The CORLAT Handbook

Compiled by
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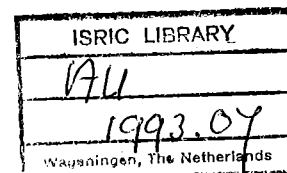
The CORLAT Handbook

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

Compiled by
G.J.J. Aleva
at the request of ISRIC

International Soil Reference and Information Centre
Wageningen, the Netherlands
1993

[CORLAT Draft]

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Proposed miscellaneous tables

- Conversion table for selected units.
- List of some low-pressure and/or low temperature minerals.
- Short list of the main rock-forming minerals mentioned (after Deer et al, 1972).
- Pedogenetic iron compounds, courtesy Dr Schwertmann, ...
- A short summary on clay minerals (after Deer, et al. 1976).
- Some common minerals of the weathering zone (after Deer et al, 1976).

(Note: Deer et al. will be replaced by Ninth ed., 1990.)

PREFACE BY DR. W.G. SOMBROEK

Foreword

During the Plenary Session, the participants of the Second Seminar of the Unesco-sponsored IGCP Project 129: Lateritisation Processes, recommended:

> the establishment of an International Interdisciplinary Laterite Reference Collection, later named CORLAT,

> the compilation and publication of a Handbook on the description of laterites and laterite profiles for interdisciplinary use (McFarlane & Sombroek, 1984),

> this collection to be housed at the International Soil Reference and Information Centre (ISRIC), the Netherlands.

Dr W.G. Sombroek, then Director of ISRIC, succeeded in the course of 1991 to obtain limited but sufficient funds from the EEC to:

> organise an International Workshop to discuss a draft text for this Handbook, and the printing of this Handbook, including a limited number of colour plates.

Next Dr Sombroek searched for a compiler to prepare a first draft of the Handbook, to be discussed at the International Workshop, planned for March 1992 at ISRIC, Wageningen. He succeeded in convincing the undersigned to pick up this "opportunity" or "challenge" (as a retired exploration and mining geologist).

A preliminary draft was circulated amongst a small group of interested scientists in the fall of 1991, a first draft was more widely circulated in the spring of 1992 and served as the text to be discussed at the Workshop in March 1992 at ISRIC, Wageningen.

In view of the individualistic tendencies among scientists interested in laterites, this draft was received — amazingly — without producing an uproar of criticism. This was possibly due to the strong accent put on the necessity of an interdisciplinary approach of any laterite research.

Acknowledgements

The Handbook, as it is now available as a printed book, has obtained its final form through the often detailed cooperation with, and the liberal critical advice received from, a large number of scientists — from many continents — who studied laterites, both in the field and in the laboratory. It is only thanks to this cooperation, and in particular the contributions by the CSIRO Group, composed of Drs Anand, Butt, Robertson and Smith, Division of Exploration Geosciences, Wembley, Western Australia, that the text is more or less up to date with the present state of scientific knowledge.

The Staff of ISRIC has played an essential role in the production of the successive draft versions and this final version of the Handbook. I want to thank in particular my colleague as a geologist Dik Creutzberg for his untiring activity in assisting me to prepare the final text of the manuscript and transferring it from WP5.1-mode into the printed text. His critical comments and enthusiastic support are gratefully acknowledged. Also the work of Wouter Bomer who prepared the figures and illustrations of this manuscript is greatly appreciated.

The following list of participants to the Workshop may serve to give an indication of the persons who have been instrumental in the shaping of the final text of the Handbook. I sincerely thank all persons that provided advice, in whatever form or language, to arrive at the text as printed.

I thank Dr E.M. Bridges, presently at ISRIC in Wageningen, for his painstaking perusal and corrections of my English texts which he transformed into an Anglicized version.

Time will show if it indeed will contribute to a world-wide and better understanding of laterite: what it is and how it may contribute to the well-being of mankind.

List of participants in the Workshop, March 16 - 21, 1992

Dr E.M. Bridges, Chairman of the Workshop on behalf of ISRIC.
Prof. Dr J.M.N. Alexandre, Liège, Belgium.
Mrs Dr Alexandre, Liège, Belgium.
Dr R.R. Anand, CSIRO, W. Australia.
Dr S.W. Buol, Raleigh, NC. USA.
Mr D. Creutzberg, ISRIC.
Prof. S. Batista de Rezende, Viçosa, Brazil.
Mrs Dr B. Durotoye, Ile-Ife, Nigeria.
Dr A.K. Nandi, Nagpur, India.
Dr D. Newill, Crowthorne, Berks. U.K.
Dr I.D.M. Robertson, CSIRO, W. Australia.
Dr P.Smart, Glasgow, Scotland, UK.
Prof. Dr G. Stoops, Gent, Begium.
Prof. Dr Th. Varghese, Trivandrum, India.
Dr S Zauyah, Serdang, Selangor, Malaysia.

1 Introduction

The term 'laterite' was coined by the British East India Company's surgeon Francis Buchanan in 1807, when making a reconnaissance trip through the western part of peninsular India. It was a curious rock that could be cut with steel implements and, after drying in the sun, could be used as building bricks for small to very large buildings, for these bricks resisted the influences of the weather for centuries.

The material had been used world-wide in tropical regions for building purposes before it obtained its latin name, with which it became part of the Earth Sciences vocabulary. By 1844 the term laterite had become — at least in India — well known, to the extent that Newbold, in his account of an East-West reconnaissance trip through Peninsular India, did not bother to give a detailed description or an explanation of the term.

Scientific interest in the material started by the end of the 19th century by earth scientists of various disciplines, e.g. the geologists Walter (1889); Harrison (1898, 1910); Dubois (1903), who made a distinction between eluvial (residual) and alluvial (transported) laterite; Fermor (1911); Lacroix (1913); and the soil scientist Van Bemmelen (1904). Later geographers and geomorphologists joined in the study of laterites. More recently, laterites have been studied and discussed by the soil scientists Alexander & Cady (1962) and the geomorphologist De Swart (1964).

The economic importance of laterite, in particular its presumed present day negative effect on food production in tropical areas, initiated a renewed interest, including that by the UNESCO. In the context of a joint venture of UNESCO and the IUGS (International Union of Geological Sciences), under the acronym IGCP (International Geological Correlation — later Cooperation — Programme), the study of laterites in the widest sense was included. As a result, the study of laterites accelerated in all parts of the world.

The Director General of the Geological Survey of India proposed to the IGCP Board a project entitled "Lateritisation Processes". It was accepted in 1975 as Project 129: Lateritization Processes, with the Director General of the Geological Survey of India as its global leader. During the life time of the Project, 1975-1983, Dr P.K. Banerji, GSI, has been its very active and imaginative convenor. Dr Banerji was also the editor of the six Newsletters that were issued between 1980 and 1984. These Newsletters contributed to a lively and informal exchange of ideas. In addition, two international seminars were held under the title: "Lateritisation Processes":

(i)   Trivandrum, India, 1979; Proceedings published in 1981, containing 51 contributions, (450 pp.).
(ii) São Paulo, Brazil, 1982; Proceedings published in 1983 by Melfi & Carvalho, Eds., containing 46 contributions,(590 pp.).

The Final Report of IGCP Project 129 was published in 1986: Lateritisation Processes, GSI Memoir 120, P.K. Banerji, Ed. (102 pp.).

These symposia rekindled a general interest in laterites and laterite research, which resulted in four more international symposia:

(iii) Bauxite Symposium, Los Angeles, California, Febr. 27 — March 1, 1984. Proceedings 'Bauxite', L. Jacobs Jr., Ed., Soc. of Mining Engineers, AIME, New York, USA, 918 pp. 28 contributions deal with the geology and mineralogy of bauxites.
(iv) International Seminar on Laterite 1985, Tokyo, Japan. Proceedings published in a special issue of Chemical Geology, No. 60, 1987 (396 pp.).

(v) International Symposium on Bauxite prospecting and mining, Tapolca, Hungary, 1985, with the Proceedings published in the Travaux ICSOBA, Vol. 14-15, 1984/'85, 268 pp. and Vol. 16-17, 1986/'87, (223 pp.).

(vi) 6th International Congress of ICSOBA, São Paulo & Poços de Caldas, Brazil, May 11-20, 1988, with Proceedings published in Travaux ICSOBA, Lahodny - Šarc, Ed., Vol. 19, 1989 (477 pp.).

At the 2nd Seminar in São Paulo (1982), during a Plenary Session, the assembled scientists recommended the creation of an Interdisciplinary Laterite Reference Collection (CORLAT) — in analogy of the soil profile collection of the International Soil Reference and Information Centre (ISRIC, Wageningen, The Netherlands). The meeting accepted, after a suggestion by Dr Sombroek, then Director of ISRIC, that this CORLAT collection would be housed at ISRIC in Wageningen, The Netherlands. This International Reference Collection was intended to be realized as a central depository of typical laterite profiles and drill hole cores of world-wide derivation, and as such illustrating the national efforts in studying laterites in the countries represented. The purpose of the Collection is to provide reference material and guidelines for classification of laterites, using a rational descriptive terminology. The potential users of the collection include geologists, mineralogists, soil scientists, geomorphologists, and the practical users of these sciences, such as civil engineers and agronomists. It was recommended that a 'CORLAT Handbook' be produced and distributed, with the intention that such a Handbook would contribute to maintaining or creating a common language to be used world-wide for the description of laterites.

In this context mention must be made of the following two research groups:

(i) "Eurolat, a European Network on Tropical Laterites". It held its most recent and 5th meeting "EUROLAT '91", under the title 'Supergene ore deposits and mineral formation' in Berlin, Germany, August 23 - 24 , 1991, Prof. K Germann, Chairman of the Organizing Committee. During this meeting a new President was chosen, to replace Prof. Dr Yves Tardy, who acted as President for many years: Dr H. Zeegers, BRGM, Department of Exploration, BP 6009, 45060 Orléans, France. The permanent Address of Eurolat is BRGM - EUROLAT, Département Exploration BP 6009, 45060 Orléans, France.

(ii) IGCP Project 317: Paleoweathering records and paleosurfaces. It held its first meeting in Fontainebleau, France, November 25 - 29, 1991, under the title 'Mineralogical and geochemical records of paleoweathering' which is also the title of the Proceedings, edited by J-M Schmidt and Q. Gall (1992), École des Mines de Paris, Centre de Géologie Générale et Minière, 35 rue Saint-Honoré, 77305 Fontainebleau Cedex.

By far the most common laterites have an iron/aluminium composition, resulting from the weathering of the more common acid to fairly basic igneous, metamorphic and sedimentary rocks. If not specified otherwise, these are the laterites discussed in this Handbook.

Lateritization (as defined by Schellmann, see Chapter 2) is a process that acts independently of the chemical composition of the rock involved. However, the results of that process are clearly dependent on the chemical and mineralogical composition of the rock attacked: a granite weathers to a different form of laterite than e.g. a peridotite, as the elements accumulated are different — see Chapter 4: Specialized laterites.

1.1 Interdisciplinary use

This text has included in its title the qualification: "for interdisciplinary use". It is all but impossible to use only those terms which have exactly the same meaning in all related disciplines. Creating new terms, or redefining the existing ambiguous terms, does not seem an acceptable solution for this problem — it would only add another term to the already large technical vocabulary.

When perusing guidelines for descriptions in related sciences, e.g. the Handbook for Soil Thin Section Description (Bullock et al., 1985; published under the auspices of the International Society of Soil Science), it appears that — in the soil sciences — there are only a few terms which are defined in a way clearly deviating from their definitions in geology and petrology. However, terminology has been evolving in geology as well, where the term 'fabric' has largely taken the place of the former 'texture'.

Still, there are situations in which some confusion might occur by using a term that has different meanings in different disciplines. For such situations the following convention will be used in the present text: if confusion could occur through a different meaning of a certain term in other disciplines, the name of the discipline from which the term derives is added between brackets, in order that the reader is aware of the derivation of that term, e.g. texture (petrology) is in a modern text mostly replaced by 'fabric'.

One of the objectives of this Handbook is the promotion of international homogeneity in the terminology used to describe laterites. For that purpose Annex III provides a number of charts and tables, which contain most of the terms that are needed for the macroscopic, and partly also microscopic, description of a laterite. For colours an international (Munsell) rock colour chart should be used.

1.2 The place of laterite in the family of rocks

In geology, three major groups of rocks are distinguished: igneous, metamorphic, and sedimentary rocks, each having their own, more or less well defined physical and chemical characteristics, as well as environments in which they were formed.

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

Laterites cannot be placed in any of these major groupings: they are not soils, and they do not fit in the triplet of igneous-metamorphic-sedimentary rocks. They may, however, be considered to be metasomatic rocks: rocks whose chemical composition has been substantially changed by the metasomatic alteration of its original constituents.

Metasomatism may be described as the process of practically simultaneous capillary solution and deposition of mineral matter, by which a new mineral of partly or completely different chemical composition may grow in the body of an existing mineral or mineral aggregate, often to the extent that the original mineral is completely replaced (after Lindgren, 1928). In current usage, the presence of interstitial, chemically active pore liquids or gases contained within the rock body, or introduced from external sources, are essential for the replacement processes. These processes often, though not necessarily always, occur at constant volume and with little disturbance of fabric or structural features.

1.3 Laterites and its neighbours in space

Laterites are formed at the earth surface. They are the the product of subaerial alteration, also called weathering. After their formation, many laterites have been covered by younger sediments, or they have been transformed further under subsequent different atmospheric conditions.

Table I provides an overview of the position of laterites within the regolith. The regolith itself is defined as the upper, unconsolidated part of the Earth between the consolidated rocky core (the domain of petrology) and the atmosphere, including the recent to subrecent soil.

Table IIA provides an impression of the variability of almost all the characteristics that comprise a laterite. This variability is so large, that it is possibly the most characteristic feature of a laterite.

Table IIB provides a characterization of laterite, based on the − presumed − processes of its formation.

Table I - The place of laterite in the regolith profile

The profile is synthetic as the author has nowhere seen (and is not aware of a reference to this effect) all separate zones in one continuous succession. This is also unlikely to happen, as the stone-line (as characterized by Aleva (1983a & 1987b) and Johnson (1993) requires a sloping surface, while laterite is typical for horizontal surfaces. However, each of the zones mentioned has been observed in the position given in the profile. Stone-lines containing laterite fragments have been observed world-wide – Brazil, South Africa, Bintan Island, Indonesia – but often not recognized as such (e.g. Hernalsteens, 1982)

AGE & RELEVANT DISCIPLINE	STARTING MATERIAL	PROCESSES AND RESULTS	ROCK NAME
Recent to subrecent realm of the soil sciences	In situ transformation of mineral & organic matter by various recent environmental processes (chemical, physical and biological).	Soil formation: may contain continuous layers of indurated material; Fe as important cement; organic matter absent.	Soil Petroferric phases
		Soil with ≥ 40 % coarse oxidic concretions of hardened plinthite fragments, ironstone etc., ≥ 25 cm thick, top within 0.5 m of the surface.	Skeletic phases
Geological or Fossil realm of deep weathering and the regolith	Transported, unconsolidated material: – no original structures nor fabric remain – original volume unknown – may be cemented after deposition by circulating groundwater (Fe-, Ca-, and Si-cretes).	Transported in an abundant, low density medium (water, air).	Alluvium UCS ≤ 1.0 MPa [1)] Density ≤ 1.8 g/cm^3
		Transported as a high density mixture of water & solid matter.	Colluvium USC ≤ 1.0 MPa [1)]
	Boundary or transitional zone	Removal of matter through eluviation, elutriation, solution and chemical action, resulting in structural collapse, and the accumulation through down-slope transport of weathering resistant particles – largely of residual origin – into an accumulation horizon or zone.	Carpedolith or Stone-line
	In situ material – no change in volume – original fabric frequently present – chemically weathered to the extent that most original rockbuilding silicates are destroyed and most alkali- and alkaline earth elements are removed in aqueous solution.	Frequently an indurated ferruginuous capping.	Laterite (if rich in Al: bauxite)
		Accumulation of sesquioxides, no parent rock silicates left – but its fabric may be well preserved.	
		Clay zone (kaolinite mainly) with an upper zone with ferruginous secondary structures and a lower plasmic or arenose zone.	Mottled zones Plasmic
		> 20 % of the weatherable parent rock minerals altered, primary fabric pseudomorphosed but recognizable	Saprolite
		Transition zone with < 20 % of parent rock material altered.	Saprock
Realm of petrology	Magmatic, sedimentary and metamorphic rocks	Original or parent rock material	Fresh rock

[1)] USC = unconfined compresive strength in megapascal

Table IIA - Macroscopic characteristics of laterites for field use

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

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

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

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

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

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

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

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

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

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

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

Table IIB - A process-oriented characterization of laterite

LATERITES may be considered as metasomatic[1]) rocks, formed at or near the earth surface, for which the essential process parameters are estimated to be:

— high average ambient temperature, in the order of 20-25 °C in order to promote sufficiently high reaction speeds;

— high supply rate of fresh process water, i.e. the solvent[2]) (> 1200 mm/year rain during at least, say, 9 months per year), to promote sufficient leaching[3]) activity;

— a surface relief with a minimum of slope and sufficient vegetation to minimize erosional activity resulting from the abundant precipitation.

— high rate of percolation of the process water in order to evacuate the leachate[4]) and bring fresh process water (solvent) in contact with, as yet, unleached matter;

— sufficient topographic height above the local and/or regional erosion base to promote a continuous high rate of percolation of the process water and transport of the leachate;

— sufficient organisms and decaying organic matter to make the percolating process water (solute = rain) a chemically and physically aggressive fluid;

— a parent rock or material which

    i.   has a physical constitution that allows a continuous and pervasive flow of process water and which provides sufficient reaction surfaces to promote active leaching, i.e. not too fine-grained to become too tight for percolation and not too coarse-grained to reduce the area of active solution surfaces;

    ii.   contains sufficient soluble Al and Fe (and in specialized laterites Ni, Mn, etc.) present in silicates, to form a skeleton of newly formed hydroxides and oxides of Al and Fe (and Ni and Mn);

    iii.   allows for the removal through solution of large parts of its original volume;

    iv.   preferably contains a certain content of coarse quartz to promote continuous porosity by providing a non-collapsible skeleton to maintain a high rate of percolation.

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[1])   Metasomatism: the process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly different chemical composition may grow in the body of an old mineral or mineral aggregate (Lindgren, 1928).

    The presence of interstitial, chemically active pore liquids or gasses contained within the rock body, or introduced from external sources, are essential for the replacement processes, which often, though not necessarily, occur at constant volume with little disturbance of fabric or structural features. (GG)

[2])   Solvent: anything that dissolves another thing.

[3])   Leaching: removal of a soluble material from an otherwise insoluble solid phase by dissolution in a liquid solvent.

[4])   Leachate: solution obtained by leaching, and which contains substances from the original material leached; syn.: lixivium.

2 Laterite described and defined

2.1 Glossary

The preferred meaning of the terms used for the various rocks and soils discussed are given in the Glossary at the end of this book; all terms marked in the text with an asterisk (*) are also included in this Glossary. These definitions will be adhered to as much as possible. Where deviating from these given definitions, or where additional definitions are required, it is stated clearly and an alternative definition is given.

2.2 Laterite* — descriptions, ideas, and definition.

(i) Origin of the name.

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

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

And in Vol. III, page 66-67:

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

This description by Buchanan is a feeble basis for a clear understanding of the essential characteristics of laterites. Neither did this description deal with the physical appearance of the material identified as laterite, nor did it describe the highly variable physical properties and appearances that produced the confusion about laterite - see Table II. The confusion was enhanced by the lack of understanding of the processes that cause lateritization*.

(ii) Early descriptions

J. Canter Visser, Chaplain with the Dutch East India Company at Colhin during the years 1717 to 1723, reported on this rock — later to be called laterite by Buchanan — as follows (see V.A.C. Sarma, 1982):

> "...the local stone is very well adapted for building. There are quarries here from which the stone is hewn; and I have seen a piece of this stone when being cut from the rock, split like wood under the stroke of the axe. The stone is reddish-yellow and spotted, very porous and full of holes, in which the lime used in building gets mixed up, and the whole gets so well consolidated that old stone is often preferred to new. The East India Company finds this stone very serviceable for erecting their fortresses and factories, and the inhabitants use it for building their houses...."

J.T. Newbold (1844), F.R.S. and Assistant Commissionar at Kurnool, Andhra Pradesh, provides descriptions of laterite, as studied by him during an official journey from Masulipatan or Machilipatnam, at the Bay of Bengal, to Goa, at the Arabian Sea, hence an East - West transect through the northern part of Peninsular India. He discusses in detail the laterite of Beder (now Bidar), at 17°56'N and 77°35'E):

> "...The laterite of Beder, generally speaking, is a purplish or brick red, porous rock, passing into liver brown perforated by numerous sinuous and tortuous tubular cavities either empty, filled, or partially filled with greyish-white clay passing into ochreous, reddish and yellowish brown dust; or with a lilac lithomargic earth..."
>
> "...The clay and lithomarge exhibit lively coloured patches of yellow, lilac, and white, intersected by a network of red, purple, or brown. The softness of this rock is such that it may be cut with a spade; hardening by exposure to the sun and air, like the laterite of Malabar..."
>
> "...The debris of this rock washed from the surface by rains is often seen accumulating in low situations, and reconsolidating into a nodular conglomerate; when fragments of the laterite have been much rolled they assimilate externally to pisiform iron ore, but have neither its specific gravity, internal concentric structure, nor distinguishing lustre."
>
> "...this *alluvial laterite* is seen in all lateritic areas in the S. of India and is easily to be distinguished by its nodular and pisiform character, its position, and the thinness of its beds from the *true laterite*, as the reconsolidated debris of quartz, mica, and feldspar is from the true granite rocks, at the base of which it is often seen, in India, to accumulate in beds of some thickness and tenacity."

Newbold further describes a deep section, as studied in faces of cliffs, up to 60 m high, and some deep wells near Beder:

> "... the laterite sometimes presents a homogeneous cellular structure from summit to base. Generally speaking however, it becomes softer and more sectile as it descends; and the cavities in the lower portions are better filled than those higher up."
>
> ". . . The deeper wells and springs are usually found at its basis where it rests upon impervious trap*. Near the line of junction the trap is almost invariably observed to be in a state of disintegration either as a friable wacke, or as a brownish or greenish grey clay. The laterite is no longer hard or porous; its cavities are broken up or filled with lithomarge* and ochrous earth; and in short, it presents a dense bed of clay variegated with shades of purple, red, yellow, and white. . ."
>
> "... The disintegration of the trap rock rarely extends more than four or five feet below the junction."

Near Calliany (now Kalyani) Newbold describes a bazaar, excaved in the laterite cliffs:

"A street has been cut from the rock (= laterite), running along the side, about midway up the ascent, in the scarp of which a long row of now deserted houses and shops have been excavated, and also small caves supported by pillars of the laterite left untouched, while excaving."

Elsewhere he mentions the ubiquitous occurrence of laterite on all the higher summits in the countryside, which — he muses — must mean that "a great body of laterite" once covered the total country side, "enormous masses of which have been removed by denudation". He than makes a comparison with the Old Red Sandstone cappings of Scotland, which at that time had been described as the erosion remnants of a once much more extensive and continuous cover.

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

"1. The term laterite is used in two ways, namely, stratigraphically as the name of a geological Formation, and petrographically as the name of a tropical superficial rock. The following discussion relates only to the use of the term as a rock name.
2. Laterite (or rather some varieties of it) is formed by a process, the modus operandi of which is not discussed here, by which certain rocks undergo superficial decomposition, with the removal in solution of combined silica, lime, magnesia, soda, potash, and with the *residual* [Compiler's italics] accumulation, assisted, no doubt, by capillary action, metasomatic replacement, and segregative changes of a hydrated mixture of oxides of iron, aluminium, and titanium, with more rarely, manganese. These oxides and hydroxides of iron, aluminium, titanium, and manganese are designated the lateritic constituents*.
3. This residual rock is true laterite, and the presence of any considerable proportion (> 10 percent) of non-lateritic constituents requires expression in the name, as it always indicates want of completion in the process of lateritisation. True laterite contains, then, 90 to 100 percent of lateritic constituents.
4. There is often a gradation in composition between true laterite as defined above and lithomarge*, which is taken as the amorphous compound of composition $2H_2O.Al_2O_3.2SiO_2$, corresponding to the crystalline mineral kaolinite of the same composition. For rocks intermediate between laterite and lithomarge the terms lithomargic laterite and lateritic lithomarge are available, the former being applied to forms containing 50-90 percent of lateritic constituents, and the latter to forms containing only 25 to 50 percent of lateritic constituents.
5. The presence of any considerable amount of quartz, either residual or secondary (this form has not yet been noticed, so far as I am aware, in Indian laterites), should be indicated by naming the rock a quartzose laterite, unless the amount of quartz and other non-lateritic constituents exceed 50 percent, when the word laterite should appear only in the adjectival form, as in paragraph 4.
6. Many rocks to which the term laterite has been applied would be more aptly termed soils, earths, clays, and sands, with (if >25 percent) or without (with <25 percent of lateritic constituents) the attributive lateritic. [See the final remark of this section 2.2].
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 (1898) and Dubois (1903), are not true laterites unqualified, but are either quartzose or lithomargic laterites, or lateritic earths. Many of them are detrital rocks, sometimes rich enough in lateritic material to be called detrital laterite or lateritite*. True laterites do, however, also occur.
13. Fermor's last point: The classification of laterite . . . put forward in this paper . . . is of course of a more or less tentative nature . . ."

