample is placed in a nickelsteel bomb of 15 ml volume, 10 ml of the plant-type caustic soda solution is added and the bomb is heated - while rotating - to the plant operating temperature (150°-250°C). After a standard lapse of time, the bomb is opened and the various required analyses are made on the highly charged fluid. This involves determination of Al_2O_3, Fe_2O_3, and (reactive) SiO_2. Generally used operating temperatures are ~150°C and ~250°C.

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.

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 termal gravity instrument is well suited ("Gibbsite analyser", 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.

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 numnber of similar sized samples along the slit, and combine these to one final sample to be analysed.

When more detailed information, e.g. horizon by horizon, is required, the sampling should employ one sample for each horizon, and where horizons are thicker then 1 metre, a second sample should be taken for the remainder of the horizon. The sampling slits preferably to 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 be between 1.3 and 1.8.

In the office

Prepare a summary report on the observations made and the analyses executed. 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 Annex IV)

Soil mapping, but in particular mineral exploration, mine planning and civil engineering work generally require detailed and closely spaced observation and data collecting spots of the laterite/bauxite formation under study. Depending on the purpose, this will require drilling, pitting or trenching. 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.

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!.

6.2: Drilling

Mostly a fast method, and depending on the method used and 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 paramters follow:

a/ *Suriname Coastal Plain*: partly swampy - up to 2 m deep - and completely waterlogged. Banka* drilling with 5 cm Ø casing, unconsolidated overburden (when detailed sampling is not required) blown out by water jet (5 cm Ø centrifugal pump with small gasoline engine). Sampling starts from the top of the hard duricrust/accumulation zone; samples taken over every successive one metre penetration seperately. Profile description based on macroscopic study of the sludge and the hardness, i.e. penetration resistance. Drilling bit for the laterite/bauxite horizons is preferrably of the fish tail type with two narrow, pointed tungsten carbide tipped teeth. Drilling bit 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.

b/ 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 18 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 pickax 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. 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 channels from the pit wall, after the field geologist had marked (with 10 cm long nails) the (sub)horizon boundaries; one sample for each (sub)horizon or maximum 1 m plus a sample for the remainder of the (sub)horizon.

c/ Amazon tropical forest - well drained, same location: core drillig producing 15 cm diameter cores; compressed air to flush the cutting 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) horizon by horizon. 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.

d/ Australia, Darling Range - well drained: drilling with a rotary type vacuum drill mounted on an agricultural tractor. The simple 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 underlaying 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. Ore reserve drilling will often start at a 200 × 200 m grid, later to be reduced for quality control purposes locally to as little as a 10 × 10 m.

6.3: Trenching

This is a superior method as continuous geological observations 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 in particular usefull - and often adequate equipment can be obtained near the site.

Trenching by hand is used in e.g. Guajarat, N.W. India, for the exploration (and mining) of refractory grade bauxite (small tonnages can already be economically interesting), which 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: Description of (fresh) road cuts, and correction for talud slope

Knowledgeable Volonteers requested for this paragraph!

same for field and laboratory criteria to distinghish monocyclic from polycyclic profiles!

REFERENCES

ALEVA, G.J.J. 1965 The buried bauxite deposits of Onverdacht, Suriname, South America. Geol. Mijnbouw, 44, p. 45-58.

--- 1983 Suggestions for a systematic structural and textural description of lateritic rocks. *In* A.J. Melfi & A. Carvalho, Eds., Lateritisation Processes; II Intern. Seminar on Lateritisation Processes, São Paulo, Brazil, 4-12 July 1982, Univ. São Paulo, Brazil.

--- 1984 Lateritization, bauxitization and cyclic landscape development in the Guiana Shield. *In* Bauxite, L. Jacobs, Ed., Proc. 1984 Bauxite Symp., Los Angeles, Cal. USA, Febr.27-March 1, 1984, AIME, New York, p. 297-318.

--- 1986 Classification of laterites and their textures. *In* P.K. Banerji, Ed., Lateritisation Processes, chapter II, p. 8-28, Mem. vol. 120, 102 pp., Geol. Survey of India.

--- 1987 Voids in laterites: suggestions for their decription and classification. *In* Proceedings ICSOBA Intern. Symp. Tapolca, Hungary, Travaux ICSOBA, Vol. 16-17, p. 141-153, Zagreb, 1986/1987.

ALEXANDER, L.T. & J.G. CADY 1962 Genesis and hardening of Laterite in soils. Techn. Bull. No. 1282, Soil Conservation Service, U.S. Department of Agioculture, V + 90 pp + 8 plates.

BÁRDOSSY, G. & G.J.J. ALEVA 1990 Lateritic Bauxite. 624 pp, 16 colour plates, Developments in Economic Geology 27, Elsevier Amsterdam-Oxford-New York-Tokio.

BATES, R.L. & J.A. JACKSON 1980 Glossary of Geology. American Geol. Inst., 751 pp, 2nd edition.

BECKER, G.F. 1895 Reconnaissance of the gold fields of the southern Appalachians. U.S. Geol. Survey, Annual Report, 16th, pt 3, p. 251-331.

BERTHIER, P. 1821 Analyse de l'alumine hydratée des Beaux, département des Bouches-du-Rhône. Annales des Mines, VI, p. 531-534.

BOCQUIER, G., B. BOULANGÉ & J.P. MULLER 1983 Remarques au sujet d'une classification des laterites. Presented to the Working Group meeting of the IGCP Project 129, Gent, Belgium, October 1983 by B. Boulangé, 2 pp.

BRIDGES, E.H. 1990 Soil horizon designations. Tech. Paper 19, ISRIC, Wageningen, 111 pp.

BUCHANAN, F. 1807 A journey from Madras through the Countries of Mysore, Canara and Malabar etc. 3 Volumes, (circa 1500 pp) London.

BULLOCK, P. et al. 1985 Handbook of soil thin section descriptions. Prepared under the auspices of the Intern. Soc. of Soil Science, Waine Research, Albighton, UK, 152 pp, 146 fig., 2 appendices.

DELVIGNE, J. 1965 Pédogenèse en zone tropicale - La formation des minéraux secondaires en milieu ferrallitique. ORSTOM, Paris, 177 pp.

DOEVE, G. 1955 De bauxietexploratie op het Nassau gebergte. Geol. Mijnb.k. Dienst, Suriname, 68 pp, 51 annexes.

DRIESEN, P.M. & R. DUDAL, Eds, 1989 Lecture notes on the geography, formation, properties and use of the major soils of the world. Agricult. University Wageningen & Katholieke University Leuven, 296 pp.

ESSEN, M.J. van, J.A.C. HEYNEN, A.H. van der VEEN & G.H. VONKEMAN 1971 A simple gibbsite analyzer for rapid field determination of the available alumina content in bauxites. Mineralia Deposita, 6, p. 41-48.

EYSINGA, F.W.B. VAN 1975 Geological Time Table. Elzevier Scientific Publ. Co., Amsterdam.

FAO-UNESCO 1988 Soil map of the world: Revised legend. World Soil Resources Report 60, FAO, Rome. 119 pp. Reprinted as ISRIC Tech. Paper 20, 138 pp.

FAO-UNESCO 1990 Guidelines for soil descriptions (Final draft). Food and agriculture organization of the U.N., Rome.

FERMOR, L.L. 1911 What is Laterite? Geol. Mag., NS, Dec. V, vol. 8, pp. 454-462, 507-516. 559-566.

FOX, C.S. 1932 Bauxite and aluminous laterite. Sec. ed., Crosby Lockwood & Son, London.

--- 1936 Buchanan's Laterite of Malabar and Kanara. Records of the Geol. Survey of India, Vol. 69, part 4/April, p. 389-422 & plates 26-32.

GOUDIE, A. 1973 Duricrusts in tropical and subtropical landscapes. Clarendon Press, Oxford, UK.

HAMMEN, TH. van der & T.A. WIJMSTRA 1964 A palynological study on the Tertiary and Upper Cretaceous of British Guiana. Leidse Geol. Meded. 30, p. 183-241.

HARROSSOWITZ, H 1926 Laterit. Material und Versuch erdgeschichtlicher Auswertung. Fortschr. Geol. Paläont. 4, Heft 14.

KONTA, J 1958 Proposed classification and terminology of rocks in the series bauxite-clay-iron oxide ore. J. Sedim. Petr. 28 (1), p. 83/86.

KRONENBERG, B.I., J.F. COUSTON & B. STILIAMID FILHIO, W.S. FIJFE, R.A. NASH & D.SUGDEN 1979 Minor element geochemistry of the Paragominas bauxite, Brazil. Econ. Geol. 74(8) p. 1869-1875.

LAMPLUGH, G.W. 1902 Calcrete. Geol. Mag. NS. Dec. IV, 9, p. 575.

LEPRUN, J.C. 1979 Les cuirasses ferrugineuses des pays cristallins de l'Afrique occidentale seche. Génèse - transformations - dégrédations. Thèse, Sciences Géologiques Strassbourg, Mém. 58, 224 pp, 13 plates, 3 annexes.

LUCAS, Y. 1898 Systèmes pédologiques en Amazonie Brésilienne - Équilibres, déséquilibres et transformations. Thèse, Univ. de Poitiers, 157 pp, 3 annexes.

MCFARLANE, M.J. 1976 Laterite and landscape. Ass. Press, London, 151 pp.

PEDRO, G & A.J. MELFI 1983 The superficial alteration in tropical regions and the lateritisation phenomena. *In* A.J. Melfi & A. Carvalho, Eds., Lateritisation Processes, Intern. Seminar on Lateritisation Processes, São Paulo, Brazil, 4-12 July 1982, p. 3-13.

ROBINSON, G.W. 1949 Soils, their origin, constitution and classification. Thomas Murby, London, 537 pp.

SCHELLMANN, W. 1982 Eine neue Lateritdefinition. Geol. Jahrbuch, D. 58, p. 31-47, Hannover.

--- 1983 A new definition of laterite. Natural Resources and Development, 18, p. 7-21.

SOMBROEK, W.G. 1966 Amazon soils - a reconnaissance of the soils of the Brazilian Amazon region. Thesis 292 pp; Centre for Agric. Publ. (Pudoc), Wageningen, The Netherlands.

THOENEN, J.R., M.C. MALAMPHY & G.K. DALE 1945 Application of the Ternary diagram to Arkansas bauxite. Am. Inst. Mining Metall. Engineers, Tech. Publ. 1915, 13 pp.

U.S. SOIL SURVEY STAFF 1951 Soil Survey Manual. Agricultural Handbook No 18 U.S. Dept. of Agriculture..

--- 1975 Soil taxonomy. Agricultural Handbook No. 436, 50 pp., U.S. Dept. of Agriculture

VALETON, I. 1972 Bauxites. Developm. in Soil Sciences 1, 226 pp, Elsevier Publ. Co., Amsterdam-London-New York.

VISSER, W.A. 1980 Geological Nomenclature. R.Geol. & Mining Soc. of The Netherlands, 540 pp.; Scheltema & Holkema, Utrecht.

GLOSSARY

Definitions or explanations are given for all terms marked in the text with te symbol •. The derivation or author of the term is given between brackets. GG marks the term's explanation is taken from the Glossary of Geology, by Bates & Jackson (1980),

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

Accumulation zone: (weathering) that part of the lateritic weathering profile which is characterized by the accumulation of Fe or Al, or both; it is generally harder than the underlying saprolite, whence indicated in French as 'carapace'.

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 humid and hot tropical climate. The main components are kaolinite or gibbsite, or both, with Fe compounds and weathering resistant minerals such as quartz.

Arkose: a sedimentary rock largely composed of feldspar grains; a feldspar-rich 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 IV.

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

Banka drilling: a drilling method for unconsolidated material (sediments or weathering products) in which a steel tube is

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(Geol.Nom.) refers to VISSER 1980: Geological Nomenclator.

lowered (by rotating under vertical 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 IV.

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 (Bárdossy & Aleva, 1990).

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

Coating: a thin, often thinly banded, dense (cryptocrystalline) layer of lateritic matter, which covers as a coat of paint, the walls of open cracks and voids or on the surface of concretions.

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

Cuirass: (weathering) the hard, upper subhorizon of the accumulation horizon in the laterite profile, particularly enriched in iron oxide minerals.

Degradation: changes in composition and structure/texture, resulting from the equilibration of the mineral association to a lower pressure and temperature regime, and - in the laterite context - a drier climate.

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, Techn. Paper 20, ISRIC 1989).

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).

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.

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.

Not leached 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).

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

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

Horizon (soil): layer of soil material approximately parallel to the surface and differing from adjacent genetically related layers in physical, chemical and/or biological characteristics, or in colour, structure, texture, consistency, etc. (Geol.N.)