C.S. Fox (1936): On the urging of L.L. Fermor, the then Superintendent of the Geological Survey of India, C.S. Fox, studied the type area where Buchanan coined the term laterite. His mission included in particular the collection of samples for chemical analysis of the rocks which caused Buchanan to suggest the name laterite. He had 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 composed of four, successive samples, each 5 ft (152 cm) long. No mineralogical analyses were made, but the normative composition for an epi*-norm mineral association was calculated 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* calculation for the lowermost sample does not lead to an acceptable paragenesis.

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

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

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

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

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

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

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

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

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

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

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

Hence they left out the requirement of the residual nature of the parent material, as stated by Fermor (1911).

The Glossary of Geology, 2nd ed. (Bates & Jackson, 1980) gives the following succinct description:

"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' ".

(iii)   Definition of laterite

The IGCP Project 129: Lateritization Processes provided a true definition of laterite, prepared by Werner Schellmann (1982, 1983a, and in Banerji, 1986). He followed the rules of Aristoteles, giving the Class to which the defined subject belongs, and providing the criteria by which the subject is distinguished from others in this Class. With respect to the Class to which laterite belongs, *Schellmann* (1983a) states:

> "There can be no doubt that laterites are mineral assemblages which have formed as a result of intensive subaerial [surely an intentional pleonasm — compiler's note] weathering of rocks. They attain considerable thicknesses and are in no way limited to the soil zone which is characterized by biological activity. Therefore, laterites are primarily to be regarded as rocks. They belong to the group of residual rocks which are either classified with the sedimentary rocks or may be regarded as a separate rock group in their own right" (the compiler prefers the latter: a separate rock group).
>
> "Classifying laterites as rocks does not contradict the fact that in their surface regions laterites may also be regarded as soils, which can be classified according to pedological criteria. Including lateritic weathering products in the systematics of tropical soils does not run contrary to a petrographic classification as long as the same designations are not used for differently defined materials."
>
> "If laterites are comprehended as rocks, they should be defined according to the same criteria as other rocks, i.e. on the basis of their genesis [weathering — compiler's note] and of their mineral content. The laterites are most severely weathered types within the group of residual rocks. The definition of laterites must therefore clearly demarcate them from less weathered material. At this higher classification level all the severely weathered varieties should be included in the laterite group, regardless of the parent rock and the morphological-physical properties. Limiting the term laterite to the hard or indurating varieties would exclude a large number of lateritic products, in particular the gibbsite-rich and iron oxide-rich earthy-weathered covers overlying basic rocks, and the especially soft Ni-bearing limonites over ultramafic rocks. Special characteristics must be taken into account at a lower level, i.e. when classifying laterites after they have been defined."

Schellmann then states that a distinction should be made between the highly weathered (laterite) and the less strongly weathered residual rocks (saprolites). He lists the chemical-mineralogical reactions which characterize the weathering of rocks into saprolite and laterite:

> "1.   Kaolinization of Al-Si-bearing minerals;
> 2.   Formation of Fe oxides from Fe-containing minerals;
> 3.   Formation of Al hydroxides by incongruent* solution of kaolinite minerals (occasionally also directly from feldspars, foids, etc.);
> 4.   Congruent* dissolution of kaolinite minerals;
> 5.   Dissolution of quartz."

The reactions 1, 2, 3, and 5 cause an enrichment of iron and aluminium in the weathering residue; reaction 4 only increases the iron content. Consequently, laterites are commonly composed of a mixture of goethite, hematite, Al-hydroxides, kaolinite minerals and quartz. Based on the above type of considerations, but see the original text for the complete discussion, Schellmann gives the following definition of laterites:

> "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".

Schellmann then continues with examples of the results of weathering of various rocks, using the concept of the weathering ratio r_w = SiO_2 : (Al_2O_3 + Fe_2O_3), accompanied by graphical representations in triangular diagrams. It should be noted that Schellmann specifically mentions the residual nature of laterites.

In summary: following Schellmann, laterites
— are rocks, in the widest sense of the term,
— belong to the group of residual rocks,
— are formed by weathering processes,
— are classified on the basis of their mineral content.

Schellmann (1983a) specifically remarks that at this highest level of classification all intensely weathered varieties should be included, regardless of parent rock and morphological or physical properties (e.g. hardness, induration).

(iv) Classification and nomenclature

The IGCP Project 129 also provided an opportunity to discuss the classification of laterites — as defined by Schellmann — at a lower level. There was general consensus that such classification should be directly related to the type of parent rock: through its variations in mineral and chemical composition, and its fabric, the parent rock impresses a distict signature on the resultant laterite, e.g. a nickel laterite or a bauxite (= aluminium laterite). See section 2.3 and Table III (after Aleva 1986).

The nature of the weathering process, i.e. dissolution, may play havoc, however, with the concept of full autochthony, which is related to in situ weathering.

Nature provides abundant examples of the transformation of feldspar, pyroxene or hornblende crystals that are in situ replaced by gibbsite, the new gibbsite crystals still showing the size and structure of the original silicate mineral, i.e. pseudomorphism.

Inherent to the processes of dissolution and pseudomorphism, is the formation of watery solutions containing the elements that are soluble in the newly created environment: in particular the alkalis, silica, and iron oxides. Some of these elements travel long distances and are lost to the weathering environment, other elements may be precipitated nearer by, as e.g. iron minerals, and to a lesser extent silica.

Hence, the structures and fabrics of the newly formed minerals are of a residual nature, but at least part of the chemical elements present will have come from elsewhere, presumably from the directly surrounding environment, while other elements, such as K, Na, Mg, Si in part, have been evacuated from that same environment (Plate C and F).

Deposits formed from the elements that travel longer horizontal distances before being bound into newly formed minerals, cannot be incorporated in the rock type 'laterite', as defined above. Aleva (1986) suggested to name such mineral aggregates 'exolaterites' or 'lateritoids' (see also Annex II).

This discussion on classification may seem theoretical, but in practice the term 'laterite' is used frequently in an erroneous way, in particular for ferruginous deposits at or near the surface of planation surfaces or at the bottom of local slopes. Such iron-rich, hard crusts are not the product of in situ weathering, but are formed from iron-rich solutions derived from (former) upslope weathering areas. The precipitates come in a variety of shapes: e.g. massive or banded layers or as pisoids*, or as a ferruginous cement in between local debris (in which case they could be described as ferricretes* in the sense of Lamplugh (1902), see also Aleva (1991).

(iv) Some other terms

Laterite vs laterite is a peculiar distinction made by De Swardt (1964), an eminent geomorphologist, who worked mainly in the African Shield, and formalized the then existing — schizophrenic — laterite nomenclature, which said laterite ≠ laterite. The following quote is from the Introduction of his influential 1964 paper:

> "1. Two main laterites are present in both West and East Africa. The older is a primary deposit which now forms cappings on erosion remnants and is now separated from the lower laterite by a scarp. The younger is composed largely of reworked material from the older formation which has been recemented to a hard pavement. . ."

Groundwater* vs. pedogenetic* laterite is a later version of this same duality; it is a distinction made by some earth scientists (e.g. McFarlane, 1976). These terms originally derived from the processes at that time presumed at work during the formation of laterites.

Groundwater laterites are, what could be said, 'true laterites', often of great thickness (up to 60 m and locally even more); they are found in most continents and provide most of the lateritic Fe, Al and Ni ores mined.

Pedogenetic laterites refer to relatively thin layers or beds of mainly Fe enrichment, which occur near the surface in a variety of soils. However, these deposits are not of a residual or in situ nature: they represent concentrations of mainly iron oxides occurring at the bottom of hill slopes. They are composed of:

— either particulate fragments of iron oxide deposits formed at higher levels and transported as detrital particles to their present position at the foot of the slope, and already reported by Newbold (1844),
— or the Fe concentration is due to Fe-rich solutions, which flowed, underground, down the hill slope and precipitated at the foot of this slope.

As neither of these hardened Fe oxide concentrations are formed in situ, but are the result of downslope transport of Fe with a large horizontal component, they do not belong to the Class of Laterites (see definition by Schellmann, 1982). Such deposits could be named exolaterites (see Aleva, 1986, or Annex II) of the type 'soil impregnated lateritoids', respectively 'lateritoid sediments' (colluvium).

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 (i.e. composed of laterite constituents* - Fermor, 1911) that occur on the walls of near-surface cracks in major laterite deposits and of the, locally banded, veins of lateritic composition found in the near-surface zone 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 zone of already existing laterite profiles.

In the Bakhuis Mountains, Suriname, lateritic bauxite deposits observed by the compiler in the top few metres of the laterite profile, contained abundant, strongly anastomosing veins, subparallel to the surface, composed of a black, shiny material (presumably goethite). The configuration of these veins suggested that they filled cracks resulting from the decompression of the lateritized igneous parent rock (cf. exfoliation of granite).

The soils, covering the laterite in such areas, are thin, generally not more than a few decimeters to one metre thick, and the vegetation may be of a grassy or forest nature. The local present day climate may vary from the tropical monsoon type in Suriname (N. coast of South America, at 5° S. Lat.) to the humid climate of the Natal highlands, South Africa (between 28° and 31° S. Lat.) and the mediterranean climate of the Australian West coast (Darling Ranges, between 31°

and 33° S. Lat.). On the Buganda high plateau surface, a coating of lateritic composition directly overlies the fresh parent rock (circa 0° - 1° N. Lat., at an elevation of over 3000 m high). Such coatings do not represent laterite, but a deposit presumably of an Fe-Al-Si composition, precipitated from circulating ground or surface water.

Hence, true laterites are — at the time of their formation — bound to the surface or near-surface environment, where the atmospheric influences causing weathering of the local substratum are strongest; they are of an in situ, residual nature, and should not be called soils. In this context the weathering process may be considered as the re-equilibration of the locally present mineral phases to the pressure and temperature conditions of the surface environment at that point and time. This process of re-equilibration proceeds fastest under conditions of high temperature and abundant precipitation (rain) — to maintain a high rate of leaching — and in the presence of organic acids and CO_2, which promote the chemical attack of the silicates.

The definition of laterite does not deal with the physical appearance or characteristics of the material defined. However, contained in it is exactly the high variability of characteristics that produced the earlier confusion about laterite.

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

Borrowing some pedological terms, laterites may be considered to be, at the time of their formation, of a zonal* nature: restricted to climates of high surface temperature and high humidity and/or precipitation. They were, at the time of their formation, also intrazonal*, as the chemical composition and structure/fabric of the parent rock determined 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. This is commonly the case and their elevated position promotes the necessary high rate of internal rain water drainage. Most present day laterites have survived erosional attack as result of their hard to very hard capping with an iron-rich accumulation zone (cuirass), while a few deposits were buried by younger sediments shortly after their formation, and were so protected against erosion and subsequent laterite weathering processes of later periods.

The topographically high laterites will follow, in their composition and fabric, the changes in climate with successive mineral and structural/fabric re-equilibrations. Hence many, if not all, exposed laterites are polyphase in origin with high complexity in structures and fabrics. 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, deviating 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 (where the conditions or the available time were presumably insufficient to produce thick and massive laterites). The other group of 'monophase' laterites are those that were covered by sediments shortly after their formation, e.g. those in the Coastal Plain of the Guyanas (Bárdossy & Aleva, 1990).

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

Stratigraphic methods have been successful in the Coastal Plain of northern South America, where Van der Hammen & Wymstra (1964) were able to date several lateritic bauxite deposits through palynological methods (Palaeocene-Eocene pollen were found in grey to black, earthy to clayey intercalations in and below the arkosic sedimentary parent rocks). See also Bárdossy & Aleva (1990), and Valeton & Wilke (1993).

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

Laterite Derivative Facies* (LDF), Goldbery (1979) — this is a lithofacies* dominated by sediments of a laterite provenance. Goldbery separates ten lithofacies, three of which are purely allochthonous, composed of e.g. pisolite conglomerate, laterite arenite, claystone granule conglomerate, i.e. normal sediments composed of clasts derived from an older laterite (cf. the Exolaterites of Annex II).

The other seven lithofacies are of an autochthonous nature: i.e. the in situ products of lateritization, of which all but one have been altered — again in situ — by changed environmental circumstances. The rock types formed are described as laterite, pisolite-bearing argillaceous dolomicrite, (pisolitic) hematite claystone, laterite arenite, pisolitic conglomerate, flint clay, etc. The environment of formation seems to have been comparable - at least in part - to a karst bauxite environment: karstic depressions and sink holes in a coastal plain, followed by uplift and subsequent lateritization and other related processes.

Laterite sensu lato* — the suffix 'sensu lato' indicates the less strictly defined use of the term, where the emphasis is more on the process of intense weathering under humid tropical conditions. In this sense it will be used e.g. in Chapter 3 - The Laterite Formation. In such contexts, the term laterite is used - as a type of shorthand - to indicate the group of processes that, over a sufficiently long period of time, result in the genesis of a Laterite Formation. Detailed study of such laterite occurrences may establish that it should be named e.g. a ferriferous bauxite, or a bauxitic or aluminous laterite - see the ternary diagram of Fig. 1. In other contexts the 'sensu lato' might be used to include the exo-laterites - see Annex II.
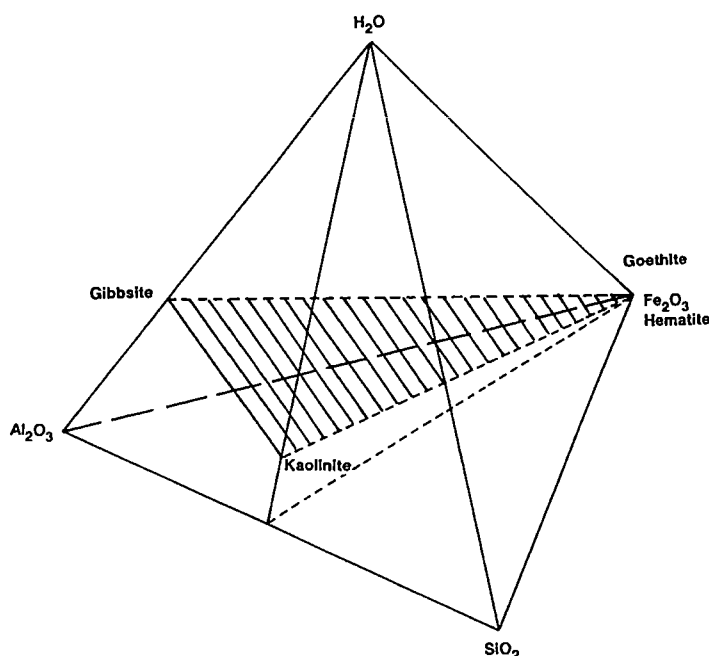
Fig 1A. Compositional tetrahedron with Al_2O_3, SiO_2, Fe_2O_3 and H_2O at the apexes.

The position of gibbsite and kaolinite is indicated. The shaded triangle is transformed into the equilateral triangle of the ternary compositional diagram, Fig 1B.
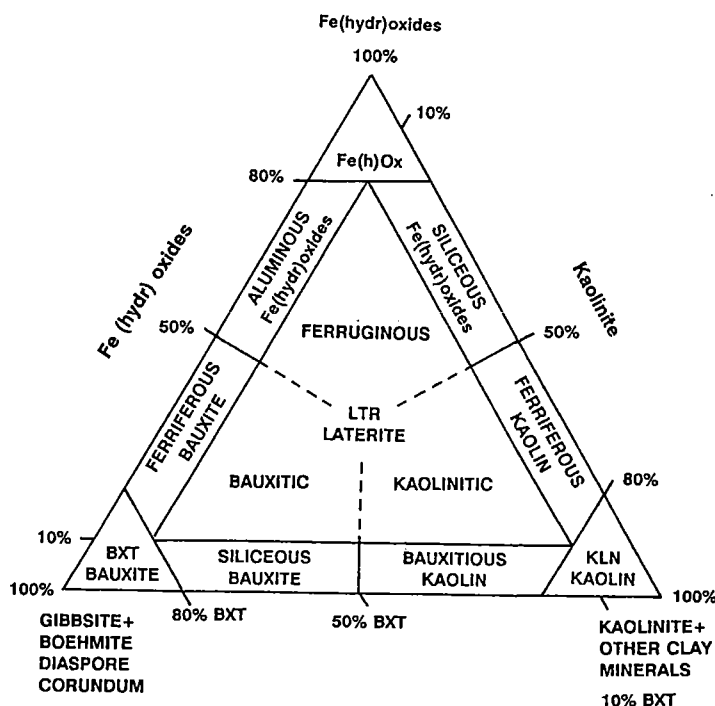
Fig 1B. Ternary compositional diagram, illustrating the nomenclature of the weathering products of the humid tropical climates; in addition quartz and unweathered parent rock minerals may be present.

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

2.3 Parent rock influence on laterite composition.

A direct result of the residual nature of laterites, is the close relation between the mineral composition of the parent rock and the elements concentrated in the accumulated weathering residue, which is called the lateritic accumulation zone. The laterite definition does not specify the type or composition of the original or parent rock, although it tacitly supposes that Si-Al bearing minerals are in the majority. This is true for the average composition of igneous rocks: Rankama & Sahama (1950) give the following average composition (after Clarke):

Average mineral composition of igneous rocks

Mineral	wt. %
feldspar	59.5
quartz	12.0
hornblende	16.8
biotite	3.8
titanium minerals	1.5
apatite	0.6
others	5.8
total	100.0

There are igneous and metamorphic rocks that are largely composed of "other" minerals, in particular olivines (and their autometamorphic alteration product serpentine) and deposits mainly composed of iron or other metallic elements, such as banded iron formation.

The common Fe-Al-Si laterites are produced from rocks, which are mainly composed of feldspar, quartz, and smaller amounts of hornblende, pyroxene, and biotite. These are the laterites which — in their name or designation — usually do not carry an additional denominator. And if so, that is then the name of the parent rock, e.g. "basalt-derived...." (see Table III).

Table III - Parent rock versus laterite composition

Parent rock	Elements concentrated by lateritic processes	Resulting type of laterite
Average igneous rock	Fe + Al	Laterite
Mafic igneous rock	Fe + (Al)	Ferruginous laterite
Leucocratic granite/gneiss, anorthosite	Al + Fe	(Ferruginous) laterite
Basalt, andesite	Fe + Al	Laterite, bauxite
Average sedimentary rock	Fe + Al	Laterite
Arkosic sandstone	Al + (Fe)	Bauxite
Alkaline complex, carbonatite	Fe + Al, Ti	(Bauxitic) laterite; anatase rock
Ultramafic rocks	Fe + Ni	Fe or Ni laterite
Serpentinite	Ni + Fe	Ni laterite
Gondite gneiss, Mn silicate	Fe + Mn	Lateritic manganese ore
Banded iron ore	Fe	Lateritic iron ore
Khondalite gneiss	Al + Fe	Bauxite
Fresh and weathered erosion products collected in karstic voids and grottos	Al + Fe + (Mn)	Karst bauxites

*Bauxites** — An exception is often made for the laterites called bauxite: these are normal laterites produced from common Al-Fe-Si containing parent rocks — although the Al content is usually relatively high. This special name is historically derived: a reddish brown rock found on the hills of Les Beaux in Southern France, was analyzed by Berthier (1821), assuming it to be a possible iron ore. To his amazement he found the highly aluminous composition, without any other elements to speak of; he published his findings about this 'ore from Beaux', hence the name bauxite. Only later, the lateritic nature of this karst-related rock was established, but still all aluminous lateritic rocks are called bauxite.

Bauxites or *Al-laterites* are aluminium rich, gibbsitic laterites, mostly formed from parent rocks with much feldspar and little iron-rich components, e.g. arkosic sandstone, leucocratic granite and gneiss, e.g. the khondalites of India. Bauxite is essentially an economic term, as other qualities than a high aluminium content play a role in their economic usefulness, e.g. the lowest possible content in kaolinite in the main laterite mass. As a result, some profitable bauxite mines are mining products in the range of $\geq 30\%$ extractable Al_2O_3 and $< 20\%$ SiO_2 present as kaolinite minerals. This may represent the following ranges (in %) in mineral composition for the main ore zone and for the hard upper layer: (Saddleback area, W. Australia, after Ball & Gilkes, 1987, see Table next page).

Common parent rocks for lateritic bauxites, however, are arkosic sediments, leucocratic granites, gneisses and anorthosites, khondolites (India), relatively leucocratic basalts, andesites and alkaline rocks.

Range in mineral composition of bauxite at Saddleback area, after Ball & Gilkes, 1987

Mineral	Main ore zone (%)	Hard upper layer (%)
gibbsite	30-70	20-35
goethite	10-30 [1]	20-40 [1]
hematite	5-20	20-40
boehmite	0-5	
anatase	0-5	0-5
kaolinite	1-15	0-5
quartz	0-5	0-5

1) with 15-20 mole Al_2O_3

*Specialized laterites** — Some parent rocks deviate so much in composition, that the resulting laterite, both in the details of its formative process and in its ultimate product, fall outside the range of 'common laterites'. These are the laterites that have been derived from parent materials other than the more common igneous, metamorphic and sedimentary rocks, and which produce different lateritic end products, e.g. lateritic iron ore, lateritic nickel ore, etc. These products of lateritization, what remains after the leaching out of all but the most resistant elements, could be called 'specialized laterites', i.e. laterites formed from uncommon parent rocks by the usual chemical processes, which also formed the 'common' laterites. Most of such 'specialized' laterites have parent rocks that are not mainly composed of alkali-aluminium silicates, such as feldspar with quartz and relatively minor amounts of pyroxene, hornblende, etc. Examples of such specialized laterites are the nickel laterites derived from olivine-pyroxene-bearing parent rocks, and the manganese laterites derived from highly manganiferous parent rocks, such as the Mn silicate rhodonite, the Mn carbonate rhodochrosite, and the gondite gneisses of Central India.

In Chapter 4, after a discussion of the 'standard laterite profile', some of these specialized laterites and their profile development will be discussed (see section 4.3).

Table III lists a number of common laterite parent rocks with their resulting lateritic products. Iron, almost universally present in the parent rock, is generally also concentrated in the resulting laterite, but depending on the other main components of the parent rock, it is not necessarily the main component of the laterite.

2.4 Some remarks on the processes of lateritization.

There exists an abundant literature on the (presumed) processes that result in the formation of a laterite. The accumulation of elements such as Al, Fe, Ni, etc. may have occurred in at least two ways, as pointed out by D'Hoore (1954):

— *Subtractive or relative enrichment*: certain elements have been removed from the near-surface volume of earth crust, thereby increasing the relative amount of the elements that remain.
— *Additive or absolute enrichment*: through the addition of elements, derived from elsewhere in the regolith, into the volume under consideration. In this context it must be realized that such elements must first be made free from the mineral(s) in which they occur in the original consolidated or unconsolidated parent rock.

In the weathering environment it is difficult to establish which of these processes, or how much of each of these processes, has been at work in the laterite under study.

Millot & Bonifas (1955) showed that the use of volumes — instead of weights — of the weathering profile under investigation, could provide the answer on the type of accumulation. They studied samples of accurately determined volumes of the various laterite facies throughout a weathering profile, and well into the fresh parent rock, in which the rock fabric and structure was still clearly visible. The relict fabric established that the original volume was still present, hence the chemical analyses of the material could then establish the additive or subtractive nature of the elemental accumulation found. It appeared that relative accumulation of Fe_2O_3 and Al_2O_3 represents the major process of enrichment, which could occur through the removal in solution of bases (mainly Na, K, Mg, and Ca) and silica. Higher up in the profile, however, absolute accumulation, in particular of iron, is of common occurrence.