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

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

(ii) a laterite in which the (sesquioxide) precipitates 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-textured, 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 the fissures, joints and pores of a rock to reduce its porosity (Bárdossy & Aleva, 1990).

Intrazonal soils: soils whose characteristics are the result of strong local dominance of soil forming factors other then climate (Driessen & Dudal, 1989).

Iron crust: a substantial concentration of an iron compound in a relatively thin surficial layer and hence harder than underlying horizons.

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 L.T. Alexander & J.G. 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, kaolinte minerals and quartz, The SiO2 : (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 kaolonite plus the primary quartz.

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

Lateritic: the adjective for a true laterite; it should not be used in the sense of "somewhat similar to 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).

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. (L.L.Fermor, 1911).

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

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

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

Lithomarge: a smooth, indurated variety of common kaolin, consisting at least in part of a mixture of kaolinite and halloysite (GG).

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).

Parent rock: the rock mass from which a soil's or a weathering mantles parent material is derived (after GG).

Pedogenetic laterite: laterites in which the precipitates develop in a zonal soil where alternating conditions of wetting and drying occur (McFarlane, 1976).

Petroferric or skeletic phase: 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 upper part must be within 100 cm of the surface (FAO-Unesco Revised Legend, 1988).

Pisoid: (weathering) a more or less spherical textural or structural element, between ~3 and ~30 mm in diameter, consisting of a core or 'nucleus' and an outer rind or 'cortex', both composed of lateritic matter; see text Ch. 5. (Bárdossy & Aleva, 1990).

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

Plinthite: 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 aggregates on exposure to repeated wetting and drying. In a moist soil, plinthite is usually firm but it can be cut with a spade. When irreversibly hardened the material is no longer considered plinthite, Such hardened material is shown (on the soil map) as a petroferric or skeletic phase (Revised Legend, Soil map of the world, FAO/Unesco, 1988; Sombroek (1966) distinguishes soft, hard and fossil plinthite - see chapter 2.5 of this text).

Residual: formed in place by the weathering of the local rock and the removal of some of its components through solution and eluviation.

Rock: an aggregate of one or more minerals, e.g. granite, shale, marble; or a body of undifferentiated mineral matter, e,g, obsidian, or of solid organic material, e.g. coal (GG).

Rotten rock: still coherent but strongly weathered rock, in which the silicate minerals are partly decomposed.

Saprolite: a soft, earthy, typically clay-rich thoroughly decomposed rock, formed in place by chemical weathering of igneous, sedimentary, and metamorphic rocks. It is characterized by preservation of structures that were present in the unweathered rock (Becker 1895). Frequently, the saprolite horizon contains a lower subhorizon with preserved structures and an upper subhorizon in which the parent rock structures have disappeared.

Siallitic: the soil horizon characterized by Al-silicate minerals, i.e. kaolinite.

Silica: dioxide of silicon or SiO_2 (GG). In the weathering context two versions are commonly recognized, i.e. *reactive silica*: in the laterite/bauxite context 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 the silica contained in unweathered silicates from the parent rock (e.g. feldspar).

Soil: (i) 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 (Driesen & Dudal, 1989).

(ii) Engineering: all unconsolidated material above bedrock.

(iii) GG: 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.

(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).

Structure: (petrology) a megascopic feature of a rock mass; also smaller-scale features of a rock in which the texture or composition is different in neighbouring parts, e.g. banded structure (after GG).

Structure/texture: see Chapter 1, § 1.

Structured: see saprolite.

Texture: (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 partcles (after GG).

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).

FIGURE CAPTIONS

Fig. 1A - The compositional tetrahedron with Al_2O_3, Fe_2O_3, SiO_2 and H_2O in its apices.

Fig. 1B - The ternary diagram hematite-gibbsite-kaolinite, with the suggested nomenclature of the weathering products in the various partitions.

Fig. 2A - The typical laterite profile as developed over granitic parent rocks.

Fig. 2B - Observed variations in the relative thicknesses of the successive horizons of the laterite profile.

Fig. 3 - Sketch after photograph of epigenetic veins in the accumulation horizon of bauxite in Onverdacht, Suriname.

ANNEXES

Annex I - Chemical composition and computed normative mineralogical composition (see Bárdossy & Aleva, 1990, chapter 8.2.3/C) of two samples of laterite, collected by Fox (1936) near the original site of Buchanan's description.

Annex II - Suggestions for the consistent description of laterites and related rocks.

a: structures
b: pisoids
c: consistensy and response to pressure and stress
d: description and classification of voids
e: abundance terminology.

Annex III - A: Suggestions for chemical analytical work for possible comercial Al-rich laterites (bauxites).

B: Suggestions for chemical and mineralogical work for soil scientific purposes

C: Major related literature references.

Annex IV - Description of various sampling procedures & methods-see Ch. 6.

Annex V - Colour Chart

CHARTS

Chart I & chart II, After G. Pedro & A.J. Melfi (1983)

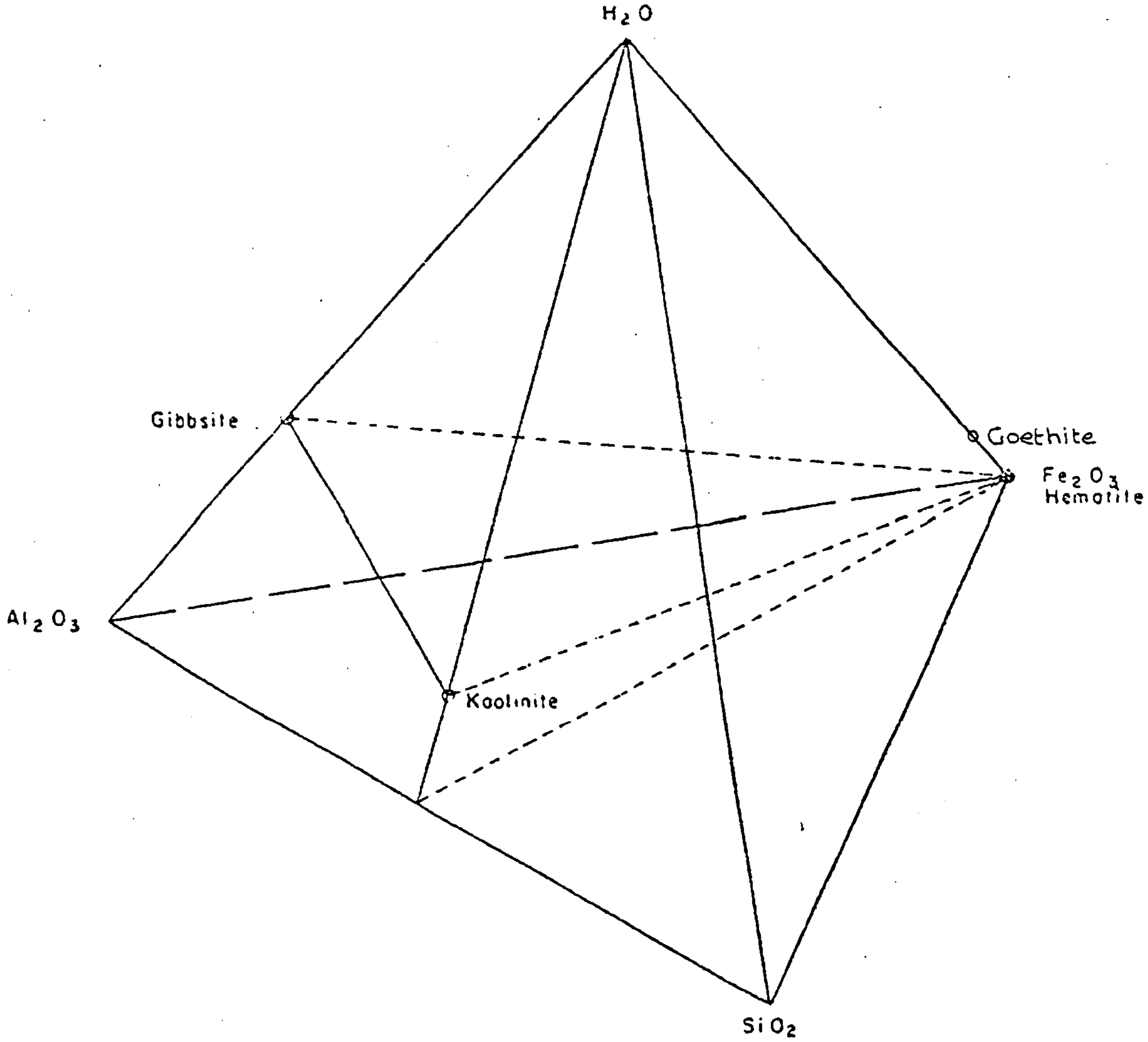


Fig. 1A:

Compositional tetrahedron with Al_2O_3, SiO_2, Fe_2O_3 and H_2O at the apexes. The position of gibbsite and kaolinite is indicated.

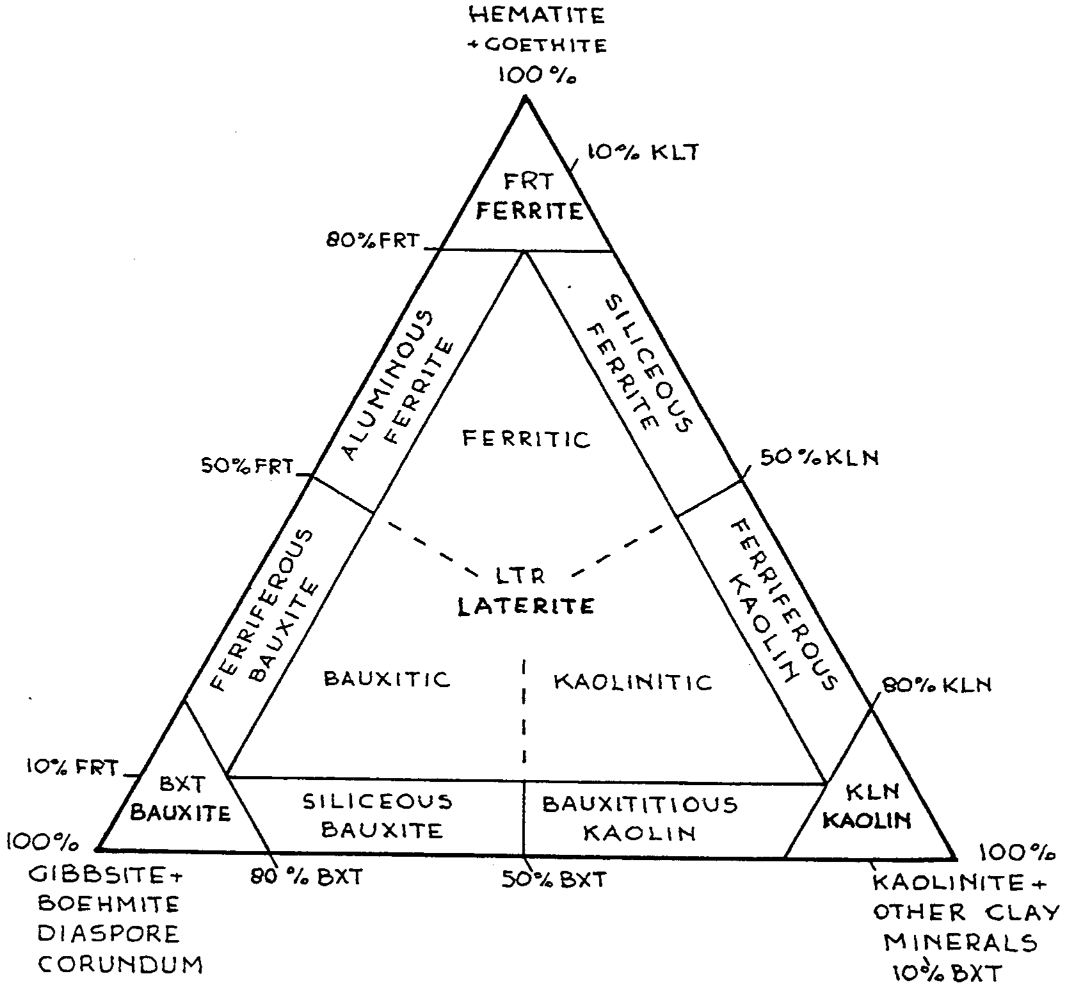


Fig. 1B: Ternary compositional diagram, illustrating the nomenclature of the weathering products of the humid, tropical climates; in addition quartz and unweathered parent rock minerals may be present.