Pedro & Melfi (1983) presented an interesting characterization of the lateritization processes, including the successive minerals formed, as well as the environmental requirements and the sequences of the laterite minerals formed. Their publication is accompanied by two Charts, which are added to the Handbook as Chart I & II, with an abstract [by the Compiler] of the paper itself.

Boulangé (1984) has shown that in detail the process of lateritization follows two different routes:

(i)   The isovolumetric transformation, with relative accumulation of Al and Fe through removal in solution of the other elements. Relict fabric and structures are common: e.g. original feldspar crystals are transformed into gibbsite skeletons, without loss of outside shape and with the mimicry of the feldspar cleavage.

(ii) The allovolumetric transformation, with mainly absolute enrichment of Al and Fe through filling up of voids resulting from intensive leaching of the other elements. The gibbsite formed is largely derived from desilicification of earlier weathering products such as kaolinite.

Boulangé's figure 23 is reproduced here as fig. 2, after translation and some simplification of the original diagram.

2.5 Nomenclature and terminology

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

Suggestions for such a nomenclature have been incorporated in the Final Report of the IGCP 129 Project (Banerji, 1986). These terms were adopted, and improved upon, by Bárdossy & Aleva (1990). Later, suggestions were published for the description of voids, one of the most essential fabric entities in laterite, by Aleva (1987a). Since the publication of these terms no serious objections have been raised against them, and as no further improvements have been suggested they might now be considered as having been accepted by the community of laterite geologists and other interested scientists. The complete set of suggestions is presented in a number of diagrams and tables, and are presented in Annex II and III.

—   Annex II deals with the differentiation between the true, residual laterite* and the allochtonous lateritic deposits, which after transport and hardening are often difficult to distinguish from the true* laterites: they are not in the original place where the weathering process produced this more or less lateritic material, hence the name exolaterite*. The chart
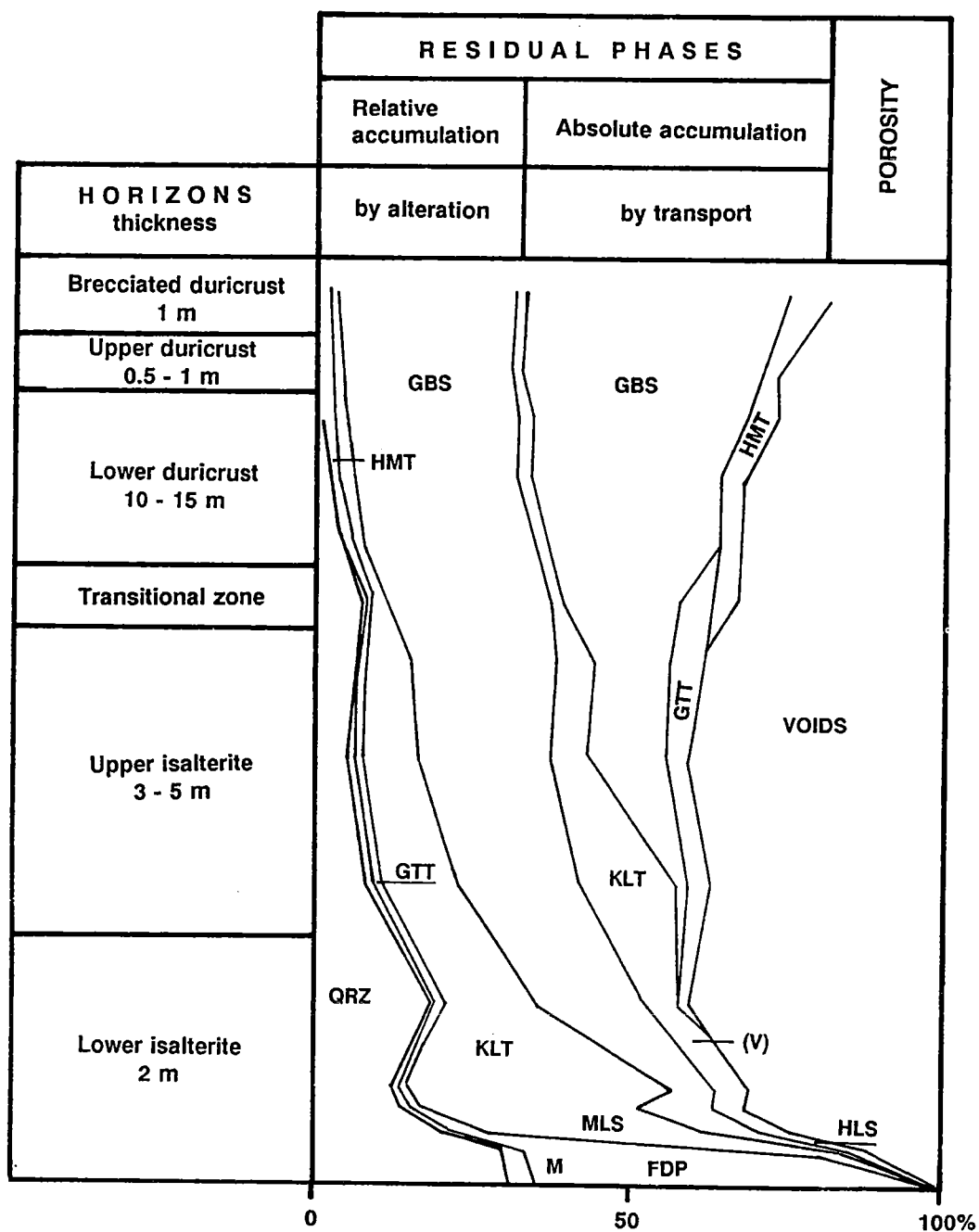
Fig. 2. - Quantitative estimation of the occurrence of the birefringence (plasma) fabric (plasma d'altération) and the transported matter fabric (plasma de transfer) in a laterite profile in Côte d'Ivoire, after Boulangé (1984).

The mineral codes represent:

FDP	feldspar	GBS	gibbsite	GTT	goethite
HLS	halloysite	HMT	hematite	KLT	kaolinite
M	mica	MLS	metahalloysite	QRZ	quartz
V	vermiculite				

does not require further elaboration. In the past, some of these materials have been identified by the name ferricrete*, which could be an appropriate name only in cases where the original lateritic material has been transported by fluvial action — to form a gravel of lateritic composition — followed by cementation in their new environment by percolating iron-bearing solutions. The resulting rock is no more a laterite but might be called an impregnated lateritoid*, a name that tells the reader something about the rock's origin, which is not the case with the term ferricrete, as it is now commonly used.

— Annex III provides all the terms required for a complete fabric description of true lateritic material.

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

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

— Annex III-c provides a diagram showing the observed variations in nucleus-cortex relationship in pisoids. Pisoid* is defined as any spherical body with a relatively smooth surface, independent of its internal structure, in diameter varying from 2 - 60 mm. Following Simone (1981) the term pisoid is suggested to replace the confusing term pisolith, which is one of the grains that make up a pisolite*: a sedimentary rock, usually a limestone, made up chiefly of pisoliths cemented together; a coarse-grained oolite.

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

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

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

3 The individual units of the regolith

3.1 Short profile description

Regolith* is an old term, introduced by Merrill (1897) for the entire unconsolidated, and possibly secondarily recemented, cover that overlies the more coherent bedrock. In the past it was also known as "mantle rock" or overburden (Table I). It is largely synonymous with the engineering term 'soil' (i.e. any material that can be dug and transported without the use of a blasting agent).

Recent studies have shown that the regolith is much more complex than just a mantle of weathering products. It may be of allochthonous, autochthonous or mixed allochthonous-autochthonous derivation.

Generally, the greatest volume of the regolith is of *allochthonous* origin. This upper part is composed of the products of weathering, erosion and denudation of areas upslope from the point of observation. The transport of these denudation products may have taken place by fluvial, colluvial and eolian means.

A relative small volume of the regolith is of mixed allochthonous-autochthonous derivation; only recently have these deposits been distinguished as being of a special character. Johnson (1993) discussed the origin of these deposits, which are restricted to slightly sloping terrains covering the weathered, in situ parent rock. He described 'three-tiered-soils' occurring in tropical, subtropical and temperate landscapes that illustrate a dynamic evolution. They are characterized by:

The three successive tiers are:
- (i)   an upper tier or horizon of recent soil with its vegetation and animal life recent soil with its vegetation and animal life;
- (ii)   an intermediate accumulation horizon, called stone-line , resulting from the mechanical accumulation of weathering resistant parts of the regional bedrock, i. e, the stone. This accumulation is caused by the complete structural collapse of the bedrock through solution of its weatherable components, through the mechanical action of animals, roots, collapsing trees, etc. and through downslope movement by gravity.
- (iii)   the underlying, completely weathered in situ parent rock of horizon (ii) and possibly — in part — also of horizon (i).

The fully *autochthonous* facies of the regolith is represented by the in situ weathered parent rock, best preserved in a landscape with a near horizontal surface, where the weathering residues are not disturbed by mass transport and the original parent rock fabric remains mostly intact; they may be — in part — become transformed into laterites.

These weathering residues appear to have a characteristic organization of successive zones which produces the typical laterite profile. Fig 3A illustrates the classic ideas of Millot (1964) and Lelong (1969) on the nature of such profiles. Fig 3B illustrates the highly variable thickness of the successive zones found in actual laterite profiles (Aleva, 1986).

Hence the autochthonous regolith should not be considered as a massive and homogeneous blanket covering the bedrock; it represents a succession of reaction zones between the solid bedrock and the atmosphere, and — in the laterite context — as it may develop in regions with a low relief.

The successive zones of the laterite profile are separated by more or less clearly visible interfaces. These interfaces appear to be reaction fronts in the sense of the "weathering front" as postulated by Mabbutt (1961). The term 'front' is well chosen, as it can be observed that each

A

TRUNCATED COMPLETE PROFILE

METRE THICKNESS

| SOIL |
| DURICRUST |
| BAUXITE |

ZONE OF ACCUMULATION

LATERITE

SAPROLITE

ZONE OF LEACHING

CORE BOULDERS

PARENT ROCK
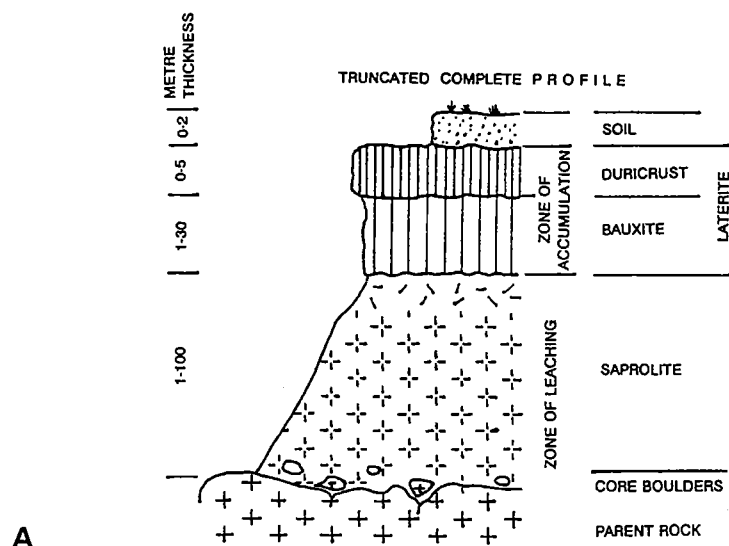
Fig. 3A — The classic 'typical laterite profile' adapted after Millot (1964) and Lelong (1969)

B

ATMOSPHERE

Interface V - Surface of the Earth

SOIL

Interface IV - Surficial weathering front

LATERITE: ferruginous

aluminous

MOTTLED ZONE

Interface III - Cementation front

PLASMIC ZONE

Interface II - Pedoplasmation front

SAPROLITE

SAPROCK

Interface I - Deep weathering front

PARENT ROCK
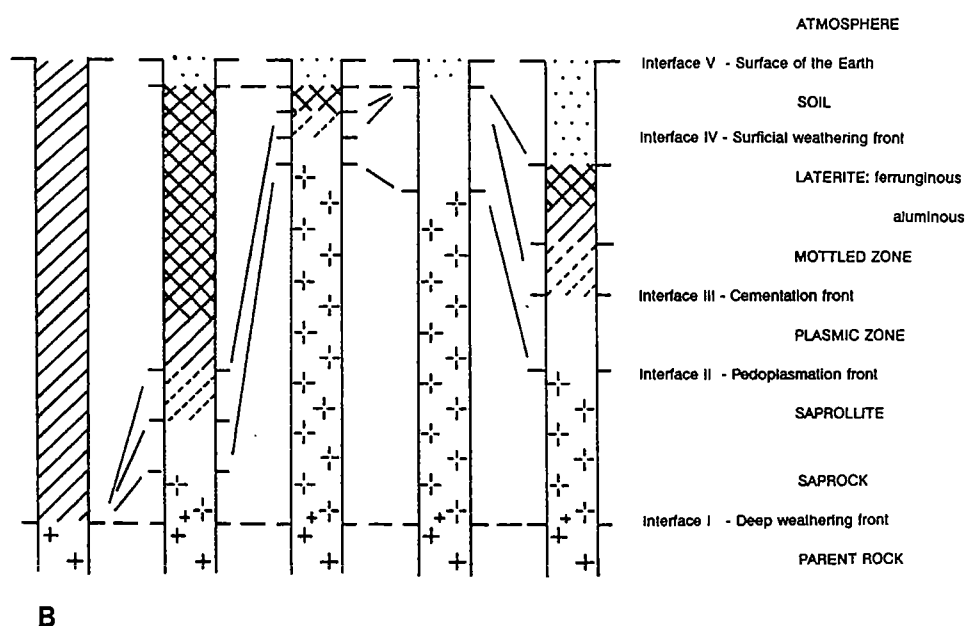
Fig. 3B — Some examples of actually occurring profiles, showing variation in thickness (down to complete absence) of one or more zones (Aleva, 1986).

Recent work in Australia has led to the inclusion of one more interface: the 'pedoplasmation front' which marks the transition of the saprolite with relict fabric, into the plasmic zone without this fabric. See Table IV for the proposed designations.

of the boundaries between the successive zones of the profile is progressively moving downward, in a way that resembles an advancing army. Locally some parts are in advanced positions, and elsewhere much retarded where the front meets more resistance to weathering. Hence the shape of the primary weathering front, and of each of the successive fronts at a higher position, is of a three-dimensional nature. Also successive fronts are independent from overlying or underlying fronts, to the extent that two or more interfaces may coalesce, resulting in the local absence of one or more zones - see Fig 3B.

Table IV presents a recent version of the concept of the typical laterite-saprolite formation; it includes several suggestions made by the CSIRO Research Group of Anand, Butt, Robertson & Smith, West Australia.

Table IV — The typical laterite-saprolite formation

This table incorporates several suggestions made by the CSIRO Group of Anand, Butt, Robertson & Smith, based on their research work in Western Australia — see also Chapter V.

Zones	Description	Field characteristics Consistency[1]
Atmosphere	LAG: laterite-derived nodules and fragments, may be indurated	Transported material; loose or secondarily cemented; s/h

------------------V - PRESENT DAY SURFACE OF THE EARTH---

Pedogenesis	SOIL: may contain (hard) pedogenetic accumulations, petroferric and/or skeletic phases	Allochthonous (e.g. air transported) and autochthonous soils: alluvium, colluvium and eluvium. Locally overlying secondary weathered kaolinite; s/h

-----------------IV - SURFICIAL WEATHERING FRONT--

Fe + Al accumulation zone	cuirass LATERITE: .... main zone (Fr: carapace) .... knife-sharp/gradual contact	Mainly Fe/Al minerals, often with parent rock relict structures; p/h. In specialized laterite with Ni, Mn, etc.; h/s
	MOTTLED ZONE: irregular Fe-accumulations in kaolinitic matrix	Only secondary structures

------------------III - CEMENTATION FRONT--

Leaching and neo-formation zone	PLASMIC ZONE or unstructured saprolite	Kaolinitic clay with relict quartz, no primary structures left; s

-----------------II - PEDOPLASMATION FRONT---

Leaching and neo-formation zone	SAPROLITE s.s.:structured	Kaolinitic clay with relict quartz; > 20 % of weatherable minerals altered; relict parent structures; s
	SAPROCK: transitional material	same, but < 20 % altered; s/h

------------------I - DEEP WEATHERING FRONT---

Bedrock	generally the parent rock of the above profile	Fresh rock; h/p

[1] Consistency, or tool required for taking a specimen: s = soft, spade. h = hammer. p = pickaxe

For descriptive purposes each of the interfaces has received a name and a Roman numeral in order to facilitate their identification. The weathering profile should be studied from the bottom upward, hence the numbering starts also at the parent rock surface, which is the weathering front of Mabbutt, here indicated as Interface I: the deep weathering front.

A detailed description of the successive zones of the typical laterite profile is given in Chapter 4. In its complete succession, this regolith profile can be observed world-wide in a low and mid latitudinal belt excluding the near polar (> 65° N and S) regions. The complete sequence of zones may not be developed in full, and at any one place one or more of the zones may be missing.

3.2 Soil*

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

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

Bridges (1990) gives the following description: "Soil: the collection of natural bodies, formed at the earth's surface from a variable mixture of mineral and organic materials, under the influence of the soil forming factors. These factors act through chemical, physical and biological processes to produce pedological features identifiable in the soil profile. Soil is the altered upper part of the regolith which provides support, nutrients and moisture for plants and therefore is a fundamental basis for life on earth".

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

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

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

combinations of specific properties, generally accepted to have resulted from soil forming processes, define the diagnostic horizons. These diagnostic horizons are the basic identifiers in soil classification.

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

A further differentiation of the classes of soils is based on the presence or absence of diagnostic properties. For example: *plinthite** (see section 3.3) is an iron-rich, humus poor mixture of clay and quartz that hardens irreversibly on drying. Ferralsols which have plinthite within 125 cm of the surface are placed in the soil unit: Plinthic Ferralsols.

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

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

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

The occurrence of a lateritic accumulation zone in the regolith succession is generally restricted to flat and horizontal landscapes. Johnson (1992) presents a general denudational theory, which involves a sloping land surface with two or three tiered, partially autochthonous soils. Such a land surface model with sloping surfaces could well be more common than the flat, horizontal landscape which contains the lateritic accumulation zone.

The soil zone is generally not well developed over laterites. In a more general context, in particular on sloping landscapes, the laterite zone is generally missing in the regolith. Instead, an important zone of more or less transported, unconsolidated material is present, named colluvium for the little transported, and alluvium for the distinctly transported material. These deposits could still be considered to represent a type of accumulation zone, but this accumulation would be of a distinctly allochthonous and particulate nature, and not a chemical, mineralogical one.

The overlying soil represents the most recent reworking by physical, chemical and biological processes of the top part of the regolith, and as such constitutes the realm of the Soil

Sciences. This introduces a new aspect in the laterite discussion, as some soils contain zones of ferruginous nodules, called plinthite*, that have some similarities to laterites.

3.3 Plinthite*

This relatively recent term is the result of an uneasiness among soil scientists with the (former) use of the term laterite. This may be illustrated by the following quotes, derived from three successive papers, published by the US Soil Survey Staff in 1951, 1975 and 1981.

(i) The Soil Survey Manual (Soil Survey Staff, Agriculture Handbook No. 18, 1951, p.184) states: "Laterite is found in many soils and is a distinguishing feature of Ground-Water Laterite soil. In the profile of a Ground-Water Laterite soil one may designate the horizons as A1, A2, A3, and B1, down into the B2 or perhaps into the B3. The same material may continue practically without change for another 25 feet or so with no definite place for dividing the solum from the material underneath it. It would be unreasonable to exclude the upper part of the laterite from the solum; and it seems unreasonable to include the lower part, far removed from the influence of organisms."

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

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

3.4 Hardened versions of plinthite

These hardened versions of plinthite, variably known as hard pan, ironstone, petroferric or skeletic phases, have caused, and still cause, much confusion with laterite. There follow three quotes to illustrate the more recent opinions on these materials.

(i) *Petroplinthite*, a term proposed by Sys (1969): "Individualizations of iron oxides which are irreversibly hardened. In the humid stage petroplinthite cannot be cut by a spade. They are hard

concretions within a clayey matrix, or occur as a carapace. The petroplinthite corresponds to the laterite definition by Alexander & Cady (1962)". The term seems to be superseded by "petroferric phase"; see the Revised Legend, Soil Map of the World (FAO-Unesco, 1988) — see below.

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

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

For completeness sake, one more or less related term is mentioned here as well: *ironstone** — any rock containing a substantial proportion of an iron compound, or any iron ore from which the metal may be smelted commercially; specifically, an iron-rich sedimentary rock, either deposited directly as a ferruginous sediment or resulting from chemical replacement.

Summarizing, plinthite and hardened plinthite, etc., are considered products of the (sub)recent processes of soil formation, and as such they are formed in situ although the iron concentrated is not necessarily of local derivation. There seems to be a close genetic — and time — relation between petroferric phases, skeletic phases and what has been called pedogenetic* laterites by some geomorphologists.

3.5 Ferrallite/ferralite*

The study of 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_2O_3 = gibbsite) and/or iron (as $\alpha FeO.OH$ = goethite) remaining. Harrassowitz (1926) gave the name allite* or allitic to the soil horizons and laterite layers mainly composed of these sesquioxides, and contrasted these with the horizons and layers mainly composed of the Al-silicate kaolinite: the siallitic* horizons and layers. As the sesquioxide zone is generally a mixture of Al and Fe (hydr)oxides, Robinson (1949) suggested the name ferrallite* for this mixture, which is also the common term used by the French workers in West Africa. Robinson uses the molecular ratio silica : sesquioxide to separate the siallitic clays from the (fer)allitic clays, with the ratio 2 as borderline. See also Chart I & II (with explanation) after Pedro & Melfi (1983).

Concluding remarks

Laterite and laterite genesis centre around the two common sesquioxides Al_2O_3 and Fe_2O_3, the main and characteristic compounds of most laterite accumulation zones. However, these two sesquioxides are very different in their behaviour under most climatic conditions:

Iron is probably the most mobile element in the near-surface environment. In particular because of its easy transition from Fe^{3+} to Fe^{2+}, and back again, it is usually in equilibrium with the present day soil near-surface environment.

Aluminium has different properties resulting in its much more stable behaviour in the near-surface soil environment. Only under extreme climatic situations, i.e. very high rainfall and relatively high temperatures, can aluminium become as mobile as iron. Three examples: (i) soils high up on the slopes of the Hawaii volcanoes, or (ii) 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 (iii) at a much lower topographical level: the Kerikeri bauxite (sic) deposits in the Northern Island of New Zealand, at an elevation of about 200 m and with 1250 mm rain per annum (Bárdossy & Aleva, 1990).

The following quotation from Norton (1973) seems to be in place here:

> "Laterites and bauxites are surficial accumulations of the products of rigorous chemical selection, developing where conditions favour greater mobility of alkalies, alkali earths and Si than of Fe and Al". See also Chapter 4.

3.6 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 of the common laterite minerals gibbsite, kaolinite, hematite and goethite with respect to these apices. Transforming the triangle formed by connecting the points for hematite, gibbsite and kaolinite into a isosceles triangle, produces the compositional ternary diagram of Figure 1B; for practical purposes goethite is considered to reside in the hematite apex.

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

3.7 Chemical and mineralogical analyses of lateritic rocks (Annex V & VII).

The standard chemical rock analysis does not provide the information required to fully describe the essential composition of a laterite. A laterite contains silica that is derived from three, completely different genetic sources, i.e. silica contained in

(i)   primary, unweathered quartz,
(ii) unweathered parent rock silicates (e.g. the minerals zircon, mica, staurolite),
(iii) newly formed kaolinite.

Aluminous laterite (bauxite) constitutes the main economically viable aluminium ore for the production of alumina (Al_2O_3) and aluminium metal. The generally applied process to convert

(bauxitic) laterite into alumina and aluminium, is based on the solubility of the weathering-derived Al minerals, including kaolinite, in a hot, diluted solution of soda (NaOH).

The following will show the reason for the interest of bauxite geologists into the sources of the silica that is present in the aluminous laterite. A distinction can be made between
- non-reactive silica, i.e. quartz and certain rock silicates, such as zircon, which do not take part in the chemical reactions during the digestion phase of the Bayer process;
- reactive silica, i.e. mainly the silica present in the mineral kaolinite, but also small amounts of amorphous silica incorporated in most laterites.