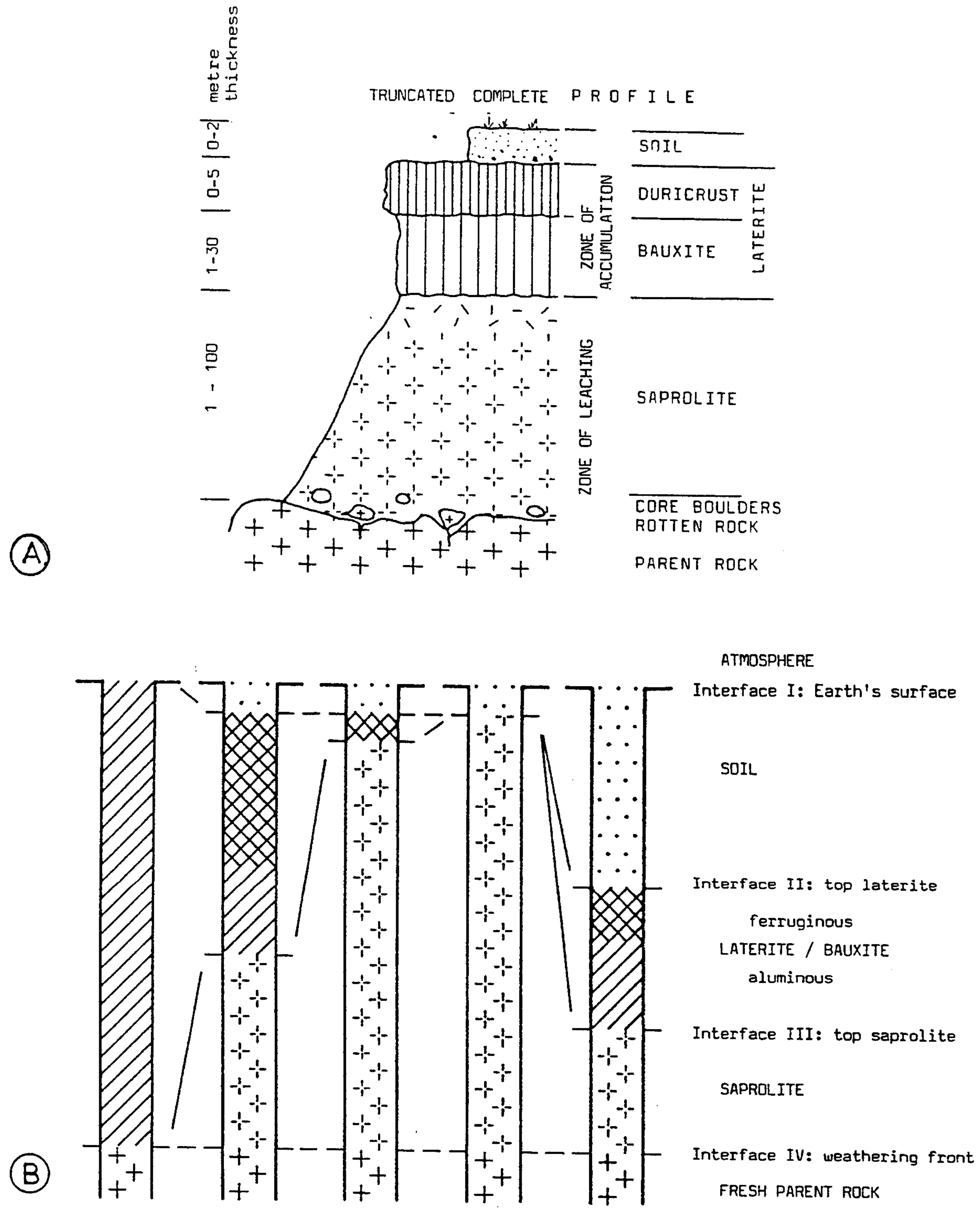
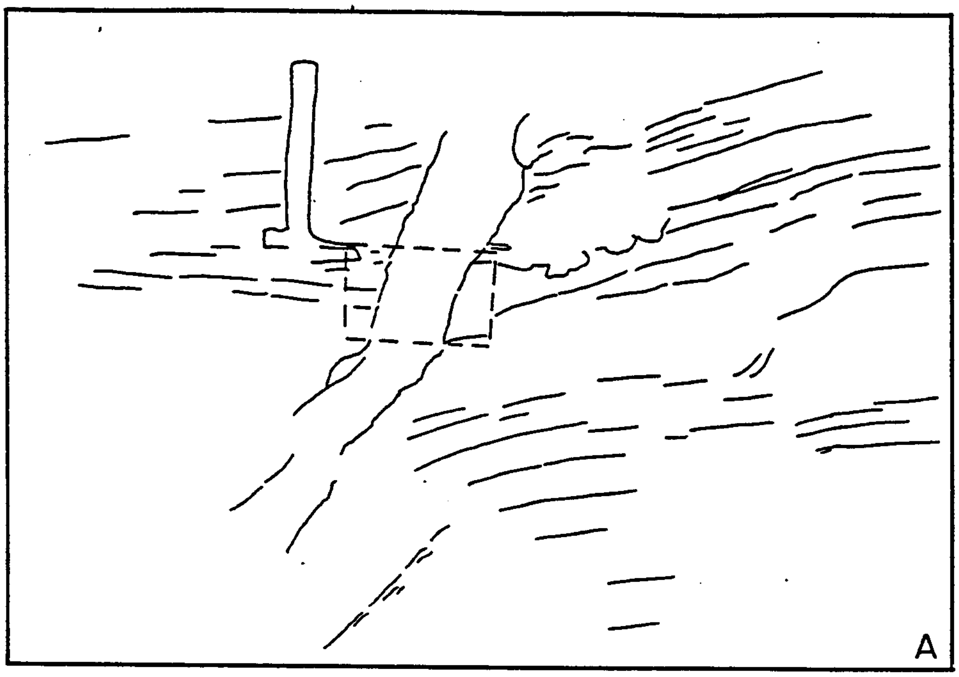


Fig. 2- A: Sketch of the typical laterite-saprolite weathering profile. B: Examples of reduced and truncated weathering profiles, illustrating the absence of one or more of the typical horizons.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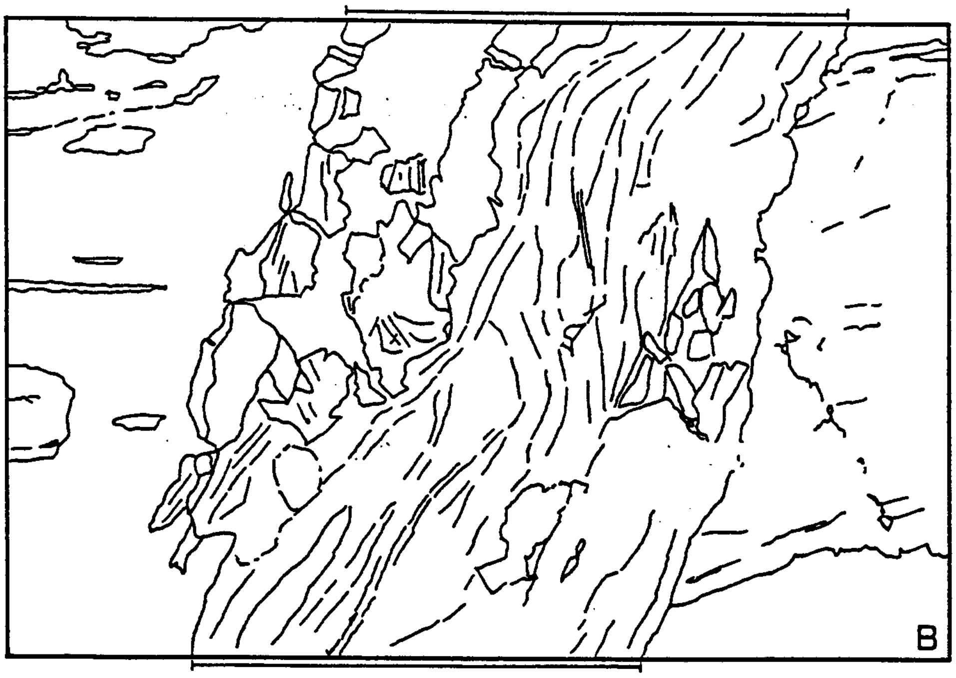
B

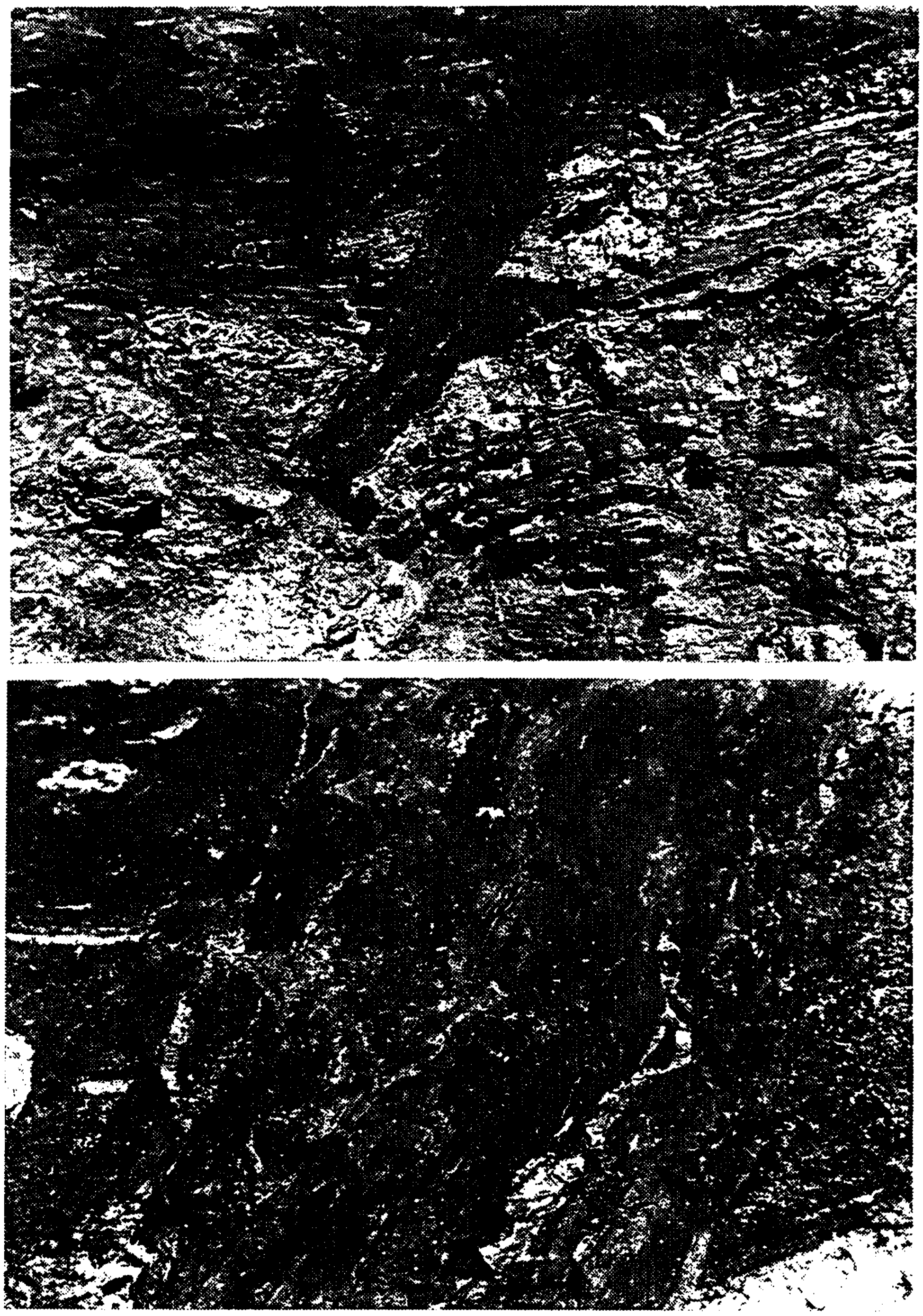

Fig. 3 - Photographs of a cross-cutting bauxitic vein in the bauxite accumulation horizon, Onverdacht, Suriname.

A - Overview with hammer standing with its head on a narrow ledge; the hammer handle is 29 cm long. The relict sedimentary bedding of the bauxite parent rock is clearly visible to the richt of the vein.

B - Detail - from a little different standpoint, and after removal of the hammer - of the cross-cutting vein, with at right and left the bedded bauxite. Note brecciation along the vein contact; in the vein the colour banding is visible.

EXPLANATION TO CHART I AND CHART II

G. Pedro & J. Melfi (1983) The superficial alteration in tropical regions and the lateritisation phenomena. In: A.J. Melfi & A. Carvalho, Eds., Lateritisation Processes, Proc. IInd International Seminar on Lateritisation Processes; São Paulo, Brazil, July 4-12, 1982.

This extended abstract of the above is added because of the concise way it explains the different environmental requirements and restrictions for the formation of either plinthite, ferralllite or laterite. The paper is summarized by the authors in the two attached charts.
N.B. - Between [...] synonymous terms added by the reviewer; the spelling of technical terms has not been changed.