The silica-bearing minerals present are of prime importance to the main industrial user of aluminous laterite: the aluminium industry. Aluminium metal is produced by two successive processes: first the hydrometallurgical Bayer Process, which is essentially a refining process that produces pure Al_2O_3 from the mineral mixture called bauxite, followed by the electrolytic Hall-Herault process that reduces the aluminium oxide obtained into aluminium metal. This Al metal must be of very high purity, with other elements such as zinc, silica and copper only present in the low parts per million ranges.

The Bayer process requires the bauxite to be crushed to minus 2 mm, whereafter it is taken up (digested) into a hot soda solution (150-300 g Na_2CO_3 / litre). The required process temperature in the closed pressure vessels is determined by the Al minerals in the bauxite used: gibbsite requires ~150°C, boehmite ~250°C. The pressure in the reaction vessels rises to 0.8 MPa; the residence time required for complete digestion varies between 0.5 to 3 hours.

After pressure release and partial cooling, the solution passes filter presses, where the Al-bearing solution is separated from the undissolved minerals such as quartz, mica, etc. together called 'red mud', the colour being due to the high content in iron oxides. The clear solution is further cooled and seeded with small, synthetically produced gibbsite crystals to start the complete precipitation of the synthetic gibbsite produced with this process. This precipitate is washed with fresh water and then calcined (heated to bright red colour) in rotating killns to 1000 - 2000°C to produce the commercial grade raw material 'alumina' used in the electric reduction process after Hall-Herault.

The Bayer process is based on the following reactions (see e.g. Bárdossy & Aleva, 1990):

(1) gibbsite ($Al_2O_3.3H_2O$) + soda (2NaOH) + heat $\rightarrow$ Na-aluminate ($2NaAlO_2$) + water.

(2) kaolinite ($Al_2O_3.2SiO_2.2H_2O$) + soda (6NaOH) $\rightarrow$ Na silicate ($2Na_2SiO_3$) + Na-aluminate ($NaAlO_2$) + water.

(3) Na-silicate + Na aluminate $\rightarrow$ desilication product [= $Na_2O.Al_2O_3.2SiO_2$]$\downarrow$ + soda (4NaOH).

(4) Na-aluminate ($2NaAlO_2$) + $4H_2O$ + cooling $\rightarrow$ 2 soda (2NaOH) + gibbsite$\downarrow$ ($Al_2O_3.3H_2O$).

The final product, alumina, derives from the calcination of the pure gibbsite precipitate obtained:

(5) gibbsite ($Al_2O_3.3H_2O$) + heat (ca. 1000-2000 °C) $\rightarrow$ pure alumina (Al_2O_3) + water ($3H_2O$) (calcination).

Reaction (1) is the essential reaction to extract the aluminium contained in the bauxite. Reactions (2) and (3) produce the Al-containing desilication product, the amount of which is directly related to the amount of reactive silica, i.e. kaolinite, in the raw material (see reaction 2). The reaction formulae indicate that quartz is an inert or refractory burden, while kaolinite is directly detrimental to the alumina recovery.

Thus, the economical or metallurgical value of an aluminous laterite is inversely related to the kaolinite content, as that mineral combines with soda to form the insoluble 'desilication

product', thereby excluding part of the alumina from the metallurgical process, i.e. the not-available alumina.

The main and older analytical methods used are the wet chemical analyses, using a tri-acid solution to bring the powdered laterite sample into solution, whereby the unweathered Al-silicates and quartz report in the insoluble rest.

A newer and more process-comparable method employs a scale model of the alumina plant process: the powdered laterite sample is taken up in an aliquot of the plant's soda solution, heated in a closed 'bomb' to the operating temperature of the alumina plant (150°C or 250°C, depending on the presence of only gibbsite or a gibbsite-boehmite mixture) for a specified time, after which the bomb is cooled, opened and the solution analysed for contained Al_2O_3 and reactive silica. Both analytical methods are cumbersome and time consuming and they require a well trained staff.

During the sixties, the XRF analytical method became commonly employed for routine analyses in the aluminium industry; these methods are much faster than the wet chemical and bomb-digest methods, but again do not provide the answer to the kaolinite content. Also neutron activation methods have successfully been used to analyse the enormous numbers of samples that were analysed during the exploration campaigns for large bauxite deposits. Again, the kaolinite or 'bound-silica' content had to be determined on separate samples, mostly of a composite nature.

The great advance in physical mineral determination since 1970 has changed the routine procedures considerably. In the Sixties, a 'gibbsite analyzer' was constructed and employed for the direct gibbsite determination of the bottom sample of the bauxite ore bed in an exploration campaign in a remote area in NW Australia (Van Essen et al., 1971), which worked on the principle of thermo-gravity analysis.

The above shows that it is necessary to define the required number of routine analyses to be made, the elements or the minerals to be determined, and the cost per sample of the more attractive analytical methods, before a decision can be made on the method routinely to be used in the laboratory.

The more commonly employed methods were:
— Elemental analysis:
    Wet chemical analysis; slow and cumbersome;
    Bomb-digest analysis; slow but closely process designed;
    Atomic absorption: labour intensive;
    Neutron-activation analysis: radiation hazards;
— Mineral analysis:
    Differential thermal methods;
    Thermo-gravity methods.

See also the relevant paragraphs in Annex VII

Also in this context must be mentioned the complete mineral phase analysis of a laterite, a cumbersome and time consuming analytical procedure but necessary to obtain a full understanding of the mineralogical-chemical composition of the laterite and its component minerals. It involves the determination of the chemical composition of each of the minerals of the laterite under investigation. This will provide information on the distribution of aluminium over the minerals gibbsite, boehmite, kaolinite, hematite and goethite. Such information may be of direct interest for the alumina plant engineer, the research mineralogist, and the geologist who is interested in the genesis of the deposit.

4 The mappable laterite unit and its field appearance

4.1 The rock Formation

A formation* may be defined as "a persistent body of igneous, sedimentary or metamorphic rock, having easily recognizable boundaries that can be traced in the field without recourse to detailed paleontological or petrologic analysis, and large enough to be represented on a geological map as a practical or convenient unit for mapping and description"[GG].

Fermor (1911) already mentioned the use of the term laterite to identify the laterite rock formation. Bocquier et al. (1983) suggested restricting the use of the term laterite to the mappable unit, composed of a series of successive layers that together form the typical laterite profile development. In this Handbook it is used both for the mappable unit, as well as for the essential accumulation layer - see Table IV.

The following text is summarized in Table IV; it includes the results of recent research by CSIRO in the Darling Range, SW Australia (Robertson, Anand, Butt & Zeegers), including detailed mapping in the field and through the use of artificial exposures. Also other work has been incorporated, e.g. by Leprun (1979) and Boulangé (1984). It is not always possible to indicate exactly from which author certain ideas or opinions are derived as the 'science' of laterites is still in a fluid stage of development. The compiler has referred to the authors who contributed their ideas and research results to the general improvement in the understanding of laterites and lateritization processes, and who helped in the compilation of this Handbook.

Alterite*, the common term in many French publications for the alteration profile and its individual rocks produced by weathering, has not been adopted, mainly because the term is already widely, and for a long time, in use for the strongly weathered - and hence undeterminable - grains found in heavy mineral concentrations used in sedimentary petrology (see GG).

4.2 The typical profile described

A typical profile is an idealized concept which combines the features observed in many described profiles. It is summarized in Table IV and in Fig. 3A & B (Chapter 3). The parent rock is the essential governing factor in the final laterite produced, hence, any description should begin at the bottom of the section. The following description is influenced by the ideas and terminology of various researchers. These include the West Australia group of Anand, Butt, Robertson and Smith of CSIRO, several geomorphologists, e.g. Alexandre (1991), Johnson (1992) and soil scientists e.g. Stoops. However, the compiler is responsible for the text and ideas as expressed here.

The typical profile from bedrock to atmosphere is shown in Table IV. It includes the full thickness of the regolith. The profile has been divided into characteristic zones, separated by five interfaces. Each interface marks the more or less abrupt changes in the appearance, nature or composition of the material.

Interface I — the *weathering front*: it overlies the fresh parent rock (although in some instances the actual parent rock has been completely altered). It is a typical weathering front in the sense of Mabbutt (1961), and by definition it is geometrically discordant with respect to the underlying parent rock (Millot, 1983). Its three dimensional shape has the appearance of a rolling countryside with ridges and hollows often of a non-directional, irregular nature. Only after mining the overlying (bauxitic) laterite can the morphology of this interface clearly be seen. The most conspicuous feature is that fine-grained, or very coarse-grained, massive igneous rocks

resist weathering most effectively in which case the parent rock is frequently directly overlain by the laterite, with the interfaces II and III absent — Plate C.

Otherwise, the undulating front may be ahead of irregularly shaped or rounded masses of little or not altered parent rock — the core boulders* and core stones* — in size varying from a few cubic decimetres to several cubic metres.

Depending on the nature of the parent rock, there is a distinctly transitory type of rock, the *saprock** or proto-saprolite (with <20% of the original, weatherable minerals weathered) that is still hard and cohesive, but in particular the feldspar minerals have lost their gloss and sparkle, and have become milky white and liable to be scratched by hammer and spade.

*Saprolite** overlies the weathering front and the half-way stage called saprock. The essential feature is that more than 80% of the original, weatherable minerals are completely weathered, mostly to hydrated secondary minerals: kaolinite in case of feldspar-rich parent rocks, serpentine in the case of ultramafic rocks.

A typical feature of the saprolite is that the original, lithic fabric of the parent rock is still clearly visible — a characteristic of isovolumetric weathering — although the original, weatherable minerals have been altered completely into clay minerals. Quartz remains largely unaltered; its crystal faces remain fresh and sharply angled, its grain sizes represent the original size distribution as found in the parent rock (Aleva, 1960).

In certain older publications, the saprolite is often indicated as lithomarge*, a term with the meaning of compact, common kaolin clay. Dana (1858) gives the German synonym 'Steinmark' which relates the material to the nearness of solid rock.

Interface II — the *pedoplasmation front*: has been clearly identified in SW Australia, e.g. by the CSIRO Group of Anand et al., by which also soil micromorphological methods were used. The disappearance of all relict parent rock structures (lithic fabric) had been observed already in the Fifties and Sixties, e.g. during off-shore drilling for cassiterite placer deposits in drowned river valleys in the South China Sea. Weathered bedrock was considered to be reached when the granitic fabric was clearly visible in the saprolite core brought to the surface. Cf. the distinction made between structured and unstructured saprolite (Aleva, 1981).

The thickness of the interval between Interface I and II is highly variable, from 0 to many metres.

Interface III — *the cementation front*: this has been identified as the result of relatively recent work, also by the CSIRO Working Group of Anand et al. Above this front most older fabrics have disappeared, the main mass shows crystalline structures represented by newly formed clay minerals. A comparable observation had been made earlier by Leprun (1979) in West Africa: his 'altération pistache', in the Kay 7 profile, Bourkino Faso, West Africa.

Within the lower part of this zone Al, Fe, Mn and Si may have been accumulated as oxides and oxyhydrates in colourful, irregularly shaped *mottles**: the mottled zone (French: argiles bariolées), which is not indurated but still sectile.

Separated by a contact that may vary between knife-sharp and gradual over a distance of a number of decimetres, is the main lateritic accumulation zone: the laterite s.s. Generally, this zone is composed of a lower, more or less sectile mass, often with distinct relict fabric and structure from the parent rock, and an upper hard to very hard *cuirass**, the conspicuous feature of laterites in the landscape where relatively recent erosion and denudation has occurred. These zones host the main Fe and Al accumulations of the laterite profile.

The common existence of parent rock relict structures in this zone has implications for the timing and the nature of the weathering processes, as the pedoplasmation front — above which all original structures have disappeared — lies at a much deeper level. Leprun (1979) also reported that his 'pistache zone' is younger than the overlying accumulation zone — Plate C.

Interface IV — the *surficial weathering front*: it overlies the laterite cuirass. The top decimetres to metres of the cuirass may be altered to such an extend that only 10-20% of the lateritic accumulation is remaining, the surrounding laterite has changed into kaolinite and meta-halloysite clay (Montagne, 1964). This weathering proceeds downward in root-like structures (Valeton, 1974), diminishing in size and number with depth to 4 metres (Onverdacht, Suriname, see Plate G and J).

Interface V — the *present day surface*: it is underlain by a layer of variable thickness of *recent soil*, which generally is partly of both autochthonous and allochthonous nature; the latter is certainly in part of an aeolian derivation (Millot, 1983). This soil is of more or less recent origin and may contain sediments of a colluvial and alluvial nature.

On top of this present day surface, and exposed to the present day atmosphere, is the *lateritic lag**, i.e. fragments and nodules derived from the lateritic cuirass, that after a certain distance of transport over the earth surface, has been deposited as a loose gravel, which may be secondarily cemented (mostly by iron compounds — the 'rock' is then often called ferricrete — but under certain climatic conditions calcium carbonate or silica also occur as cementing agent). The lag grains may provide a hint to the composition of the underlying rocks in their source area.

The absolute and relative thickness of the solid materials (rock, earth, soils) in between the successive interfaces may attain a thickness between many tens of metres (see Newbold, 1844: up to 60 m) or be totally absent; also the thickness may vary considerably in a horizontal direction within any one deposit.

The processes of destruction and denudation will start to attack the moment a laterite weathering profile is subjected to environmental conditions not conducive to promote lateritic weathering. The results of this process have been lucidly described by Grandin (1976) from Ivory Coast, where less than one percent of the once present bauxitic laterite remains (on the highest geographic points in the present landscape — see Table V). In other places remnants of the origial laterite-bauxite may be found in particular spots where local circumstances prevented their erosion (e.g. Brazil — see Chapter 5). In other places renewed sedimentation protected the laterite-bauxite zone, already incised by a shallow, dendritic system of rivulets, against further erosion and denudation, e.g. Suriname — see also Chapter 5.

4.3 Specialized laterites and their profile development

In Chapter 2, paragraph 3, the subject of specialized* laterites has been introduced, i.e. laterites formed through normal residual weathering from parent rocks that deviate markedly in their chemical and mineralogical composition from the more common parent rocks, that are mostly composed of a mixture of feldspar, quartz and lesser amounts of pyroxenes, amphiboles and micas.

A few parent rocks will not react to weathering by the formation of a laterite, e.g. relatively pure quartzite does not contain sufficient weatherable minerals to react materially to the near-surface and surface environment in another way than by mechanical breakdown. Other parent rocks may have a mineralogical/chemical composition that reacts to the surface environment by complete solution without producing any residue. Some impure carbonate rocks may produce weathering residues of great economic value, depending on the elements concentrated.

Well known are the karst bauxites, Al-Fe residues resulting from the weathering of presumably impure limestones (Bárdossy, 1982). For a long time, the source of the Al and Fe, contained in

Table V — Synopsis of the landscape development, Blafo-Guéto area, Ivory Coast, after G. Grandin (1976)

LEVEL name type age	HEIGHT absolute R=relative % total surface area	THICKNESS soil crust structure	CHEM. COMP. Al_2O_3 Fe_2O_3 SiO_2 average/range	MINERAL COMP. % Fe min. Kaolinite Quartz	DURICRUST FACIES main types
BAUXITE Plateau level Al-Fe crust Eocene	450-550 m R 300-400 m 0,2 %	0-0.3 m 10-15 m compact	Al 51 36-62 Fe 26 1-40 Si 2 0.2-5	Fe 17.6 KLT 4.2 QRZ 0.0	Pisolithic Granular Breccia Encrustations
INTERMEDIATE level Older piedmont level Pliocene	200-340 m R 100-150 m 0.1 %	20-30 m 4-6 m fractured	Al 15 4-18 Fe 60 50-79 Si 13 4-19	Fe 59.6 . KLT 27.6 QRZ 0.0	Concretionary Pseudo-gravel Massive Reworking
HIGH PIEDMONT level Early quaternary	80-260 m R 20-70 m 10-15 %	< 1m 1-4 m spotty	Al 17 4-18 Fe 60 50-79 Si 26 17-38	Fe 41.6 KLT 41.3 QRZ 6.8	Gravel Alveolar Platy
MIDDLE PIEDMONT level Middle quaternary	- R 2-3 m	no soil < 1.5 m	Al 16 8-24 Fe 30 17-49 Si 40 21-58	Fe 33.6 KLT 31.9 Qrz 24.1	Gravel Locally: alveolar Platy
LOW PIEDMONT level Subrecent	- R 0-2 m	some dm locally	Al 12 7-19 Fe 29 12-55 Si 47 21-63	Fe 29.1 KLT 29.2 QRZ 32.9	Not well developed Ferruginous concretions

these bauxites, has been a point of discussion, with the following possible derivation of Al and Fe:

— Amounts of these elements, as they occur in most, even relatively pure limestones, are small. However, the quantity of limestone that has to be dissolved to form the bauxite deposits would be unacceptably large, e.g. those being mined in Jamaica.
— Addition to the limestone forming environment (mostly shelf-type marine basins with a slowly lowering substratum) through e.g. the deposition of volcanic ash, as proposed for the Jamaica bauxites (Comer, 1974, 1984).
— Alluvial material, transported over variable but sometimes large distances, of an average composition for 'normal' detrital material, as suggested for the karst bauxites of Southern France (P-J. Combes, 1969).

A different, carbonate-related, weathering residue may be illustrated by the manganese ores from the Serra do Navio, State of Amapá, Brasil (Nagell, 1962). This lateritic ore is derived through the surficial weathering of the manganese carbonate mineral rhodochrosite, occurring in the gondite* type of petrogenetic environment.

Many of the banded iron formations* (BIF), occurring world-wide in Precambrian rocks and representing a large part of the iron ore resources of the world, derive their economic importance from the much later, presumably largely Mesozoic to Tertiary, weathering processes, that removed unwanted accessory minerals - including silica - and produced a strongly iron-enriched surficial weathering product.

Another group of specialized laterite deposits are those that derive from igneous parent rocks of an unusual composition: the ultramafic and ultrabasic rocks mainly composed of olivine, pyroxene, hornblende and biotite, hence with no more than traces of quartz or feldspar, or both. The parent rock names are determined by the olivine content: dunite (composed of almost pure olivine), olivinite (more than 50% olivine), peridotite (less than 50% olivine) and pyroxenite, if composed of pyroxene, amphibole, and biotite, with less than 5% olivine.

These highly specialized mineral compositions produce strongly deviant weathering products. Quartz is not present in the parent rock, and feldspar - as source of aluminium - is almost absent. The weathering of olivine, pyroxene, amphibolite, produces, besides iron minerals, large amounts of silica that becomes concentrated in fractures and cleavage planes of the original minerals, resulting in a finely meshed but highly porous silica skeleton in the final weathering product.

The weathering of basic minerals generally is initiated directly after their intrusion into the earth crust, through the re-equilibration of the mineral composition from a deep-seated, 'dry' heavy mineral (e.g. olivine) paragenesis* into an upper crust mineral paragenesis composed of serpentine* and talc*. Note the absence of both iron and aluminium in these minerals — see also Annex VIII.

Pyroxene and hornblende do not have such an extreme chemical composition. Calcium, aluminium, iron and alkali elements may be present in amounts varying from traces to 10% and even more.

In the weathering mantle overlying ultramafic and ultrabasic rocks, the following zones — from the surface downward — may be distinguished (Golightly, 1979):

Limonite* zone (laterite sensu stricto, oxide zone, 'saprolite fine' in French) with an upper Fe-rich zone (ferricrete*, canga [Portuguese], cuirasse de fer [French], iron capping). This zone still may contain the more insoluble minerals from the parent rock, such as spinel, magnetite, etc. At the base of the zone an enrichment of Mn and Co, etc. may be present.

In the lower levels relict structures of the parent rock may be discernable, at higher levels the original fabrics have collapsed.

Intermediate zone (smectite-quartz zone, nontronite zone), largely composed of smectite clays (nontronite) and crystalline quartz. Relict parent rock fabric is frequently visible. This zone is not always present.

Saprolite zone (serpentine zone, saprolite grossière [French], composed of altered parent rock with original fabrics preserved. It is generally a mixture of fresh rock, saprock and plastic saprolite, often veined with precipitations of garnierite*, manganese oxides and quartz. This garnierite is mostly a colloidal talc with Ni-bearing serpentine.

Serpentinized ultramafic parent rock.

The presence and development of each of these zones depends on the local situation with respect to water circulation and parent rock composition. Schellmann (1983b) provides interesting analytical data, derived from deposits distributed world-wide.

Figure 4 illustrates the chemical and mineralogical weathering profile formed over an serpentinite stock in Kalimantan, Indonesia. From the parent rock upwards, montmorillonite and chlorite are now the first minerals formed by weathering, followed at higher levels by gibbsite and kaolinite, with the iron minerals goethite and maghemite present throughout most of the profile.
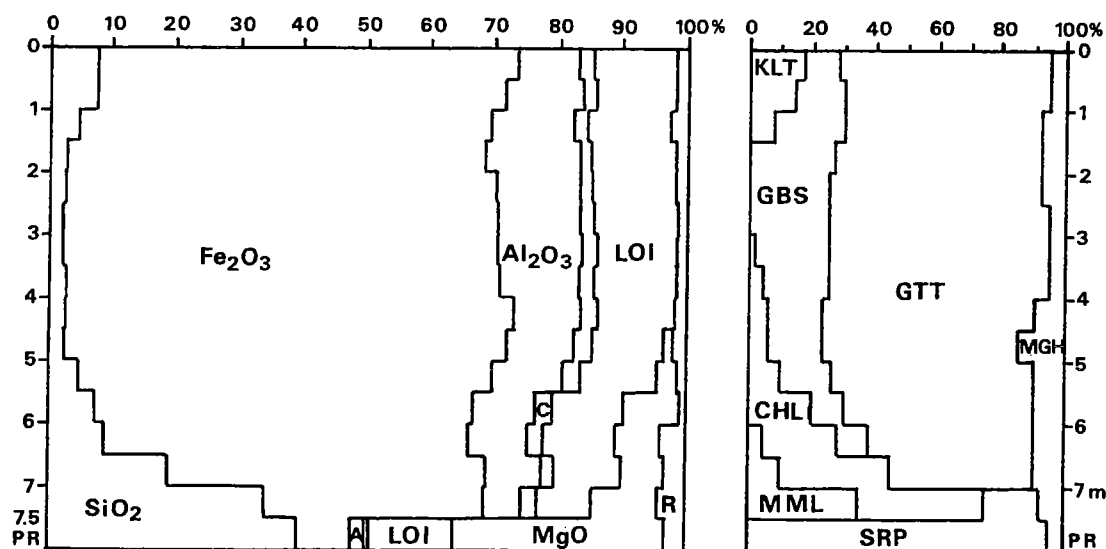
The space between the Al_2O_3 and LOI columns, marked C, represents the Cr_2O_3 content. The column R marks the sum of magnesium, nickel, titanium oxides; P_2O_5 (between 0.2 and 0,003 %) is disregarded.

CHL	chlorite
GBS	gibbsite
GTT	goethite
KLT	kaolinite
LOI	loss on ignition
MGH	maghemite
MML	montmorillonite
PR	parent rock
SRP	saprolite

Fig 4 — Chemical and mineralogical composition of a weathering profile on serpentinite, Kukusan Mountains, Kalimantan, Indonesia, representing a lateritic iron deposit. After Schellmann (1964).

Fig. 5A illustrates the elemental variation of the weathering profile overlying the nickel containing peridotite of the Colombian Cerro Matoso deposit. Fig. 5B shows a similar profile for the Nicaro nickel mine at Oriente Province, Cuba (De Vletter, 1955).

The Cerro Matoso nickel deposit has been described by Gomez et al. (1979) who distinguish the following zones, from the surface downward:

Canga: a hard, ferruginous crust, low in Ni content; locally up to 20 m thick.

Laterite: an amorphous, soft, reddish to yellowish soil, mainly composed of Fe and Al hydroxides; the Ni content is generally below 1.5%.

Saprolite: partly weathered with the fabric and appearance of the peridotite parent rock retained; average Ni content 3%. There are two types: a dark green variety just below the canga with higher Ni content, and a higher ratio Fe^{++} to Fe^{+++}; a lower, brown coloured type is common in most deposits.

Saprolitized peridotite (= saprock*): fractured parent rock peridotite with soft, weathered material along the fractures and joint blocks; garnierite may be present.

Silica boxwork, composed of veins of chalcedony and quartz that occur along fracture zones; it is essentially barren of Ni near the surface, but ore grade is reached at lower levels.

Parent rock: peridotite with relatively high Si and Mg content, Ni content in the range 0.2-0.3%.

The nickel deposit occupies an oval shaped hill rising 200 m above the surrounding landscape. The thickness of the weathering mantle varies from a few metres to over 200 m and the area is about 2000 x 1700 m.

The gradual variation, in a vertical direction, of the mineral composition and the localized concentration of certain minerals, is well illustrated in the graphical representations of Fig. 6, after Friedrich et al. (1987) from which the following explanations also derive.

Fig. 6A relates to the chromite occurrence of the small ultramafic body of the Morro do Cruzeiro, in the Sêrra area, Minas Gerais, Brasil. At the bottom of the profile altered talc schist represents the parent rock (not described in the drill hole). The laterite thickness is maximum 30 m; the profile may be summarized as follows from top to bottom:

(i)   Zone of friable sandy material, containing from the surface downward the following 'horizons':

—   dark red concretionary zone with gibbsite fragments and concretions, and organic matter;

—   a 1-3 m thick zone of gibbsite concretions in a matrix of red limonitic material;

—   a zone rich in heavy minerals, including limonite octahedra pseudomorphs after pyrite. Throughout the zone talc is abundant as coarse-grained aggregates; further occurrences are powdery magnesite, Mn hydroxide veinlets, and quartz/silica aggregates.

(ii)   Limonite zone: tough, clayey, light brown, with abundant finely disseminated talc; increasing moisture content toward bottom.

(iii)   Zone of leaching, variable thickness: decomposition of most parent rock minerals and progressive removal of magnesium.

(iv)   Saprolite, variable thickness, parent rock fabric present, indications of hydration and disintegration of parent rock minerals.

(v)   Highly altered green talc schist, preserved parent rock fabric.
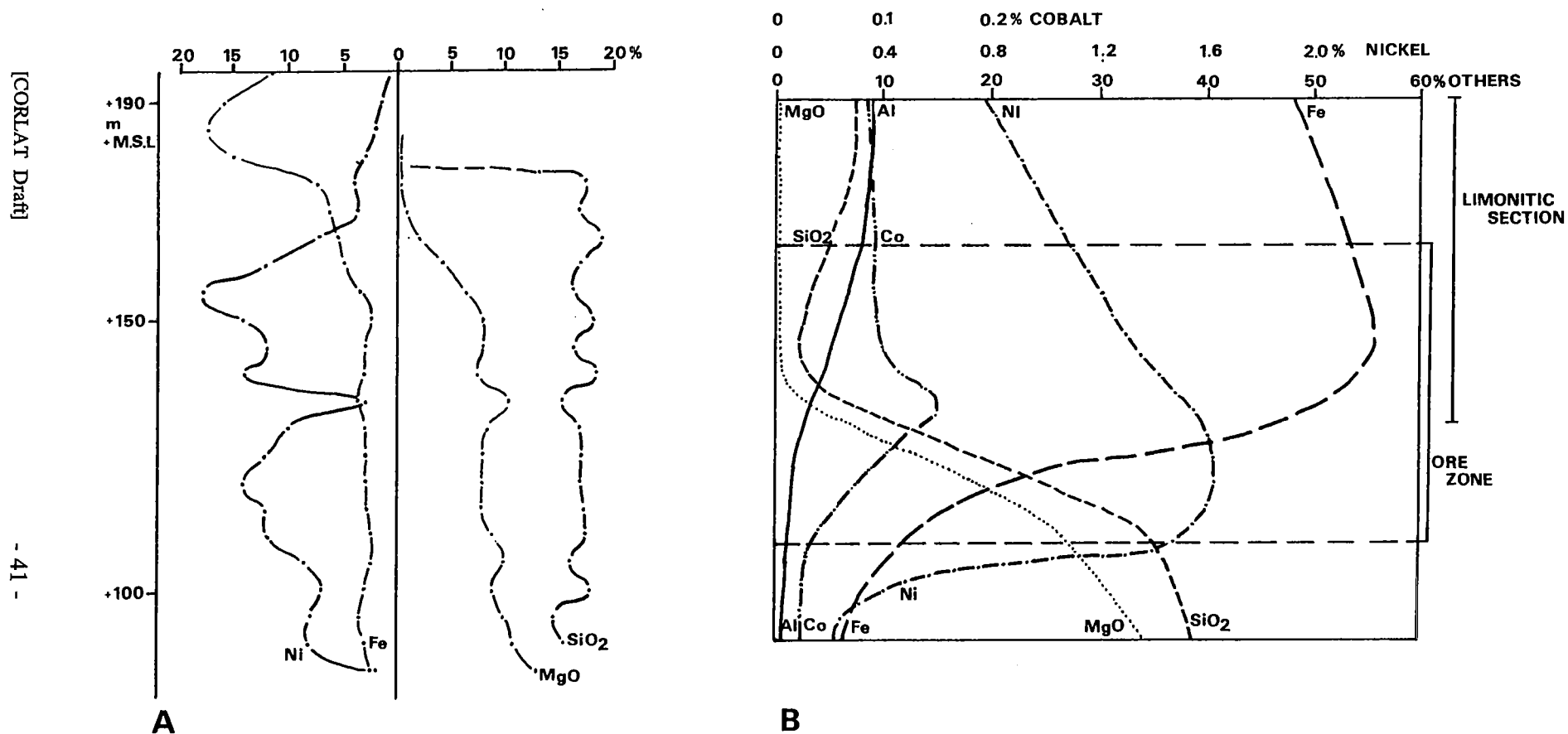
Fig 5. Two examples of the chemical composition of nickel laterites.

A. Typical section showing the vertical disstribution of nickel, iron, silica and magnesiumoxide in the Cerro Matoso nickel deposit, Province of Cordoba, Colombia (ca. 75° 30' W and 7° 55' N); ref. G. Gomez, C.T. Ogryzlo & A.A. Dorr, 1979

B. Typical section showing the vertical distribution of the main metals and oxides in the Nicaro nickel mine, Oriente Province, Cuba. After D.R. De Vletter, 1955. The thickness of the ore zone may vary between 2.5 and 6 m.
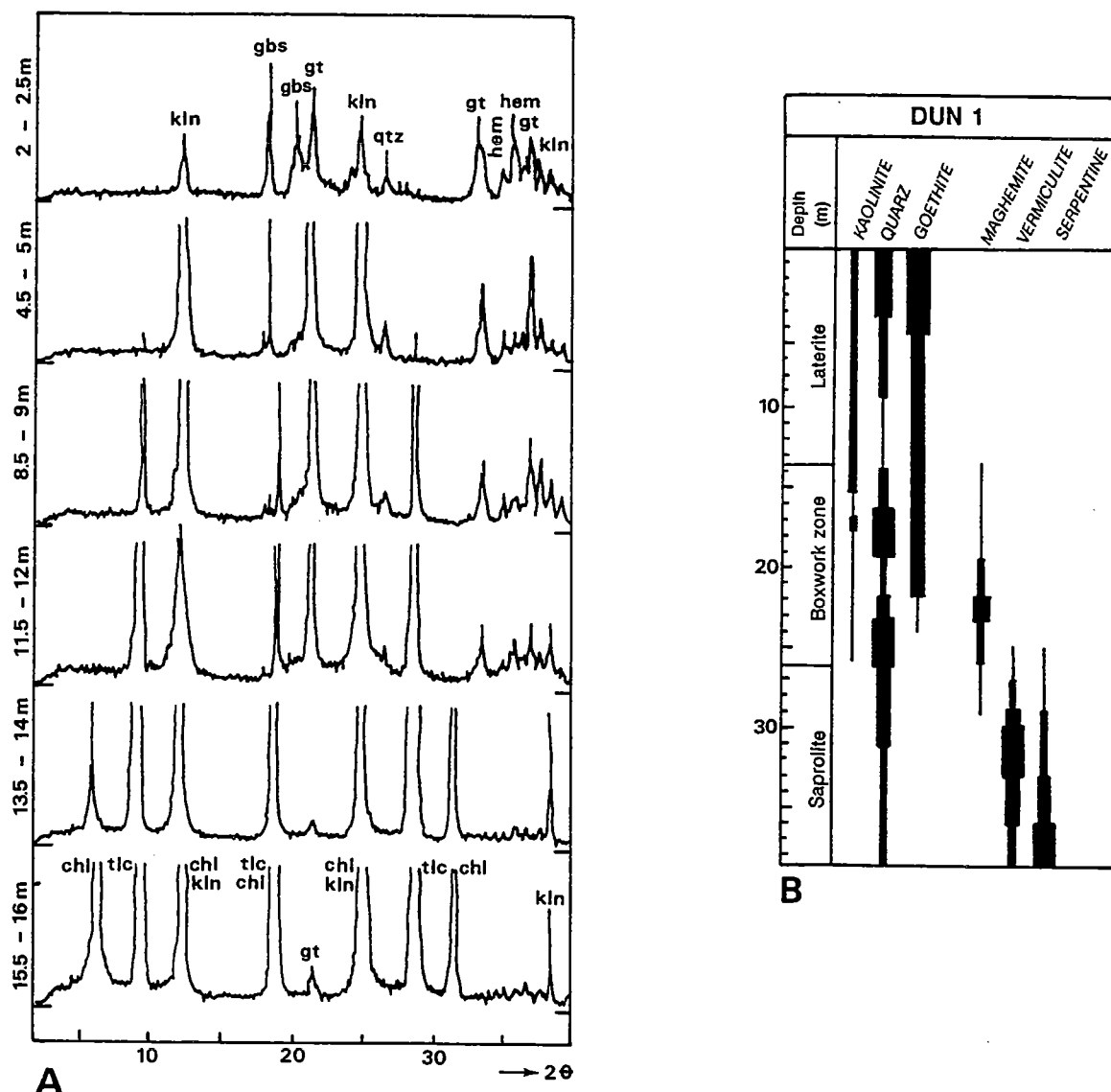
Fig 6   Two examples to illustrate the semi-quantitative mineralogical composition of the lateritic weathering profile.

A. Laterite profile from Morro do Cruzeiro, Minas Gerais, Brasil (Friedrich et al., 1987)). The graph shows the mineralogical composition of laterite bulk samples of six depth ranges. illustrating the changing mineral composition from weathered parent rock (chl=chlorite; tlc=talc; gt=goethite; kln=kaolinite) towards the lateritic crust (qtz=quartz; gbs=gibbsite;hem=hematite). The analyses were made by XRD methods.

The Precambrian parent rocks consisted of ultramafic intrusive rocks (peridotite, dunite pyroxenite) which during, or shortly after emplacement were altered into talc-schists.

B. Laterite profile from the Jacupiranga Alkaline Complex, the main minerals (X-ray detectable phases) for the upper 30 m of the regolith, i.e. from the saprolite to the surface. Note the three successive depth levels at which quartz proliferates.

Fig. 6B represents a weathering profile over an intrusive mass of dunite in the Jacupiranga Alcaline Complex, São Paulo State, Brasil. The macroscopic description of the profile, after Friederich, is as follows:

Laterite Zone:

0-6 m	:	yellow brown, soft argillacious laterite without preserved rock fabric;
6-13 m	:	purple, tough, clayey laterite without preserved rock fabric, concretions, pisoids;

Boxwork zone:

13-24 m	:	brownish laterite with yellow-white and purple mottles, rock fabric, silcrete;
24-26.5 m	:	transitional zone between silcrete boxwork and saprolite; secondary silica, kaolinized material intermixed with saprolitic serpentinite rock (greenish-black), rock fabric.
26.5-37.4 m	:	greenish to yellow-brown saprolitic serpentinite with the clay mineral vermiculite; intercalations of less weathered kaolinized syenite veins, secondary silica, occurrence of fuchsite (= chromium muscovite).
> 37.4 m	:	serpentinized parent rock.

4.4 Degradation of the lateritic accumulation layer

The formation of laterites is essentially a re-equilibration of the mineral phases at atmospheric conditions of high ambient temperature and high humidity. A change back to a lower temperature or lower humidity, or both, produces again a dis-equilibration in the mineral phases, resulting in chemical and mechanical changes in, and destruction of, existing laterite cuirasses. The geological literature provides a number of interesting studies that contain details on the 'negative' re-equilibration processes, that best can be described in one word as degradation*.

The surficial degradation of laterite back into kaolinite, is not a generally accepted process; but a clear example is provided by the Onverdacht (Suriname) bauxite deposit. In it the Fe-Al accumulation zone has been converted into a clayey material composed of kaolinite with metahalloysite.

In the Onverdacht excavations the upper few metres of the laterite cuirass are exposed, overlain by 10-15 m of Miocene sediments (Aleva, 1965). The cuirass surface presents all the features of an old land surface, with a dendritic pattern of small creeks, 1-2 m deep. About 50% of the iron-rich cuirass is bleached by a secondary process, removing all iron and replacing a large part of the Al-Fe cuirass by kaolinitic clay with some montmorillonite (Montagne, 1964). Valeton (1974) described — from the same deposit but under a thicker cover of Miocene and younger sediments — irregular veins, varying in thickness between several cm to dm, penetrating in an anastomosing fashion the ferruginous bauxite (cuirass, upper zone). These veins are composed of a core of white kaolinite with some metahalloysite, and an orange-pink 'reaction zone' between this core and the ferruginous upper zone of the bauxite-laterite cuirass. The thickness of these veins varies from 5 to 30 cm (Plate G).

In a downslope position (originally the laterite surface probably was more or less horizontal) several km north from where Valeton reported the veins, the now sediment-covered accumulation zone — cuirass — is cut by a very flat unconformity, presumably a marine abrasion plane. The underlying original Fe-Al accumulation zone is changed into a kaolinite-metahalloysite mass, containing pinkish and brown irregularly shaped patches, blocks and grains of a relatively soft lateritic material, varying in size between 1 and 20 cm, and altogether making up about 10 - 20 % of the total volume (Plate J).

These features of chemical degradation are evidence of a retrograde transformation from a gibbsitic laterite back into kaolinitic clay, which must have occurred either during the waning phases of the bauxitization period (Late Eocene) or during the following Oligocene sedimentary hiatus and Early Miocene sedimentation phase (Wong, 1989). Hence, the time period required for such degradation could well be in the same order of magnitude as that for the formation of a laterite.

Millot (1983) discussed the extensive, flat planation surfaces occurring over many old continental cores, with either tropical, subtropical or even desert climates. Comparable planation surfaces are found at the bottom of great transgressions and in erosion-notched landscapes. He arrived at the concept of 'climatic' planation, which is the result of the succession and interaction of three processes:

(i) basal, chemical weathering with regularization of the bedrock topography;

(ii) pedogenetic transformations, generating surficially leached, sandy and clayey horizons, and

(iii) surficial erosion through rain wash and aeolian erosion, producing pediments and pediplanes.

He further suggests the existance of two geometric 'discordances' (= unconformities):

(i) the first geometric unconformity is represented by interface I, the boundary between the earth crust and the weathering mantle; it is produced under climatic conditions with marked humid seasons;

(ii) the second geometric unconformity develops as the result of alternating humid and dry conditions acting on the weathering mantle under a climate with marked dry seasons, where wind and rain wash alternatingly become important denudational forces.

Under common equilibrium conditions, both fronts progress downward together, forming planation surfaces that give way to pediments. However, Millot argues, a more arid climate would retard the lower, weathering front, which ultimately would cause the two fronts to coalesce into one front, as e.g. is the situation in the Sahara: one planation surface with alterite (isovolumetrically weathered with its original fabric still present) and some soil relics.

Maignien (1966) described numerous cases of the physical and chemical attack on existing laterite cuirasses, and the subsequent deposition elsewhere of the iron component, which may travel in solution over long distances in the ground water. The resulting iron-rich deposits are frequently confused with laterite; they are in reality the represipitation of iron derived from laterite deposits by circulating groundwater. The term 'ferricrete'* has also often been used for these precipitates.

Grandin (1976) studied in detail the history of the destruction of a bauxitic cuirass on the borders of the Ivory Coast, Burkina Fasso and Ghana. The uppermost, bauxite-bearing plateau level, at 450-550 m elevation (and 300-400 m above the local base level) presumably is of Eocene age; it is still present in small caps on the highest hills, covering about 0.2% of the total surface area of the region. The compact cuirass remnants, 10-15 m thick, are mainly composed of gibbsite, goethite and hematite, with pisolitic, granular and brecciated textures and some ferruginous deposits.

The isolated bauxite-capped summits are surrounded by a succession of pediments, the highest covered with an iron-kaolinite crust without any quartz and the three lower levels covered by crusts composed of iron oxide, kaolinite and quartz (33 % SiO_2 in the lowest level).

Table V gives a summary of the results of Grandin's study (which contains several clear geomorphological block diagrams and sections). It is interesting to observe in the Intermediate level how the original aluminium concentration has disappeared and the iron content shows a maximum concentration in this level. The crusts covering the successive pediments illustrate the

gradual decrease, level by level and hence in time, in the content of iron and kaolinite, and the increase in quartz.

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

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

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

Comparable work is in progress in SE Australia by Bourman (1991), in an area with somewhat different geological history. He stated: "As surface weathering and erosion proceeded, the iron segregations, largely hematitic mottles, were progressively exposed at the surface, where they hardened, disintegrated, and formed lags*". See also the Handbook of Exploration Geochemistry by Butt & Zeegers (1992).

Recently, Alexandre (1991) published a paper summarizing the formation and transformation of lateritic duricrusts in Central Africa. The paper contains explanations of primary processes and clear descriptions of secondary processes and structures/fabrics, all pertinent to the successive changes in the landscape since Early Tertiary. The paper is accompanied by six colour illustrations of various 'structures' (fabrics).

4.5 Atypical profiles

These are of frequent occurrence; they mostly relate to variations in the thicknesses of the successive zones of the profile: almost any of the specific lithological zones may be either excessively thick, very thin or completely absent (Fig. 3B). Such variations may be of a local nature, but may also occur over a large part of a laterite formation.

A different type of lateritic accumulation zone occurs in S.E. Asia, e.g. in Vietnam where the parent rocks are Pliocene and Pleistocene basalts. The bauxitic accumulation zone, 1-10 m thick, is composed of hard bauxite nodules, blocks and concretions, 1-100 cm in diameter, which are embedded in a friable, earthy matrix (Bárdossy & Aleva, 1990). Comparable types of laterite occur in Peninsular Malaysia and in the small, Indonesian island Bintan, where the age of the parent rock has not been established (Van Bemmelen, 1940). An interesting feature of this laterite, which gives an indication of its age, is the position of the weathering profile with respect to the present sea-level: the Interface I (weathering front) occurs ~30 m below present sea-level. Hence the age of the weathering process, which produced the immature nodular profile, must predate the world-wide postglacial rise of the sea-level.

Robertson (CSIRO, Perth) described the influence of sulphides on the parent rock. Outside the sphere of influence of the sulphide vein the total regolith thickness reached 40 m, but along the dipping vein the regolith had been weathered to a depth of 230 m (verbal communication to the CORLAT Workshop, Wageningen, 1992).

4.6 Terminology

The relatively small group of scientists working on laterite and related subjects, and the relative few centres in the world where research is in a pioneering position, is probably the cause of some terminological confusion. To clarify matters a few terms may be mentioned here.

— *Carapace** is the French term for the lower, softer part of the lateritic Fe-Al accumulation zone; this term has no common translation into English.
— *Cuirasse** is the French term for the upper, hard part of the Fe-Al accumulation zone; it is used in the English laterite literature — as 'cuirass*' — and is a specific name for the zone that the mining industry refers to as 'hardcap'.
— *Ferricrete** is a shorthand term suggested by Lamplugh (1902) for a "conglomerated gravel" [quotation marks by Lamplugh] with iron oxide from outside the area as a binding substance. Hence it is by definition not of a residual nature and consequently should not be used for a residual rock such as a laterite. It could be used, however, for an iron-oxide cemented, transported rubble composed of lateritic fragments. The indiscriminate use of this term for any hard, blackish, near surface material in the weathering environment should be discouraged; full allochthony must be established first.
— *Alcrete** is a term parallel to ferricrete, i.e. a conglomerate cemented by imported gibbsite. Hence, it is definitely not a synonym for bauxite, as alcrete is an allochthonous unit, while bauxite is a true, aluminous laterite, hence of an autochthonous nature.

As a geologist, the compiler of this Handbook would say that plinthite and related 'soils' belong to the more or less recent weathering phenomena, while laterites are presumed — although not fully proven — to be products of former climates distinctly different from the present, i.e. warmer and more humid. The deviant and 'incomplete' laterites from S.E. Asia, overlying Pliocene and Pleistocene parent rocks, would be worth a closer and detailed investigation in this respect.

In summary, the formation of laterites requires:

— environmental conditions that promote complete weathering of the common silicates, i.e. a warm and humid climate to accelerate reaction speed (Van 't Hoff's [1852-1911] theorem: a 2 to 3 fold increase for every 10°C temperature rise);
— sufficient rainfall to provide abundant solvent to flush out the solute;
— a parent rock composed of more or less easily weatherable minerals, i.e. mainly alkali- and calc-alkali silicates;
— a geomorphological position that promotes the free flow of the solvent;
— sufficient time: at least several million years.

This is not the place for a lengthy discourse of the presumed weathering processes themselves, but one reference seems in place: Norton (1973) discussed the physico-chemical background of lateritic weathering, using a pH-Eh diagram to illustrate the stability areas for Fe and Al compounds — see Fig. 7 and the accompanying explanation.

4.7 Some remarks

The parent materials of laterites do not necessarily have to be consolidated rocks. 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 was, at least partly, deposited as a much coarser
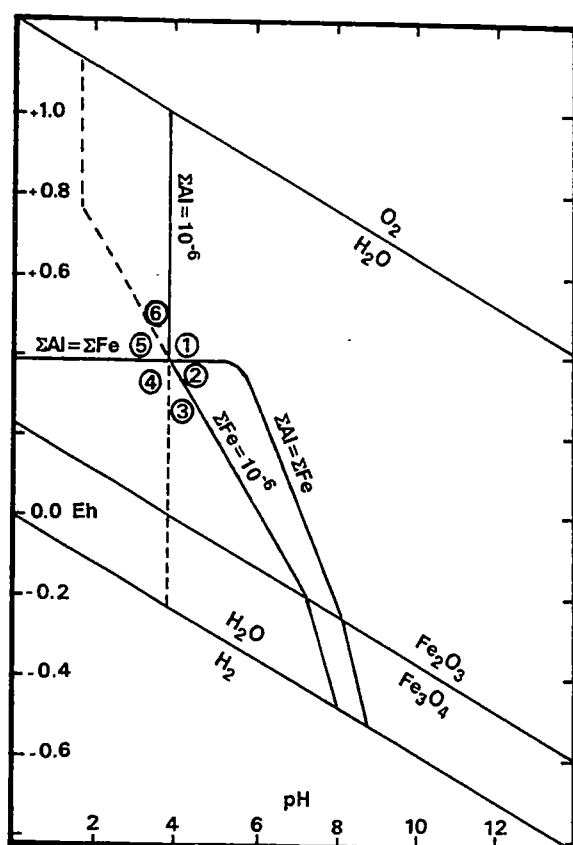
Fig. 7. Solubility relationships among gibbsite, hematite, magnetite, and water, calculated from thermodynamic data of Garrels & Christ (1965). To the right of where the contours are solid (up to pH of 10.33) both Fe and Al phases ar immobile (Norton, 1973).

1 Al > Fe in solution. BXT/LTR follows Al/Fe ratio in parent rock. Secondary enrichment Al > Fe but minor.

2 Fe > Al in solution. LTR/BXT follows Fe/Al ratio in parent rock. Secondary enrichment Fe/Al but minor.

3 Fe removed from soil −> BXT formed. Secondary enrichment Fe > > Al.

4 Fe and Al leached but Fe > Al. Secondary enrichment with increase of pH and/or Eh.

5 Al and Fe leached but Al > Fe. Secondary enrichment with increase of pH and/or Eh.

6 Al removed from soil −> LTR formed. Secondary enrichment Al > > Fe.

sediment. This is testified by the coarse, weathering-resistant minerals such as quartz, staurolite and opaque minerals which are included. Also, the grain size of these sediments has influenced the process of 'bauxitization' (i.e. the formation of an aluminium-rich accumulation layer): at some depth (varying from 0.2 to 4 metres) below the main bauxite layer there may occur 5-80 cm thick bauxite layers interbedded in the kaolinitic saprolite. These bauxite beds can be followed horizontally for many tens of metres; eventually they either pinch out or coalesce with the main bauxite layer (Aleva, 1965). The opposite also occurs: 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. The last kaolinitic lens (circa 10x30 cm in size) is fully converted into a dense, porcelaineous and very pure bauxite (composition: in the order of 63 % Al_2O_3, 2 % SiO_2 and 1 % Fe_2O_3).