The start off is with a generally accepted statement: laterites are superficial formations resulting from the meteoric alteration under tropical conditions.

General characteristic: in the past this superficial alteration [weathering] was essentially defined in mineralogical terms (types of weathering): allitisation, mono-siallisation. bi-siallisation (Harrassowitz 1926, Pedro 1964-1966). It now appears that the degree or intensity of weathering is essential (Pedro et al. 1975).

There are two great domains:
I - In humid but cold, temperate or arid climates weathering is *selective:*
a/ the most vulnerable minerals are attacked before the Al silicates; weathering is diachronic, the levels under evolution always contain primary, not yet decomposed minerals; the newly formed minerals are the result of discrete, crystallo-chemically 'transformed' constituants, i.e. clay minerals;
b/ the process is shallow, restricted to the superficial layer, i.e. the solum.
II - In warm and humid climates of the intertropical zone the weathering is *intense* and develops as follows:
a/ all weatherable minerals are effected simultaneously (synchronous) and generally disappear from the horizon under attack; the process of neoformation is dominant and evolves into a level essentially composed of sedundary minerals with no weatherable primary minerals present;
b/ weathering reaches to great depth, so much so that only the upper horizon shows a characteristic pedological evolution. In some instances the weathering profile is composed of two levels: an upper one wich is the pedological solum, and a deeper one composed of alterite.

Type of alteration/weathering. See chart I.
Ferrallitization (Robinson 1949):
1/ Total removal of alkalis from the primary minerals and complete accumulation of iron (in situ) and aluminium (relative).
2/ The iron released is seperately and independantly individualized from the clay minerals (kaolinite).
There are two parageneses:
a/ Al-hydroxide + Fe'''hydrate ⇒ Ferrallitization *sensu stricto* = ultra-ferrallitization = oxidic ferrallitization.
b/ Fe'''hydrate + kaolinite ⇒ ferrallitization *senso lato* = kaolinitic ferrallitization.

The result is a superficial material without primary minerals, except quartz and some refractory minerals, and essentially composed of kaolinite, Al-hydroxide and Fe-oxides.

Principal facies of superficial evolution in the tropical zone.
See chart II.
Three cases are discussed; the Fe is derived from weathering of the parent rock, and the facies evolution is essentially vertical.
1/ Humid and permanently percolated medium, i.e. perfect and permanently assured free draining ⇒ ferrallitic soils ⇒ oxic horizons (oxisols).
2/ Oscilating water-table; concerns the temporarily flooded part of the profile (common names used: mottled clay, argile tachetée, ground water laterite, retichron). The result of successive reduction and oxidation zones is the separation of clays and ferruginous components ⇒ heterogenous levels of gray, Fe depleted zones versus Fe enriched red zones. In time it may lead to first discontinuous (nodules) and later to continuous levels (crusts) of Fe concentrations. Hence gradual formation of plinthite [and its hardening into a skeletic phase].
3/ Tropical regions with highly contrasting zones, where the upper part of the ferrallitic material (solum) becomes ultradry in the dry season: 'Xerolysis' (Chaussidon & Pedro, 1979), i.e. the ferruginous constituents are stripped of their OH component, the Fe ions diffuse to little more humid [hori]zones, where the inverse reaction takes place: segregation of Fe in nodules ⇒ carapace ⇒ attack on kaolinite ⇒ incorporation of Al in hematite (second order ferrallitisation, Leprun, 1979).

CHART 1 - PRINCIPAL GEOCHEMICAL TYPES OF SURFICIAL ALTERATION

Place of ferrallitization +)
After G. Pedro & A.J. Melfi, 1983

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

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

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CHART II - THE GREAT WAYS OF SUPERFICIAL EVOLUTION IN FERRALLITIZING TROPICAL CONDITIONS

After G. Pedro & A.J. Melfi, 1983

Ways of Evolution	Characteristic mechanism	Corresponding phenomenon	Genetical 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	'Lateritization' *sensu lato*	Alternating pedo-climates	Alternation of humid and dry seasons	
				Alternation of humid drained periods and waterlogged periods (free groundwater)	Seasonal evolution

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 [rock] 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 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 1.)."

The norm computation 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 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 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' paragenesis represents a wrong hypothesis and must be rejected.

Both the gibbsite + goethite and the gibbsite + hematite + goethite parageneses 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 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 are the original and the recomputated chemical analyses for the samples 1, 2 and 3 (Table I), and the print-out for all four samples of the BASIC program used for the computation of the mineral parageneses.

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

To ANNEX I

Table I: 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).

The computed norms are based on three probable mineral parageneses of which the gibbsite-hematite/goethite norm seems to fit these lateritic rocks best. The gibbsite-hematite norm shows the worst fit and is therefor not given.

Sample No.	1		2		3	
	orig.	recomp.	orig.	recomp.	orig.	recomp.
Unsol.	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	
T. Fe203*		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	0.07	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
	GBS+GTT	+HMT	GBS+GTT	+HMT	GBS+GTT	+HMT
Gibbsite	1.64	9.95	-0.08	1.39	4.84	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.

N.B. Deviations of the sum from 100.00 % is rounding off error.
Mineral code: GBS - gibbsite, GTT - goethite, HMT - hematite.
See also Bardossy & Aleva (1990) for the method of computation.

```
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
```

ANNEX II

a - Shapes and sizes of structures and rock textures.

b - Shapes and sizes of grains and voids.

c - Pisoids and the observed variation in nucleus-cortex relationship.

d - Semi-quantitative relative abundanve terms

e - Classification and nomenclature of voids.

f - Consistency: state and response.

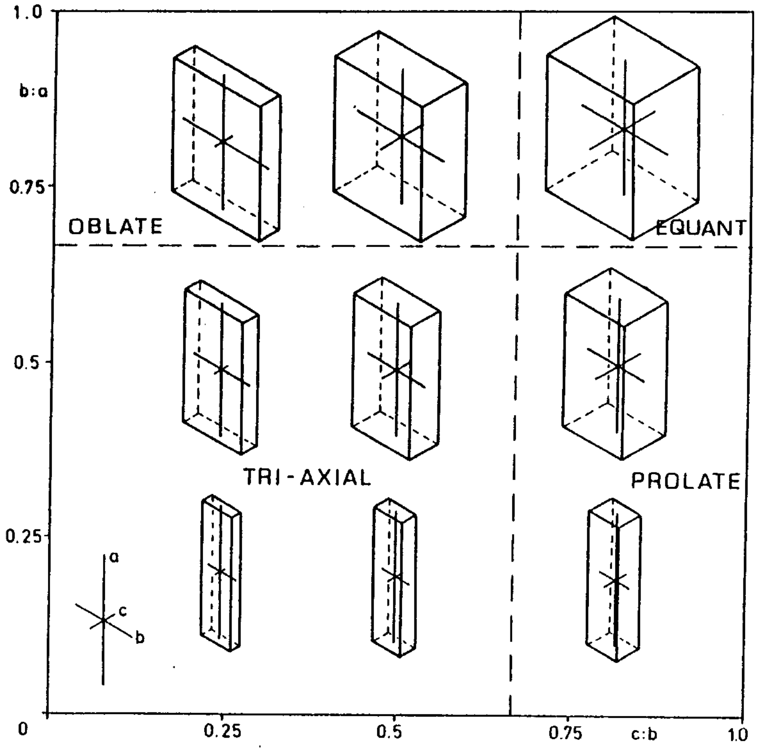
Annex II-a

Shapes / Size Groups	Homogeneous	Inhomogeneous				
		Equi-dimensional	One dimension much different from the two others			
			Cylindrical		Tabular	
			Long dimension vertical	Long dimension horizontal	Short dimension vertical	Short dimension horizontal
A STRUCTURES	Massive Pore Interstice	Bouldery Blocky^{+} Sphaeroidal Cave Cavernous	Columnar^{+} Diapiric^{+} Tube Tubular	Roll-Boudinage-shaped Pipe	Banded Bedded^{+} Layered^{+} Stratiform^{+} Lens-shaped^{+} Zonal Pillow" Fissure	Dike^{+} Fissure
B SMALLER SCALE STRUCTURES LARGER ROCK TEXTURES	Massive	As above plus Breccia-like Coated grains Concretionary Geode Pisoidal Matrix and grain-supported	Root-shaped Rod-shaped Columnar^{+} Root channel Tubule Tubular	As above plus Rod-shaped Pipe Root channel	As above plus Platy^{+} Laminated Heavy mineral streaks" Fissure Slit	Dike Fissure filling Fissure Slit
	Pore Interstice	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 Interstice Pore	Crystalline^{+} Granular^{+} Ophitic" Nodular Concretionary Pisoidal Ooidal 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



- Shape nomenclature, illustrated by rectangular prisms with their axes a, b and c, as borrowed from sedimentology (Zingg 1935, Krumbein 1941). In nature grains and voids are usually subrounded to irregular, whereas the axes will not intersect in one point.

GRAIN SIZE-TEXTURE SEDIMENTS AND SEDIMENTARY ROCKS			UNITS µm	UNITS phi 1)	UNITS mm
RUDITE PSEPHITE	BOULDER			-9	512
				-8	256
	COBBLE			-7	128
				-6	64
	PEBBLE			-5	32
				-4	16
				-3	8
	GRANULE			-2	4
ARENITE PSAMMITE	SAND	very coarse	2×10^3	-1	2
		coarse	1000	0	1
		medium	500	1	1/2
		fine	250	2	1/4
		very fine	125	3	1/8
LUTITE PELITE	SILT	coarse	64	4	1/16
		medium	32	5	
		fine	16	6	
		very fine	8	7	
	CLAY		4	8	
			2	9	

- Example of grain size nomenclature based on the Wentworth scale. 1) - International pronounciation 'fee' = $-\log_2$ grain 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 ≥ ½ radius of nucleus	normal or grain pisoid	rock pisoid	two phase pisoid	-	-
THIN < ½ 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 - .

Diagram showing the observed variation in nucleus - cortex relationship based on the definition: Pisoid = any spheroidal body with a smooth surface, independent of the internal structure, in diameter varying from 2 - 60 mm; most pisoids, however, have a nucleus and a cortex.

TABLE

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

Table

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	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 - Intraparticle pore a: INTRACRYSTALLINE PORE b: INTRAGRANULAR PORE	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 $a > b > c$

$a \geqq b \geqq c$: equant
$a > b > c$: tri-axial
$a \geqq b > c$: oblate, lensoid mold
$a \geqq b \gg c$: fissure
$a > b \geqq c$: prolate, spindle-shaped mold
$a \gg b \geqq c$: tubular

TABLE

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
<u>Consolidated</u>	
Hard	Tough, brittle, splintery
Dense, medium hard	Conchoidal (fracture)
Soft	Brittle, sectile, doughy
<u>Unconsolidated</u>	
Hard	Tough, sectile, doughy
Soft	Plastic, sectile, sticky
Earthy	Friable, crumbly
Dense	Tough, brittle, sectile
Granular	by definition loose
Powdery	
Disintegrated	

ANNEX III

a - Suggestions for chemical analysis of laterites and bauxites.

b - Suggestions for chemical and mineralogical analysis of soils

c - Litterature references.

Analytical methods

Method	LOI	TG	BD	NA	XRF	DTA	WC	XRD
Parameter								
H_2O+	#	.	.	.	.	.	#	
ABEA/MEA	.	.	#	.	.	.	.	
SiO_2	.	.	#	.	.	.	.	
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 partly or completely	=	not well feasible
.	not applicable	o	absent
		$	immaginary monitary unit

Norm formulae

Code	Mineral name	% A= Al_2O_3	% H= L.O.I.	% S= R.SiO_2	% Q= F.SiO_2	% Fe= Fe_2O_3	% Ti= 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.

$KLT = 2.151*R.SiO_2$ 1/

This is a summation of three equations

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

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

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

Remains for further assignment:

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

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

From the above mineral compositions it follows that

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

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

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

The two equations are solved as follows:

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

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

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

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

in which $0.176*A' = X$

and $A_{GBS} = Y$

Annex IV

An overview of some methods for making artificial outcrops to systematally sample the total bauxite profile

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, Bintan, South Vietnam	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	Mitchell Plat. Amazon Basin, Eastern Ghats	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 overdurden up to 80 m thick	Arkansas, Nassau, Onverdacht, (motor-driven 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 preprevent further progress	limited	limited	simple, fast and accurate when correctly used	Guinea, Pijiguaos	not for very hard bauxite; indepemdemt of moisture, even below water-table good recovery
5. 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	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. Worsley	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 circumstances, except loose, dry, small pisoids.	good	good	high degree of sampling accuracy; requires good roads	Amazonas, Lelydorp, Mitchell Pl., Bielgorod	effective in almost any type of bauxite; below water-level use triple core barrel.