The complexity of the formation of bauxite, as a particular version of the lateritization process sensu lato, is illustrated in Plate B, photograph 1, where a banked or layered bauxite (arkose derived) is transected by a cross cutting − or epigenetic − 'vein' of dense, colour-banded bauxite.

4.8 A proposed standard form for the Laterite profile description

In the soil sciences, the standard or typical soil profile has been formalized with three, later with four (FAO, 1990) genetic soil horizons:

— A horizon: the surface soil, enriched with organic matter;
— E horizon: an immediate subsurface horizon characterized by the loss of silicate clay, iron and/or aluminium through leaching or eluviation, leaving a horizon with pale colours and weaker soil structure;

- B horizon: a subsurface horizon characterized by an absolute or relative accumulation of the products of leaching and eluviation with colours and soil structure which is clearly different from the horizons above and below;
- C horizon: partially altered material from which it is assumed the overlying soil horizons have been formed. It may or may not have been through one or more weathering cycles, but it is only slightly affected by current soil formation. Unlike horizons above, it may retain features of the original geological structure.

Several earth scientists, including geologists and geomorphologists, have tried to apply this soil horizonation to laterite profiles, but without much success. A very detailed determination of the morphological, chemical and mineralogical composition is not required for laterites. Also, the rock weathering profile is much more complex and thicker, up to 60 m for laterites, than the few soil horizons can accommodate. A standardized laterite profile description requires a generally accepted and morphologically and genetically based 'typical' laterite profile. Such a typical profile seems now to be a feasible proposition, e.g. by using the profile of Table IV. This table is an adaption of data derived from the CSRIO research in SW Australia, with observations and literature data from elsewhere in the world, in particular from India, Africa and South America.

The Interfaces I to V inclusive, are the essential morphogenetic boundaries between the successive zones of this typical profile, and they should give their number to the material or zone they overly. Table VI illustrates how such a 'typical profile' would lead to a form for the standardized description of laterite weathering profiles. Table VII compares this 'typical profile' with the organization of profile descriptions by a number of authors and organizations.

The main purpose and advantage of adopting a standard laterite profile, lies in the assistance it gives in the comparative study of profiles. The observer of a section becomes immediately aware of any deviations, such as a missing zone, or a zone that pinches out horizontally, or of interfaces between zones that are irregular or which deviate or coalesce laterally.

The study of zone interfaces provides information on the genetic history of the Laterite Formation, even before detailed descriptions have been made — see Chapter 7, section 4 for the organization of such detailed descriptions.

Converging interfaces may lead to the disappearance of certain zones, e.g. the absence of saprolite, and/or the plasmic and mottled zones, which then brings the laterite zone in direct contact with its parent rock. This is not an uncommon situation. The presence of a kaolinitic zone within the accumulation zone is another, frequently observed, aberrant feature. In the aluminous laterite of the Eastern Ghats District (India), a kaolinitic intercalation is often present. This appears to be correlated with gently dipping khondalite* parent rocks (A.K. Nandi, pers.comm. 1992).

In Onverdacht, Suriname, zones of kaolinite (beds up to 1 m thick) within the arkose-derived laterite zone (5-10 m thick) appear to be related to very fine-grained parent rock beds within the sedimentary succession, i.e. kaolinitic clay beds. The fine grain size evidently prevented the transformation to laterite, presumably the result of low permeability.

Table VI — Suggestions for the systematic laterite zone designations and the description of the materials included.

Based on the more common profiles overlying acid and intermediate parent rocks. Mafic and ultra-mafic parent rocks will require an adapted outline.

Code	Name	Description
Lag	Variable	Describe derivation, size, amount, consistency, etc.
Interface V		
S	Soil Could be described by using the FAO or USDA system of soil description	Describe details, which could be added in lower case letters, separated by commas: a = autochtonous, t = transported; or al = alluvium, cl = colluvium; pf = petroferric; sk = skeletic phases.
Interface IV		
L c	Laterite: cuirass	Give complete description, incl. degradation features if any.
L m	Laterite: main zone	Give size, frequency, colour & consistency of mottles; core boulders.
M	Mottled zone	
Interface III		
	Plasmic zone	Describe amount of relict quartz and its fabric; core boulders.
Interface II		
S	Saprolite	Describe amount of quartz, its relict fabric: core boulders.
Sr	Saprock	Describe volume % of still hard material.
Interface I		
R	Parent rock	Describe fresh rock succintly

Also inculde a description of the interfaces:
    shape: flat,rolling, irregular (state height difference);
    abruptness: knife sharp, gradational over x cm/dm;
    visibility: clear because of. . . ., unclear.

Table VII - Comparison of terminology for describing laterite profiles

Zones	After Millot (1964) and Lelong (1969) as adapted by Aleva (1986)	Geol. Soc. Engin. Group Working Party; Engin. Geol. 1977, 10(4)	Valeton (1991) et al. S. de Mantequeira, Brazil	CSIRO Research RRA, CRMB & IDMR, West Australia	This CORLAT Handbook
Atmosphere				LAG	Transported LAG
INTERFACE V: Present day surface of the Earth					
Pedogenesis	A - Residual soil	(VI) Residual soil	Recent soil; Residual pebble or mineral layer; Soft yellow soil	SOIL	SOIL; may contain pedogenetic (hard) accumulations, e.g. petroferric phases
INTERFACE IV: Surficial weathering front					
Fe & Al accumulation	B - LATERITE: Accumulation zone; if hard duricrust or cuirass	(V) Completely weathered original structures intact	B_{ox}: -in situ residual breccia -in situ bauxite with preserved relict texture; 5-20 cm thick	LATERITIC GRAVEL loose nodules & pisolith LATERITIC DURICRUST; same, indurated MOTTLED ZONE; mottles in kaolinite-rich matrix	LATERITE: cuirass or main zone (Carapace, Fr.) sharp/gradual contact MOTTLED ZONE Fe-accumulations in kaolinite matrix
INTERFACE III: Cementation front					
Leaching and neoformation	C Unstructured saprolite	(IV) Highly weathered >50 % of rock decomposed		PLASMIC ZONE primary fabric replaced by clay and quartz-rich sec. structures	PLASMIC ZONE (or unstructured saprolite) kaolinitic clay & relict quartz
INTERFACE II: Pedoplasmation front					
Leaching and neoformation	D Structured saprolite E Rotten rock F Transition zone	(III) Moderately weathered with <50% of rock decomposed (II) slightly weathered, discoloured, weaker (IB) Faintly weathered	B_v: saprolite 0-x m	SAPROLITE > 20 % weatherable minerals altered, primary fabric pseudomorphosed but recognizable	SAPROLITE s.s. kaolinitic clay with relict quartz, > 20 % of weatherable minerals altered
INTERFACE I: Deep weathering front					
Bedrock	G Generally the parent rock of the above profile	(IA) No visible sign of rock weathering	C: parent rock	Generally the PARENT ROCK of the above profile	Bedrock, generally the parent rock of the profile

5 Examples of laterite profiles

A 'typical profile' is a model or abstraction developed by the knowledgeable field scientist to illustrate the essential characteristics of the multitude of profiles under study; it may be far removed from naturally occurring profiles in its lack of details. To redress this deficiency, some profile and landscape descriptions are presented from three different continents.

5.1 India (Table VIII and Fig. 8)

Dr A.K. Nandi (Nagpur) provided the typical laterite profile for two areas with completely different parent rocks. Both profiles have been slightly edited in order to fit within the standard profile terminology. This concerned the plasmic/mottled layer, which was considered as a part of the saprolite.

Table VIIIA shows the profile development over basaltic parent rocks (Deccan Trap*) as found in Central India. The chemical and mineralogical composition of these laterites had been studied by Jagannatha Rao & Krishnamurthy (1981). Their data have been transformed into the histograms in Fig. 8A and can in this way easily be compared with Table VIIIA.

Table VIIIB shows the profile development over the khondalite* rocks (garnet-sillimanite gneisses or high-grade metamorphic granulite facies of Archaean age) of the Eastern Ghats, India. The chemical variations in this type of profile have been obtained from one of the many holes drilled in the Pottangi area, South Block (pers.comm. A.K. Singh, 1985). The aluminous nature of this 32 m thick laterite profile is distinct (Fig. 8B); however, the average iron content of the upper ~ 17 m is around 10 % higher than that of the lower part of the profile.

The West Coast laterites, including Buchanan's type area at Angadipuran, Kerala State, are represented by colour photographs (Plate A). These laterites overly granitic parent rocks (see section 2.2)

5.2 SW Australia (Table IX and Fig. 9 & 10)

Drs. R.R. Anand, C.R.M. Butt, I.D.M. Robertson and R.E. Smith have provided a typical laterite profile from the Yilgarn Block (Fig. 9A), which was used as an example for the profile given in Table IV. The following paragraphs have been contributed to the Handbook by these scientists as shown by their initials. Fig. 9B presents a generalized cross-section showing some common Yilgarn regolith landform situations. This illustrates the intricate mixture of residual, erosional and depositional regimes present in S.W. Australia, where recent areas of arid and humid climate are closely juxtaposed.

Anand and Smith provided the following summary for the present Handbook:

Introduction (RRA & RES)

Laterite weathering profiles are widely distributed over the Yilgarn Block. Lateritic weathering is also an important process elsewhere in the world and is estimated to have affected about one third of the Earth's land surface, including much of Australia, India, Brazil and intertropical Africa (Gidigasu, 1976; Bárdossy & Aleva, 1990). In these regions, bedrocks are commonly weathered to depths of 10 to >100 m, depending on climate, regional tectonic stability and nature of the parent rock (McFarlane, 1976; Nahon *et al.*, 1977; Butt, 1981; Anand et al., 1989b).

Table VIII — Typical Laterite Profiles

On Khondalite (E. Ghats, India)		On Basalt (Central India)
Not reported.	**LAG**	Not reported.
. . . . INTERFACE V . . . . **Surface of the earth**		
Alluvial with laterite and bauxite pebbles, 0-1 m.	**SOIL**	Red loamy soil, 1-2 m Loosely packed Fe-rich lateritic nodules, 1-3 m.
. . . . INTERFACE IV . . . . **Laterite surface**		
Cuirasse, 0-6 m. Fe-rich duricrust, fine-grained. Main zone, 0-60 m. Ferruginous bauxite, porous. Highly aluminous bauxite, porous and soft.	**LATERITE**	Main laterite, up to 6 m. White-cream coloured hard bauxite, cracks filled with Fe and Si minerals. Fe-rich layer, 0-1 m. Goethite band, dark brown, compact.
Kaolinized khondalite clay, friable, 0-5 m.	**MOTTLED ZONE**	Not identified.
. . . . INTERFACE III		
Not identified.	**PLASMIC ZONE**	Homogenized pink, brown, purple clay; locally ochre.
. . . . INTERFACE II		
Altered into kaolinite with relict fabric.	**SAPROLITE**	Altered basalt.
Weathered and fractured khondalite.	**SAPROCK**	Weathered and fractured basalt.
. . . . INTERFACE I		
Fresh khondalite.	**PARENT ROCK**	Basalt = Deccan Traps.
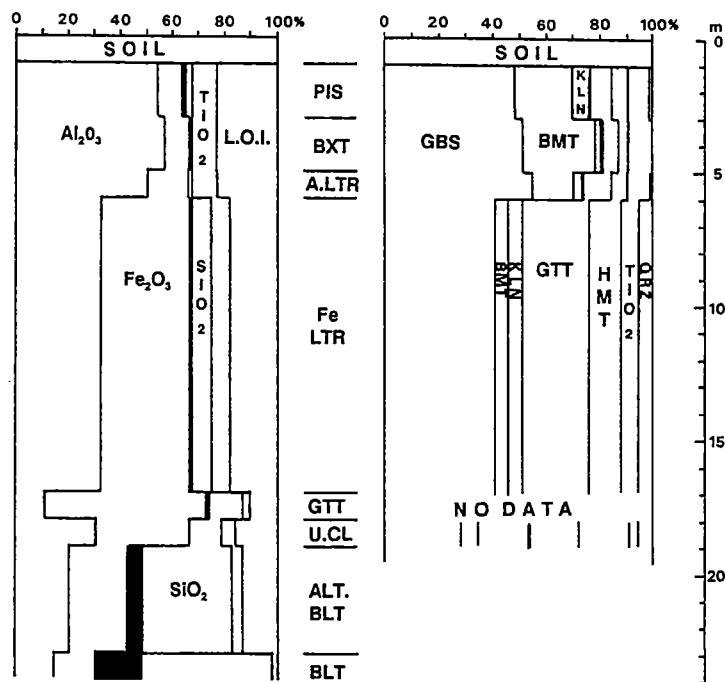
Fig. 8A - Chemical (left) and mineralogical (right) composition of the high-level bauxite deposits of Amarkantak area, Madhya Pradesh, India (22° 37/43' N; 81°39/42' E), overlying Upper Cretaceous to Eocene Deccan trap (basalt flows) mainly. Summarized after J. Jagannatha Roa & C.V. Krishnamurthy, 1980.

PIS	- pisoidal crust	GBS	- gibbsite
BXT	- bauxite	BMT	- boehmite
A.LTR	- aluminous laterite	KLN	- kaolinite
Fe.LTR	- ferruginous laterite	HMT	- hematite
GTT	- Goethite-rich zone	QRZ	- quartz
U.CL	- Underclay	black	- minerals not analysed, or
ALT.BLT	- altered basalt		difference from 100 %
BLT	- fresh basalt		
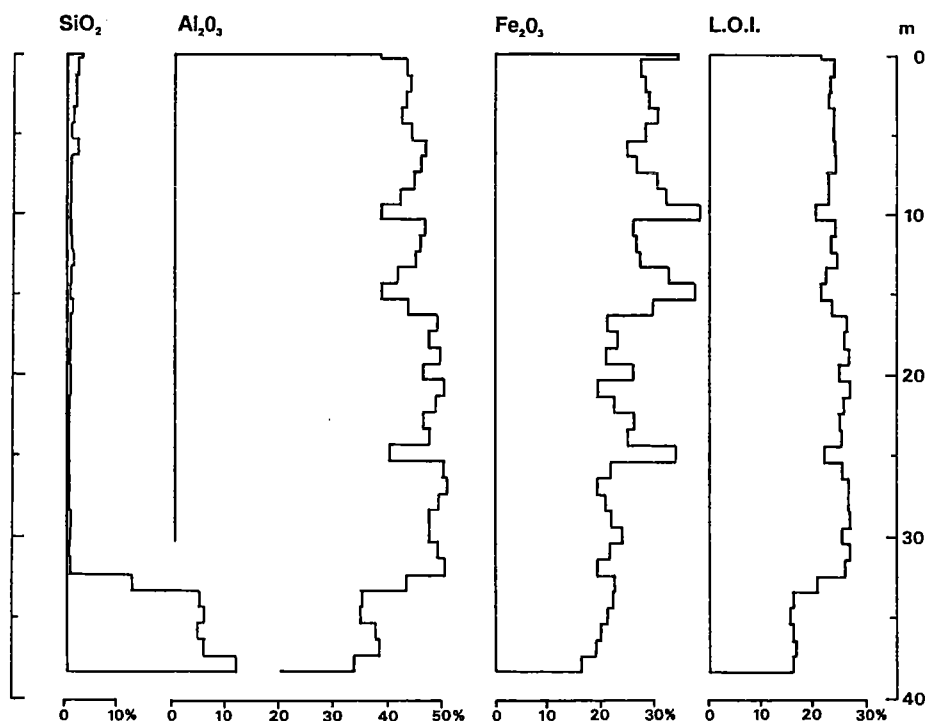
Fig 8B - Histogram illustrating the distribution of the main oxides in one drill hole (collar elevation + 1340.30 m MSL) from the Pottang area, South Block, Eastern Gatt hills, India. The lateritic rocks overly Archaean high-grade metamorphic, granulite facies rocks: khondalites or garnet sillimanite gneisses. Pers. comm. A.K. Singh, 1985. At 32 m depth the mottled zone is clearly reached: the top 0.3 m is considered to be soil.

LAG

REGOLITH	PEDOLITH	SOIL		Pisolith/noduled loose	Fe-rich secondary structures
		LATERITE	Lateritic gravel	Nodules/pisoliths Indurated	
			Lateritic duricrust		
		MOTTLED ZONE		Mottles in a kaolinite-rich matrix	
				Cementation front	
		PLASMIC ZONE		Primary fabric replaced by clay or quartz-rich secondary structures	
	SAPROLITH			Pedoplasmation front	
		SAPROLITE		>20% weatherable minerals altered	
				Primary fabric pseudomorphed but recognizable	
		SAPROCK		<20% weatherable minerals altered	
BEDROCK				Weathering front	

Fig. 9A - The typical laterite profile and profile terminology as developed by the CSIRO Research Group in West Australia (R.R. Anand, C.R.M. Butt, I.D.M. Robertson & R.E. Smith, ca. 1991) for the West Australian scene. It stood model for Table IV: the typical laterite-saprolite formation. The terms pedolith and 'saprolith' would lead to confusion with 'saprolite' as in most languages - except English - there is little or no difference in the pronunciation of both terms.

RESIDUAL REGIME (SANDPLAIN)

EROSIONAL REGIME (HILLS, EROSIONAL PLAINS, GENTLY UNDULATING TRACTS)

RESIDUAL REGIME (BACKSLOPES)

DEPOSITIONAL REGIME (COLLUVIAL OUTWASH PLAINS, ALLUVIAL VALLEYS)

Lateritic duricrust

Valley calcrete

Salt lake

Lunettes, dunes, sand plain

Yellow and red sands

Hardpan in colluvium, alluvium (sands, clays, silt, etc)

Hardpan with lateritic debris

Pedogenic calcrete, calcareous red clays

Transported lateritic gravels

Laterite

Mottled zone, saprolite

Bedrock

Iron-segregations

Shear with quartz vein and primary gold mineralization

Saprolitic gold

Lateritic gold mineralization

A generalized cross-section showing some common Yilgarn regolith-landform situations.

Fig. 9B - Generalized cross-section showing some common Yilgarn regolith-landform situations.

[CORLAT Draft]

Weathering profiles on the Yilgarn Block are commonly deep and very highly weathered. Climate has played an important, if not dominant role, in the development of the lateritic regolith and resultant landforms and patterns of geochemical weathering. The importance of past climates and weathering episodes in the development of the lateritic profiles and landscapes has been recognized by many workers (e.g. Mabbutt, 1980; Butt, 1981). Two stages appear to have been important to the development of lateritic regolith in Australia.

(i)   A long period of deep lateritic weathering, under warm, humid climates occurred particularly during early Tertiary. Lateritic profiles developed at this time are characterized by a residuum of Fe and Al oxides, overlying deep clay and saprolite zones, which are depleted in alkalis and alkaline earths.

(ii) In inland Australia, subsequent periods of aridity and semi-aridity occurred since the Miocene, continuing to the present, during which the weathering profiles have been modified (Bowler, 1976, Mabbutt, 1980). Because of the tectonic stability and generally low relief during this period, many of the products of weathering have been preserved.

Field relationships (RRA & RES)

A typical catena* on the Yilgarn Block is shown in Fig. 9B. Laterite, reaching a thickness of several metres and consisting of several fabric types (pisolitic, nodular, fragmental, vesicular), is extensively distributed over the Yilgarn Block of Western Australia. Extensive weathering and lateritic duricrusts occurred on a landscape which was undulating and from which drainage removed the soluble products of chemical weathering - the alkalis and alkaline earth elements - leaving a weathered zone up to 100 m deep or more. However, lateritic weathering profiles on the Yilgarn Block do not form a continuous blanket. Many areas are characterized by partly truncated saprolite, or even exposed fresh rock, others by an extensive colluvial or alluvial cover.

Laterite occurs not only in the higher parts of the landscape but is also widespread beneath the colluvium and alluvium. It appears that laterites have developed across landsurfaces at various altitudes (an undulating surface). Laterites occur on slopes of up to 8° in the Darling Ranges where laterite outcrops account for only 15-20% of the laterite terrain. However, regolith studies in several districts of the Yilgarn Block, involving widespread drilling in colluvial and alluvial plains, showed extensive areas of buried laterite.

Figure 10 provides a set of four laterite profiles overlying different parent rocks (A: granitoid with dolerite dyke, in a coastal area with a seasonally humid climate, B: granitoid with quartz vein, in an arid area, C: amphibolite in an arid climate, and D: serpentinized dunite, in an average type of climate). The following explanation has been prepared by R.R. Anand & C.R.M. Butt.
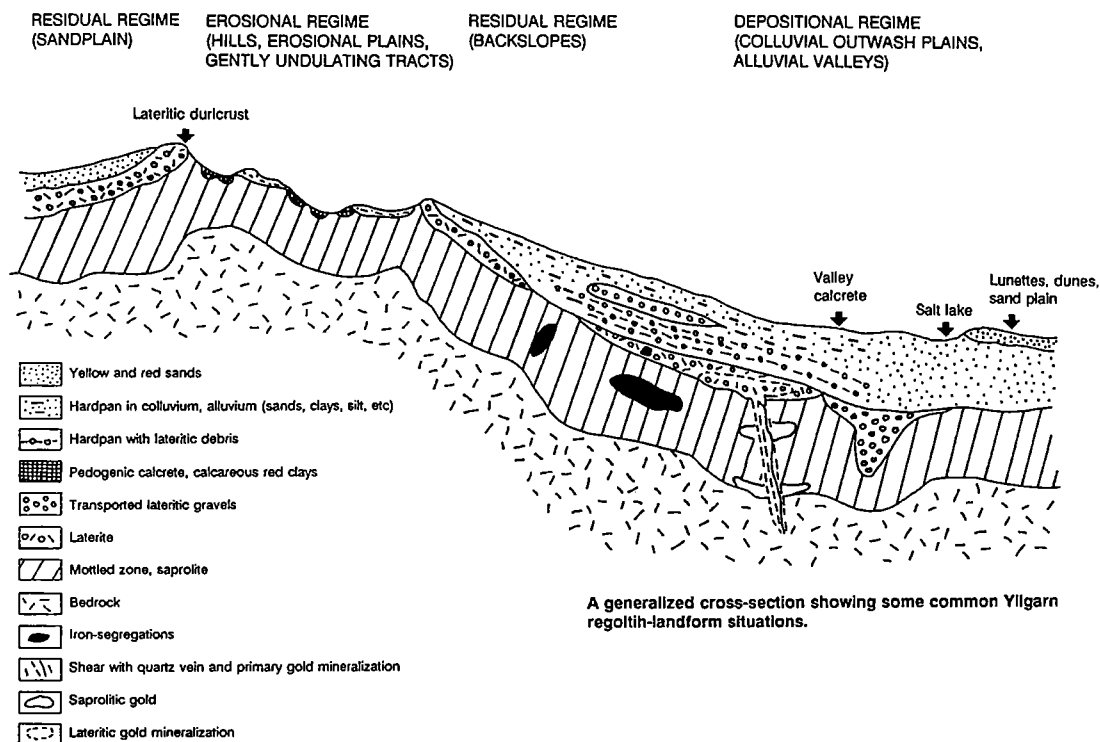
Laterite profiles - Australian perspective (RRA & CRMB) − Plates H and I

This section describes commonly occurring weathering profiles mostly from the Yilgarn Block of Western Australia. Although saprolite makes up a large proportion in many of these weathering profiles, the upper units may vary, depending on the nature of bedrock, present climate and drainage conditions. In the Yilgarn Block the present day climate ranges from seasonally humid in the SW of Western Australia, with a moderate (800 - 1200 mm) winter rainfall, to the semi-arid to arid conditions of the interior, with erratic rainfalls (averaging about 200 mm per annum). The current climate appears to control the nature of the weathering profile. The Darling Range profile is an example of a saprolite overlain by a bauxite zone. On the other hand, ferruginous saprolite, instead of a mottled zone, is extensively developed on mafic and ultramafic rocks in inland profiles. Examples of these weathering profiles are shown in Figure 10 and described with their mineralogy and geochemistry in the following paragraphs.

A

DARLING RANGES PROFILE ON GRANITE AND DOLERITE (COASTAL SEASONALLY HUMID CLIMATE)

Lag Maghemite, amorphous aluminium, hematite, quartz,
Gravelly soil Gibbsite, goethite, hematite, maghemite, quartz
Pisolitic - nodular duricrust Gibbsite, hematite, goethite, maghemite, quartz

Bauxite zone
Gibbsite, goethite, hematite, quartz

Clay zone
Kaolinite, goethite, quartz, gibbsite

Saprolite
Kaolinite, quartz, gibbsite

Saprock
Halloysite, kaolinite, quartz, smectite

Bedrock
— Metadolerite
— Granite

B

INLAND PROFILE ON MAFIC ROCKS (ARID CLIMATE)

LAG
Gravelly soil Kaolinite, goethite, hematite, quartz
Lateritic gravel Hematite, kaolinite, goethite, maghemite, quartz
Lateritic duricrust ± silicified, calcified Kaolinite, goethite, hematite, quartz maghemite
COLLAPSED FERRUGINOUS SAPROLITE Kaolinite, goethite, hematite, quartz
FERRUGINOUS SAPROLITE Kaolinite, goethite, hematite, quartz
~ Bodies of iron segregation (goethite)
SAPROLITE Kaolinite, smectite, goethite, quartz
SAPROCK Smectite, kaolinite, goethite, quartz
BEDROCK Amphibolite

C

GRANITOID - N. YILGARN BLOCK (ARID)

Quartz, minor Fe lag
SAND
ARENOSE HORIZON Quartz, allophane (hyalite, kaolinite), goethite
SILCRETE Quartz, anatase, zircon
SAPROLITE TRANSITIONAL TO ARENOSE HORIZON Quartz, kaolinite, allophane, (hyalite)·
SAPROLITE Quartz, kaolinite
QUARTZ VEIN Quartz, kaolinite, ?smectite
Quartz, kaolinite, feldspar, mica
SAPROCK GRUS Quartz, kaolinite, feldspar, mica
FRESH GRANITOID Quartz, feldspar, mica·

D

SERPENTINIZED DUNITE - N. YILGARN BLOCK

SOIL AND GRAVEL
DURICRUST (CUIRASSE) – massive, cemented. Goethite, hematite, magnesite, chromite
MOTTLED ZONE Smectite, goethite, hematite, kaolinite, chromite
Fe-CLAY SAPROLITE (Serpentine), goethite, smectite, hematite
MANGANESE-CLAY ZONE Mn oxides, goethite, quartz, smectite
SILICIFIED SAPROLITE Quartz, serpentine, goethite, chromite
Magnesite
Silicification Quartz, magnesite, dolomite, serpentinite, goethite, chromite
SAPROLITE
SAPROCK
FRESH ROCK Serpentine, chromite, magnesite
SERPENTINIZED DUNITE

Fig.10- Four typical profiles from S.W. Australia, characterizing different parent rocks and climates. Courtesy Drs Anand, Butt, Robertson & Smith (1992).
A: Darling Range on granite with dolerite dykes; coastal seasonally humid climate.
B: Inland profile on mafic rocks in arid climate.
C: Northern Yilgarn profile on granitoid rocks; arid climate.
D: Northern Yilgarn profile on serpentinized dunite; arid climate.

A   *Darling Range profile on granite and dolerite* (subcoastal seasonally humid climate, Fig. 10A)

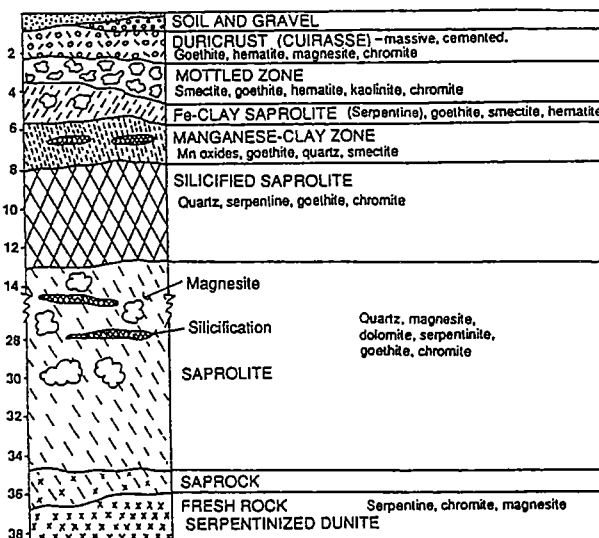The lateritic bauxite profiles generally consist of successive zones overlying fresh rock at the base, passing upward, through a saprolite and clay zone, into a bauxite zone, a lateritic duricrust and a loose, nodular, pisolitic unit which is overlain by a gravelly, sandy top soil. Depths to fresh rock range from 2-50 m (Fig. 10A). The thickness of these zones varies considerably, depending upon the nature of the parent rock.

In the Darling Range laterites, a relative increase of Al_2O_3 with respect to SiO_2 has taken place in the upper parts of some profiles to the extent that gibbsite occurs in the lateritic duricrust and mottled zone. The mottled zone is dominant and is referred to as the 'bauxite zone' or 'B zone' by the local bauxite mining companies (Anand et al., 1991). It is an earthy, porous, yellow-brown to dark reddish-brown layer, 2-6 m thick, which underlies the 1.5-30 m thick, lateritic duricrust. The boundary between lateritic duricrust and bauxite zone is gradational. The bauxite consists of ferruginous fragments, incipient nodules and, in places, is mottled. Relict saprolitic fabrics, such as gibbsite pseudomorphs after feldspar, may be present in this zone. The bauxite zone is underlain by a 10-50 m thick, multicoloured clay zone and saprolite. The saprolite merges into underlying parent rock through a 0.2-2.0 m thick saprock zone. The boundary between bedrock and saprock (weathering front) is very irregular and diffuse; weathering penetrates cracks and fractures, leaving unaltered boulders, fragments of rock and relics of primary minerals high in the profile.

Mineralogical composition (RRA): Table IX A. The detailed field relationships and mineralogical composition of these profiles are given by Grubb (1971), Sadleir & Gilkes (1976), Davy (1979), Anand & Gilkes (1984), Anand & Gilkes (1987) and Anand et al. (1991). The mineralogy of granitic and doleritic bauxite profiles is summarized below. The mineralogical characteristics of the different units of the bauxitic profile were established from X-ray diffraction and chemical analyses.

Table IX A - Mineralogical properties for bauxite from the four Alcoa mine sites

Mineral (weight %)	Willowdale (N=14)		Huntly (N=13)		Del Park (N=16)		Jarrahdale (N=26)	
	M	S.D.	M	S.D.	M	S.D.	M	S.D.
Gibbsite	49	11	38	13	42	16	45	16
Goethite	13	8	12	9	16	10	16	8
Hematite	10	6	11	10	9	9	9	9
Quartz	15	13	23	19	19	14	17	12
Kaolinite	0.8	1.3	1.2	2.0	1.6	1.6	1.4	2.0
Maghemite	2.6	3.0	1.8	3.0	0.0	0.0	0.5	2.0
Muscovite	0.5	0.5	2.9	5.0	4.0	3.5	2.1	2.1
Anatase	1.7	1.2	1.5	0.9	1.5	1.0	1.5	1.4
Ilmenite	1.0	1.7	1.0	1.5	1.1	2.0	0.8	1.8
Boehmite	0.9	1.3	0.5	1.0	0.1	0.2	0.3	0.5
Corundum	1.1	1.3	0.7	1.3	0.0	0.0	0.2	0.6

M = mean; S.D. = standard deviation

Gibbsite and Fe-oxides are the dominant minerals in the bauxite zone and the lateritic duricrust. Goethite is present in larger amounts in the bauxite zone and duricrust overlying

dolerite (20 and 19% goethite respectively) than over granite (8 and 11% respectively), owing to the higher iron and lower quartz contents of the dolerite. Similarly hematite has an average abundance of 3 and 4% for granitic bauxite and duricrust materials, respectively, and 15% for both doleritic bauxite and its duricrust.

Gibbsite abundance decreases appreciably in loose pisoliths where amorphous Al becomes the major Al mineral. Maghemite, corundum and boehmite were not detected in the bauxite horizon but were present in significant amounts in loose pisoliths and pisolitic duricrust. Over dolerite, anatase is an important secondary mineral, reflecting the higher Ti content of the dolerite protore*. Small amounts of relict muscovite occur in granitic bauxite and its overlying duricrust.

Deeper in the profile, the major change from lateritic bauxite to saprolite is marked by the disappearance of gibbsite; only small amounts of this mineral occur in the saprolite. Halloysite and/or kaolinite are most abundant in the middle saprolite and diminish in the top, bauxitic part, of the profile. Goethite and hematite are present in small amounts throughout. The lower saprolite consists of halloysite and quartz with relic minerals from the bedrock.

The degree of aluminium substitution increases up the profile. In bauxite and duricrust horizons, the Al substitution in goethite ranges from 20 to 35 mole %, whereas, in saprolite, it ranges from 8-18 mole %. A significant positive correlation exists between mole % Al substitution in goethite and the amount of gibbsite. For an increase in gibbsite of 2.5% there is an equivalent increase of about 1% Al substitution in goethite (Anand et al., 1991). The high degree of Al-substitution in goethite of gibbsitic laterite is apparently because the goethite has formed in an Al-rich environment (Fitzpatrick and Schwertmann, 1982). The relatively low degree of Al-substitution in the goethite of saprolite is consistent with the low abundance of gibbsite and high amounts of kaolinite. Aluminium substitution in hematite ranges from 3-11 mole % which is consistent with 0-16 mole % for other bauxites and soils (Nahon et al., 1977; Bardossy, 1983). Where both goethite and hematite occur together, hematite has the lesser Al substitution.

The crystal size of goethite ranges from 16-26 µm, whereas that of hematite ranges from 18-69 µm. Where both Fe-oxides occur in a sample, hematite crystals were always larger than goethite crystals by about 60%.

Geochemistry (RRA): Table IX B. The chemical composition of laterite profiles of the Darling Range has been discussed in detail by Sadleir & Gilkes (1976), Davy (1979) and Anand et al. (1991). The main geochemical characteristics of the laterite profiles are summarized below:

— The chemical composition of the bedrock is reflected by that of the lateritic duricrust. The proportion of residual quartz, together with absolute values for Fe_2O_3, TiO_2, K_2O, Mn, V, and Zr in the duricrust may be used to discriminate granite from meta-quartz dolerite.

— There is almost complete leaching of Na_2O, CaO and MgO, together with partial leaching of K_2O and a considerable loss of SiO_2. Relative to the bedrock there is an absolute gain in water and an apparent increase in Al_2O_3, Fe_2O_3, TiO_2, Cr, and V in the laterite.

— Zirconium, Ga, Sn, Nb, and Th are normally concentrated in the upper parts of the profiles. Barium, Sr, and Zn are commonly lost, whilst the abundances of Cu, Co, Ni, and Pb vary.

The chemical composition of bauxite from the Darling Range bauxite is summarized in Table IXB. Both major and minor elements are present at a wide range of concentrations resulting in high values of standard deviation relative to mean values.

The concentrations of the major elements correspond with the mineralogical data. Aluminium is mostly present as gibbsite, with smaller amounts in boehmite, kaolinite, muscovite, Al-goethite, Al-hematite and possible Al-maghemite; Fe occurs as goethite, hematite and maghemite; K as muscovite, Ti as anatase, ilmenite and rutile; Si as quartz, kaolinite and muscovite. An indication of the association of minor and major elements in bauxite is provided

by statistical analysis of the data. A correlation matrix for element concentrations in bauxite samples indicated several highly significant correlations. From these correlations the following affinity groups were recognized:

1. Si, K, Ba, Na, Mg, Rb;
2. Fe, Ti, V, Cr, Mn, Cu, Zn;
3. Al, LOI (water).

Table IX B - Chemical composition of bauxite samples

Element		All mine sites (N = 69)			S.D.	Willowdale (mean N=14)	Huntly (mean N=16)	Del Park (mean N=16)	Yarrahdale (mean N=26)
		Range	Median	Mean					
Al_2O_3	(%)	14.2-49.0	34.3	34.5	7.3	37.2	31.2	34.0	36.6
SiO_2	(%)	11.3-48.0	16.1	21.5	17.0	15.5	26.2	22.3	17.5
Fe_2O_3	(%)	3.9-69.8	17.3	21.2	14.6	24.5	22.0	19.6	21.2
K_2O	(%)	0-1.6	0.11	0.24	0.31	0.06	0.27	0.40	0.21
CaO	(%)	0-0.110	0.010	0.015	0.010	0.010	0.009	0.016	0.021
TiO_2	(%)	0.38-8.30	1.36	2.00	1.60	1.90	2.06	2.10	1.96
H_2O[1)]	(%)	0.66-2.97	1.61	1.70	0.50	1.64	1.70	1.74	1.62
LOI	(%)	6.4-26.7	19.20	18.1	5.1	18.4	15.4	18.7	18.9
P	(%)	0-0.034	0.015	0.015	0.010	0.019	0.020	0.013	0.013
S	(%)	0.014-0.227	0.076	0.084	0.040	0.089	0.079	0.093	0.085
Na	(ppm)	0-275	50	49	48	39	67	44	44
Mg	(ppm)	0-850	25	101	179	68	92	167	84
V	(ppm)	25-2380	330	512	480	533	583	427	518
Cr	(ppm)	9-790	150	172	142	329	131	129	135
Zr	(ppm)	170-910	400	407	128	449	413	344	420
Ba	(ppm)	0-490	25	63	89	13	90	118	42
Mn	(ppm)	8-420	29	72	96	60	87	76	67
Sn	(ppm)	3-35	9	11	6	12	8	8	4
Pb	(ppm)	0-28	6	8	7	13	8	7	7
Cu	(ppm)	4-110	11	19	21	25	15	20	16
Zn	(ppm)	4-156	13	19	22	15	18	30	15
Nb	(ppm)	0-55	20	22	12	26	15	14	28
Ni	(ppm)	8-96	21	23	13	24	17	29	22
Rb	(ppm)	0-45	0	7	10	1	7	11	7
Sr	(ppm)	0-35	0	2	5	3	4	1	1
Y	(ppm)	0-20	6	5	5	9	4	2	6
Ga	(ppm)	30-99	50	55	16	57	60	49	57

[1)] H_2O moisture lost at 105 °C

The elements that show no clear affinity to other elements are P, S, Ca, Sn, Pb, Ga, Sr, Y, Zr, Nb, Mo, Co, Ni. The major subdivision, is therefore, that minor elements are associated with Si or Fe or show no strong associations. The highly significant correlations indicate that there are associations of elements within specific minor minerals (e.g. Ti, Mn, V in ilmenite in Fe-rich bauxite formed from dolerite and Na, Mg, Ba, Rb, and K in muscovite in quartz (Si)-rich granitic bauxite) as has been confirmed by chemical analysis of single grains of these minerals.

Bauxites are complex chemical systems in which the abundance of some elements may be a consequence of the abundance of two or more minerals, so that associations of elements with minerals are not always predicted by simple single element linear correlations and in such cases multiple regression procedures are more suitable. Some of the highly predictive equations (R2 >0.95)produced by this type of statistical analysis are shown in Table IXC. In the first example, the equation shows that an estimate of the gibbsite contents based on total Al_2O_3 content will be in error due to the presence of some Al in kaolinite/halloysite. The theoretical values of the

coefficients based on the composition of gibbsite and halloysite/kaolinite are 1.51 and 0.60, and are similar to the values obtained by regression (i.e. 1.58, 0.49). A perfect predictive equation for gibbsite would also introduce coefficients to compensate for the Al contents of other minerals (boehmite, Al-goethite, Al-hematite, corundum, muscovite). The non-zero value of the intercept is misleading and the regression line should not be extrapolated beyond the limited range of high values of gibbsite that occur in these materials. The other relations in Table IX C are also simply expressions of the location of elements in one or more mineral species.

Table IX C - Linear relations between mineralogical and chemical properties of bauxite calculated from stepwise regression

	Regression equation	R^2
Gibbsite	$= 8.08 + 1.58\,Al_2O_3 - 0.49\,kasolinite/halloysite$	0.98
Hematite	$= 1.37 + 0.92\,Fe_2O_3 - 0.65\,goethite$	0.95
Quartz	$= 0.34 + 0.99\,SiO_2 - 0.75\,kaolinite/halloysite - 0.53\,muscovite$	1.00
Muscovite	$= 0.05 + 0.18\,Rb + 0.02\,Ba$	0.97

K is not included as a variable because it was used to determine the muscovite content.

B *Inland profiles on mafic rocks* (Arid climate) (RRA & CRMB) Fig. 10B

The mottled zone may or may not be developed, depending upon the relative depths of the pedoplasmation front and the zone of Fe-cementation. Where Fe-cementation has penetrated below the pedoplasmation front, or where the process of pedoplasmation has been unusually incomplete, the mottled zone is replaced with a zone of ferruginous saprolite. This is particularly common on some mafic rocks in inland profiles of the north-eastern Goldfields of the Yilgarn Block, where the profiles may be 50-70 m thick. The upward sequence from the parent rock is saprock, a thick saprolite, ferruginous saprolite, collapsed ferruginous saprolite, nodular duricrust and loose nodules (Fig. 10B).

Ferruginous saprolite is formed by the infusion of clay-rich saprolite with goethite and is hard, 5-15 m thick, massive to mottled, and is dominated by goethite and kaolinite. Fragments of the ferruginous saprolite are yellow-brown, non-magnetic, irregular and have an incipient nodular structure. Interiors may contain preserved relics of resistant minerals (e.g. talc, muscovite, chromite) allowing limited identification of the underlying lithology. Ferruginous saprolite forms a continuous blanket and may be overlain by collapsed ferruginous saprolite where soft, soluble, less ferruginised material of the matrix of the ferruginised saprolite may be removed by leaching, causing the whole structure to collapse. Sub-vertical quartz veins in this collapsed material lose their coherence but many remain approximately in situ.

Laterite (embracing nodular duricrust and loose nodules) averages some 3-6 m in thickness. Duricrust is not present at all localities but, where present, it varies in hardness, from weakly to strongly indurated. Nodular duricrust lies directly on collapsed ferruginous saprolite with a gradual to sharp boundary. Lateritic nodules and pisoliths are associated with the fragmentation of ferruginous saprolite; both lithic and non-lithic nodules occur.

Various forms of iron enrichments (iron segregations) also occur within the ferruginous saprolite and lateritic duricrust. These iron segregations occur as pods, lenses, and large slabs; they are black, non-magnetic and goethite rich.

Mineralogy (RRA). Weathering of mafic rocks results in vertical differentiation of several distinct zones. Starting from bedrock, there is an upward sequence through saprock, saprolite, ferruginous saprolite, collapsed ferruginous saprolite, nodular duricrust to loose nodules. Bands

of Fe-rich materials occur within ferruginous saprolite. These zones are illustrated in Fig. 10B and their mineralogy is described below.

Rock-forming minerals (amphiboles, plagioclase feldspars, chlorite) weather to secondary minerals (smectite, goethite, kaolinite) which in turn are transformed later and higher in the profile into new products, among which Fe-oxides and kaolinite are the most abundant. Amphiboles weather to smectites in the lower parts of the saprolite and these weather to kaolinite higher up. In a semi-arid climate, this smectite is preserved higher in the profile.

The saprolite is composed of moderately well formed crystalline kaolinite and/or halloysite and smectite with various amounts of goethite and quartz. Kaolinite, goethite and hematite are present in ferruginous saprolite. Smectite and quartz only occur in small proportions. Bands and segregations of Fe-rich material, within top of the saprolite, are dominated by goethite with subordinate amounts of hematite.

Iron oxides (goethite, hematite and maghemite) and kaolinite constitute about 70-90% of lateritic duricrust and loose nodules. Maghemite becomes an important constituent in loose nodules. Gibbsite and quartz are present in very small amounts over mafic rocks. Anatase is an important accessory mineral in lateritic duricrust and loose nodules.

Aluminium substitution in goethites range from 6-28 mole % in contrast to the 20-35 mole % range for goethites of Darling Range laterites. Iron segregations show the lowest Al substitution (0 to 11 mole %). These different levels of Al substitution in goethite between the two areas suggest different environments and/or mechanisms for their formation. High substitution reflects weathering in an environment with a high degree of available Al which is incorporated into the goethite structure. Goethites in the inland profiles contain relatively low Al substitution which is due to the relatively low degree of weathering as indicated by the high kaolinite and low gibbsite contents of these laterites. Very low Al substitution in the goethite of iron segregations indicates that they must have grown in an environment almost free of soluble Al.

Geochemistry (RRA). Silica, Al and Fe are the most abundant constituents in laterite and are residual products of chemical weathering. The greatest chemical changes in the profiles occur between bedrock and saprolite. The alkaline and alkaline earth elements, Na, K, Ca and Mg are strongly depleted in saprolite and the overlying horizons. In mafic bedrock, these elements occur as feldspars (Na, Ca), and ferromagnesian minerals (Mg). Lime, MgO and Na_2O concentrations are as low as 0.01-0.08% in ferruginous saprolite. Ilmenite occurs in the unweathered rocks and Ti may be present also in sphene, spinel and ferromagnesian minerals. Titanium generally increases upwards through the profile and is mainly present as anatase.

Mn, Zn, Ni, and Co are similar in chemical behaviour in the weathering environment and are strongly leached from the saprolite and laterites. Silica is generally markedly depleted, Al_2O_3 is slightly enriched and Fe_2O_3 is strongly enriched in laterite.

Vanadium, Cr, Cu, As, Ga, Nb, Mo, Sn, Pb, W, Bi, are concentrated in the upper parts of the profiles, particularly in ferruginous saprolite and laterite. These elements follow more or less the pattern for Fe, which suggests that they are associated with Fe-oxides. Some of these elements are also retained in primary minerals that are resistant to weathering, such as zircon (Zr, Nb), ilmenite (Cr, V, Ti), cassiterite (Sn) and sphene (Nb, Ti).

C   *Inland profiles on granitoid rocks (Arid Climate)* (RRA & CRMB) Fig. 10C

Granitic weathered profiles have been described from the Bar-Smith Range in the northern part of the Yilgarn Block (Butt, 1985) and, also further afield, from southern New South Wales (Banfield, 1985), and Queensland (Robertson, 1990; Robertson & Eggleton, 1991). The work from New South Wales and Queensland illustrate the lower parts of the granitic profile and the early mechanisms of weathering; the Yilgarn profiles detail the upper parts; they may be

combined to form the whole. Fresh granite passes upward through thin saprock into a thick kaolinitic saprolite, some profiles have numerous corestones of fresh rock and saprock. First plagioclase and biotite weather, followed by K-feldspar. The original granite fabric is well preserved by kaolinite pseudomorphs after feldspar and primary quartz. Close to the surface (Fig. 10C) there is a transition (pedoplasmation front) to an arenose horizon (equivalent of the clay zone of mafic rocks). Here much of the kaolinite has been removed, apparently by dissolution, leaving primary quartz. This settles and becomes concentrated into residual sandstone or grit, now largely cemented by aluminosilicates, probably siliceous allophane now recrystallised to kaolinite and amorphous silica. This arenose horizon is invaded by silica and minor titania to form silcrete, in which the quartz grains are cemented by quartz and anatase and may contain up to 3% TiO_2 and 1000 ppm Zr. In places, columns of silcrete penetrate the underlying arenose 'horizon' and saprolite. Quartz veins, which penetrate the saprolite, are distorted, showing its residual nature and isovolumetric weathering. Towards the top of the saprolite and into the arenose horizon, the quartz veins become distorted and break up, indicating residual but non-isovolumetric weathering. Within the arenose horizon, fragments of quartz, derived from the vein, form a stone line, indicating some measure of transport in the arenose material and sandy soil above this stone line. The arenose horizon may be absent where silcrete is particularly abundant on scarps whereas the silcrete tends not to persist more than 100 m from the scarp. The arenose horizon may contain incipient pisoliths which are rich in siliceous allophane.

D *Inland profiles on serpentinized dunite* (Arid Climate). (RRA & CRMB) Fig. 10D

Aspects of the weathering of ultramafic rocks in the Yilgarn Block have been discussed by Smith (1977) and by Butt and Nickel (1981). Dunites consist of olivine (igneous or, more rarely, metamorphic) or serpentine*, or partially serpentinized olivine. They may thus be considered to be almost mono-mineralic, with other phases - pyroxene, chromite, sulphides and alteration products such as stichtite*, magnesite, talc*, pyroaurite* and brucite - comprising less than 2% of the total. Serpentinized dunites have four dominant chemical components, MgO (40%), SiO_2 (34%), FeO (7%) and volatiles; the Al content is very low (<1% Al_2O_3). This restricted mineralogical and chemical composition results in a very distinctive regolith, characterized by intense silicification of the saprolite. The ultimate effect of weathering is the complete loss of Mg, and the (partial) retention of Fe and Si.

Sulphides, occurring with the serpentinised olivines of the dunite, are the first to weather, initially yielding various supergene sulphides and then decomposing completely. Serpentine is a low temperature, low pressure metamorphic mineral that has pseudomorphically replaced the igneous olivines. It is relatively resistant to weathering and may persist throughout the saprolite. It is progressively replaced by iron oxides that in turn may retain the original igneous fabric of the olivine. Magnesium and Si are leached and the resultant Fe oxide-serpentine matrix is very porous, with a low specific gravity (<1-1.5). Continuous weathering of serpentine results in an increasingly Fe-rich residue (Fig. 10D). Towards the surface, close to the palaeowater-table, collapse and combined dissolution and reprecipitation of Fe oxides destroy the original fabric and replace it with the nodular and pisolitic fabric of the laterite horizon, although secondary ferruginization may occur in the upper saprolite. Subsequent dehydration and hardening of these ferruginous horizons may result in the formation of a highly indurated pisolitic duricrust (cuirasse). Chromite is commonly accumulated in the duricrusts, which may have Cr contents of 1-5%. Incomplete leaching of the principal weathering products, Mg and Si, later in the evolution of these profiles, commonly results in their precipitation in the porous horizons of the saprolite. These thus become massively silicified (60-80% SiO_2 as quartz), but may, nevertheless, retain their igneous fabric. Veins and nodules of magnesite and, in places, dolomite, also precipitate; the Ca for the latter presumably is derived from adjacent lithologies. The massive

silicification results in a very impervious horizon and a perched water-table may develop above it. This is commonly a site for the precipitation of Mn oxides and smectites (saponite and nontronite). Scavenging by Mn oxides can result in very high concentrations of Co, Ni (and Pd). Dunites are not favourable parent materials for the formation of Ni laterites as a result of the absence of smectites in the saprolite, although Co enrichment of the Mn oxides has been exploited locally (Elias et al., 1981).

Silicification is a feature of lateritized dunites in many tropical weathered terrains. The silica is highly resistant to weathering and may form prominent outcrops. These are informally referred to as birbirites* and several have been described as being hydrothermal in origin, the true origin, i.e. weathering, not being recognized.

E *Modification, degradation and dispersion* (RRA)

A number of other processes have been under way since the formation of laterites on the Yilgarn Block. Present landsurfaces are the result of differential stripping of an extensive laterite mantle and the consequent exposure of various units of the undulating weathering profile. Truncation of laterite is common in many areas of the Yilgarn Block. The most striking consequence of erosion in laterite terrain (in Australia) is the development of breakaways*, which mark the erosion of the resistant duricrust to expose the softer, mottled zone and/or saprolite beneath (Plate I). In general the interfluves have been least affected by erosion and are dominated by lateritic materials.

Erosion and profile truncation have taken place via pedimentation and headward stream erosion which are still continuing. Dismantling of the laterite leads to the deposition of colluvial/alluvial units, rich in lateritic debris. The resultant partly eroded landscape is a complex mosaic of variable truncated regolith, interspersed with extensive sheets of transported cover.

Introduction of cementing materials is one of the most recognized modifications to a laterite profile in response to climatic change. Silica and carbonate are common features of the regolith in semi-arid regions and their products can form both near-surface and outcropping units, widely distributed over the landscape (Mabbutt, 1980; Butt, 1981; Anand et al., 1989b). Many of the sedimentary regolith units of the arid interior are now indurated through cementation by silica and Fe-oxides to form a commonly porous, red-brown hardpan which can also occur in residual regolith units such as lateritic duricrust and saprolite, particularly in the first metre or so beneath hardpanized sedimentary units. Calcification, the growth of authigenic carbonates of Ca and Mg, is also widespread in the arid interior, and can infuse soils and laterite. Locally, the lateritic duricrust has been partly replaced and/or displaced by silica or carbonates, with consequent formation of calcareous and siliceous duricrusts. Observations suggest that the process, taken to completion, would eventually result in calcrete and silcrete.

Horizons of ferruginous lateritic gravel, consisting of nodules and pisoliths in a sandy clay matrix, are frequently associated with lateritic duricrust. These horizons generally develop above or are laterally associated with indurated lateritic duricrust. Generally, the origin of this gravelly horizon may be attributed to in situ dismantling of the lateritic duricrust, followed by down slope colluvial transport. The matrix of duricrust breaks down by dissolution of its cementing components, which allows separation of nodules and pisoliths in a sandy clay matrix.

5.3 Suriname (Fig. 11)

The northern part of Suriname is situated on the northern edge of the Guyana craton, northern South America, part of which has been warped downward during Late Cretaceous and Tertiary time. A cross-section is presented in Fig. 11, extending from the high level laterite plateaux of the Bakhuis Mountains in the South, to the extensive arkose-derived bauxite deposits in the Coastal Plain of Northern Suriname, which for a large part is covered by Miocene and younger, mainly fluviatile, deposits

Typical profiles for the Bakhuis Mountains and the Coastal Plain bauxite deposits are included. Through pollen analyses (Van der Hammen & Wymstra, 1964) and stratigraphic research (Montagne, 1964; Wong, 1989), it has been shown that the Palaeocene and Eocene were humid and warm periods, while the Oligocene was a sedimentary hiatus with a dry climate. The present climate is humid and tropical, the present day natural vegetation is generally a dense, humid, tropical forest, with only the highest peaks of the mountains being bare rock and some eluvial sand plains having a poor, edaphic-controlled vegetation. The contrast between the Inland and the Coastal Plain laterites is caused by:

(i)   The inland laterites have been formed by continuous weathering since Late Eocene times, while the Coastal Plain laterites were covered by Miocene and younger sediments.

(ii) The Inland laterites are somewhat variable in composition - mainly iron content - resulting from a variety of parent rocks, varying from leucocratic anorhthositic and pyroxene granulitic intrusive rocks (Bakhuis Mountains) to more basic, meta-andesites, meta-basalts and amphibolites (Nassau Mountains).

(iii) The Coastal Plain bauxitic laterites presumably have been formed from more or less pure arkosic sands as parent rock; however, the parent rock has been completely weathered, i.e. altered, to laterite (bauxite), and no trace of the fresh or partly weathered parent rock has been found.

The substratum of this feldspathic sandstone, the Precambrian igneous and metamorphic rocks, have been weathered to a saprolite type of material with a high percentage of mica and, more to the east, staurolite. In Eastern Suriname, in the Moengo area, the contact between Precambrian basement and the highly weathered sedimentary cover is marked by a bed, 0.2-1 m thick, composed of well rounded pebbles — up to several cm in diameter — composed of gangue quartz.

The alternating or successive residual, erosional and depositional laterite regimes as found in Australia, have no parallel in Suriname. The inland laterite deposits are largely covered by high, tropical forest; the cuirass is generally rich in iron with the formation of crusts but without pisoids or abundant tubular or vermicular fabrics — the massive habit of the igneous parent rocks persists. The continuing degradation involves mainly processes of underground solution. This is accompanied by loud gurgling noises after a heavy rain storm with several dm of precipitation. The noise is caused by the invisible water draining through the abundant subsurface cracks, joints and drainage tubes. The noises may last for several days after the rain storm.

Explanation of Figure 11.

The section is a composite of features that can be observed in the northern one-third of Suriname. All data are moved to a S-N line, represented in the profile of this figure. The highest ridges and peaks are 800-1000 m, the Bakhuis mountains plateaux reach to about 400 m above sea level, separated by deeply incised, steep-sided valleys (presumably following a rectangular pattern of deep faults).
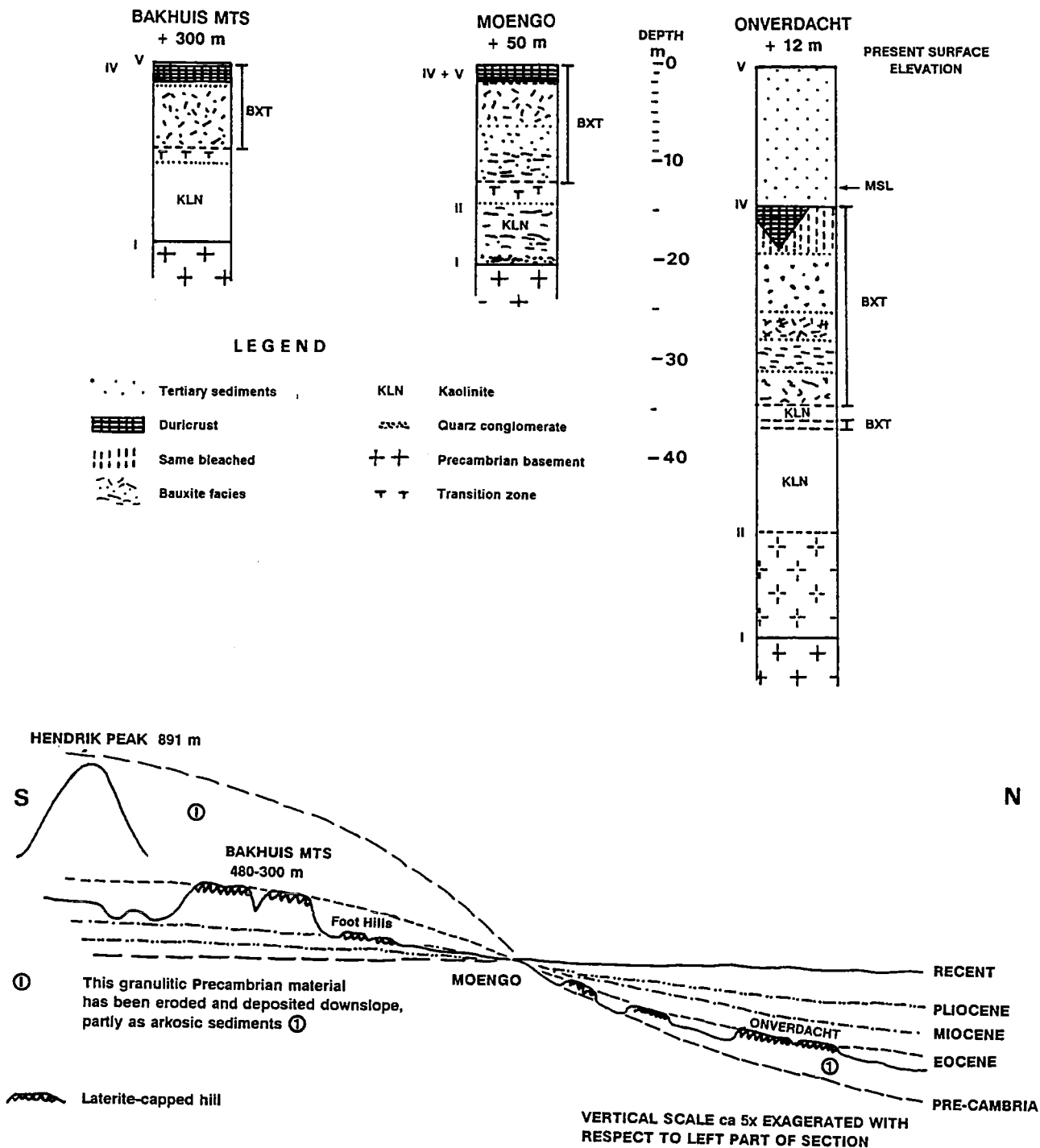
Fig. 11 - South-North section through the northern edge of the Guyana Shield, including the Coastal Plain of Suriname. In the Bakhuis Mountains and on the Foot Hills, the laterite has Precambrian basement rocks as parent rock; the Moengo and Onverdacht laterites and bauxites are derived from the sedimentary rocks of Palaeocene age. The three examples of laterite/bauxite profiles are drawn in the same scale - see the depth scale.

The South-North section is drawn on two different vertical scales: the coastal Plain area is so flat that using the scale of the Inland part would not show any detail. In the Onverdacht profile the basement fabric can be determined in the saprolite.

[CORLAT Draft]

The northern part of the Guyana Shield has been downwarped since Late Cretaceous time and the sedimentary cover over the northern edge of the Shield provides a clue to the speed of this subsidence. Note: the vertical scale of the section in the right (= North) part of the figure is 5 times exaggerated with respect to the left or southern part! This exaggeration is also a measure of the amount of denudation products that have been lost to the ocean, as the thin veneer of sediments on dry land in the North of Suriname is almost negligible with respect to the matter removed from the more Southern part of Suriname.

The laterite capped plateau hills - representing the remnants of presumably much larger, original surfaces - are marked with cross hatching to show the present day laterite caps. The age of the sediments overlying the now covered laterite caps in the northern part of the section, give an idea of the time required to produce a bauxitic lateritic cap of 5-10 m thickness, i.e. the Oligocene hiatus, or a time period in the order of 10 Ma.

Before Miocene sedimentation covered the laterite in the North - and finally stopped the lateritization process - this flat, sedimentary surface had obtained a closely spaced, dendritic drainage system, cut into the laterite to a depth of 1-3 m and 5-15 m wide, as well as an iron-rich cuirass of similar thickness. The duricrust frequently shows a breccia-like fabric, with both highly ferruginous as well as pure white, angular fragments (Aleva, 1965, 1981, 1984; Aleva & Hilversum, 1984; Bárdossy & Aleva, 1990; Janssen, 1979; Krook, 1979; Wong, 1989).

## 5.4 Brasil, the Central Shield area (Fig. 12 and Plates D & E)

The block diagrams in Fig. 12 I - IV have been contributed by Dr Sérvulo B. de Rezende, from the Federal University of Viçosa, Minas Gerais; they are situated in the centre of the Brazilian laterite deposits overlying Precambrian rocks, including the sedimentary iron ores of the "Iron Quadrangle", which were 'beneficiated' - to use an ore-processing term - by the Upper Mesozoic/Tertiary lateritization event. De Rezende provided the following explanations for his four landscape sketches (the compiler condensed the extensive explanations in Portuguese into the accompanying short English summary).

The block diagram of Fig. 12-I illustrates laterite occurrences formed through relative accumulation of iron, derived from 'itabirites'* (the Precambrian banded oxide-facies iron formation, composed of quartz with hematite, magnetite and martite), occurring at the edge of the 'Quadilátero Ferrífero', as seen from the Ouro Prêto - Bela Horizonte road (Minas Gerais); here the contact occurs between the itabirite and the Middle Precambrian phyllites and quartzites.

The block diagram of Figure 12-II, also along this road, illustrates a laterite occurrence which locally contains bauxitic accumulations, collected in palaeo-playas*, i.e. fossil, intermontaneous sedimentary basins. The most recent base level for erosion is several hundred metres lower, and superficially drained these old playas. This caused the ferrous iron to be removed in solution, resulting in a relative accumulation of alumina. Such deposits occur in several places along the present scarps of the Quadrilátero Ferrífico, where drainage is strongest; this drainage occurs largely through the groundwater, as the ferruginous duricrust acts as a barrier against surface erosion.

The block diagram of Figure 12-III illustrates another kind of bauxite formation derived from residual ferrallitic materials, which is the relative Al accumulation on remnants of old planation surfaces, which often cap the present day highest areas in the landscape. The example given — Cataguazes, M.G. — refers to a bauxite situated below an oxisol, with a total iron oxide content of 13-15%. The relative aluminium enrichment of the underlying bauxite took place during a more humid climatic period than the present, resulting in deep valleys and convex-convex valley profiles. The next lower level of convex-convex hill slopes are also deeply weathered, but only kaolinite has been formed.

The last two examples have in common a relative aluminium accumulation from ferrallitic parent material. This is attributed to fossil biological activity, i.e. worms which were active while buried in the total thickness of the regolith. Such occurrences have been found in many places in Brazil (De Rezende, 1980; Corea, 1984; Lani, 1987). These organisms form an abundance of pedotubules through which iron and silica are drained from the system, resulting in a particular profile seen in many tropical areas (Fig. 12-IV). However, the supposed fossils have never been identified.
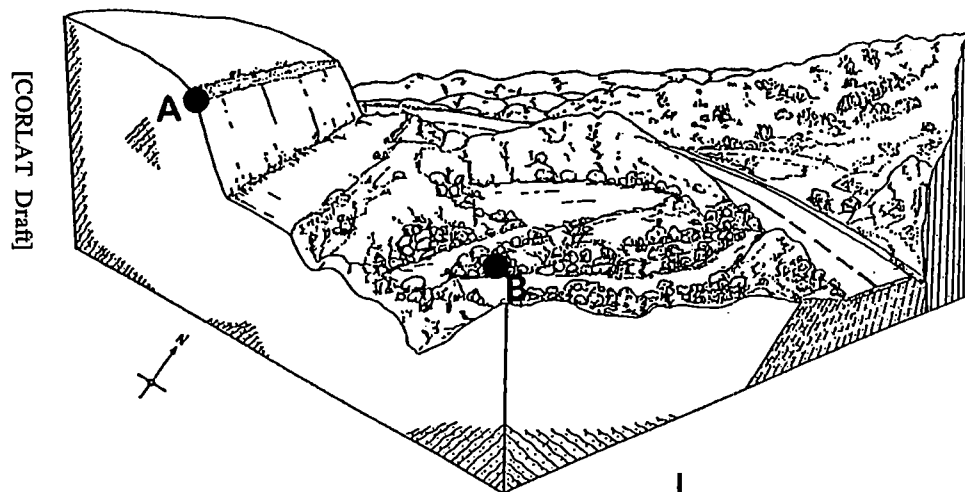
Itabirite (metamorphic iron rich rock)

Phyllite

Quartzite
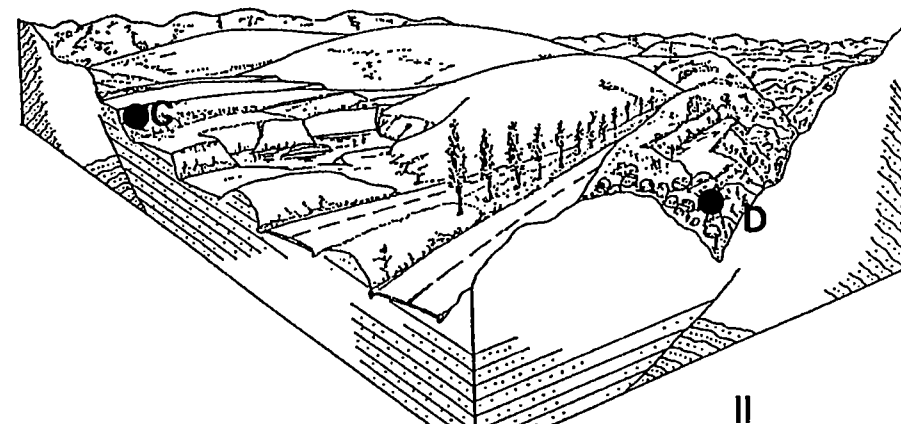
Itabirite (metamorphic iron rich rock)

Clayey bauxite deposit (paleoplaya)
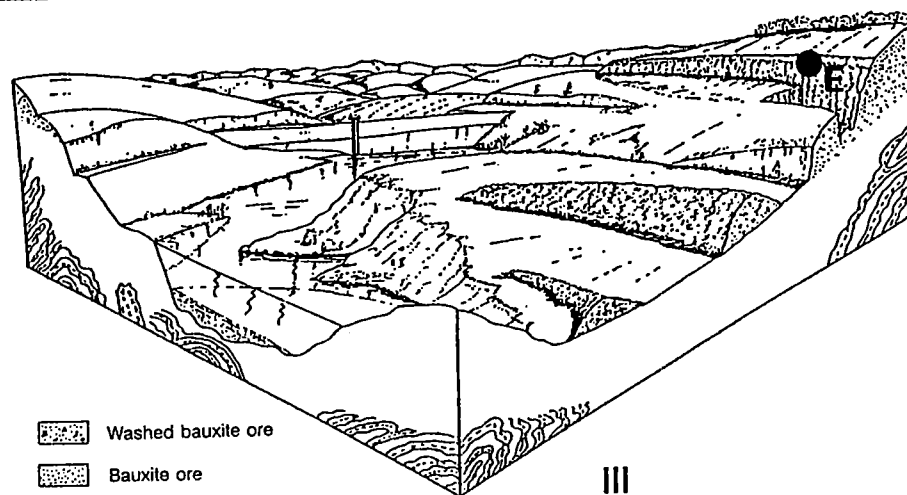
Washed bauxite ore

Bauxite ore

Igneous basic rock

Crystalline metamorphic rock
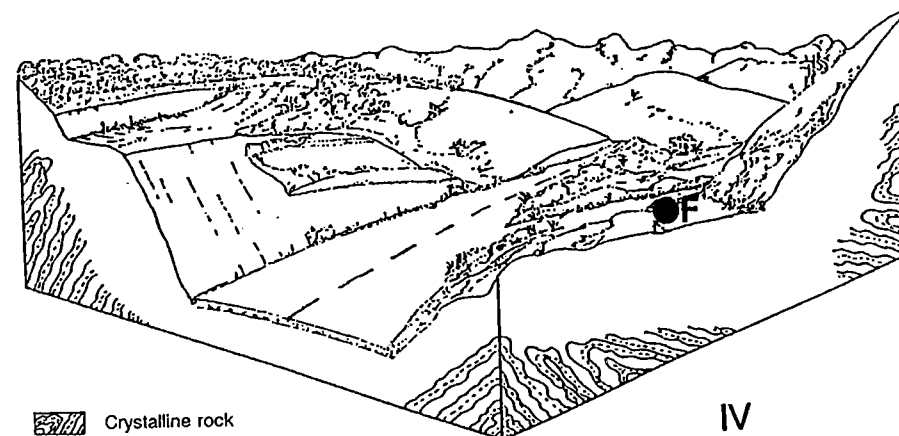
Crystalline rock

Fig. 12 - Four blocks diagrams prepared by S.B. de Rezende, Viçosa, Minas Gerais, Brazil, to illustrate some laterite features in the "Iron Quadrangle". See also Plate C & D.

6 The cyclic nature of the weathering processes and laterite formation

Weathering is essentially any change in composition and material strength of those rocks that are within the sphere of influence of the atmosphere and percolating water. A humid, tropical climate provides the most favourable circumstances for this re-equilibration process, i.e. high temperatures, abundant fresh water (the high rainfall requires good drainage in order to be effective), abundant organic matter and (micro)organisms to rework the earth and to add organic acids to the CO_2 derived carbonic acid, in order to accelerate the weathering process. Add to this the acids that are produced by the oxidation of sulphides, and the seasonal variations in pluviosity, which result in seasonally varying groundwater levels, hence a wide zone with alternating supply or lack of oxygen.

The processes at work are essentially similar to those required for the formation of soils, hence the indistinct boundaries between laterite, plinthite and soil. Products of weathering — be it in highly metamorphosed state — have been recorded in the rock succession from Archaean times onward. Palaeo-saprolites have been reported from the South African Shield, overlying basaltic lavas. Such rocks at present occur in a high temperature, metamorphic facies and generally are of greyish to greenish colour. The chemical composition indicates their 'lateritic' nature through the high Al_2O_3 content, mainly present as the mineral sericite.

These are not freak occurrences either: the Hekpoort basalt (South Africa) is altered in its upper 5 m to a very fine-grained, sericite rock (Button & Tyler, 1979); it covers an area in excess of 100 000 km² (Button & Tyler, 1981). The age of these palaeo-saprolites is greater than 2200 Ma. Generally, also these rocks have a relatively high TiO_2 content, in the order of 2.5% or even more (hence comparable to modern bauxites).

In the Keweenawan of Michigan, USA, peridotites exhibit a weathering profile comprised of a lower zone with dolomite and silica veins, overlain by a leached zone composed of chlorite, vermiculite, and hematite (Kalliokoski, 1975). The uppermost zone is residually enriched in Fe_2O_3 and Al_2O_3. An altered diabase dike, intrusive into the peridotite, still shows the original diabasic lath fabric. Button & Tyler (1979, 1981) report on water-laid rhyolitic tuffs, up to 90 m thick and 2800 Ma old, and porphyritic felsites, 2750 Ma old, altered into pyrophyllitic, respectively sericitic schists. These are a few of the older reports dealing with Precambrian 'lateritic' weathering. Recently, overviews were given by Holland & Zbinden (1988) and Retallack (1990, 1992).

Palaeosols are loci for mineralization (Button & Tyler, 1981) and this mineralization occurs on carbonate formations (chert breccia palaeo-regoliths; Mn and Al enrichment) and metavolcanic rocks (Al, pyrophylite, diaspore enrichment).

Abundant products of lateritization, in essentially un-metamorphosed state, have been recorded from the Carboniferous, from Upper Cretaceous-Eocene times, from the Middle Miocene to the Upper Pliocene, and from the Quaternary period. Lateritization is a process at the interface of the earth and the atmosphere, hence 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 them, in a generally NW direction, completely through the most favourable latitudes for weathering and lateritization. Finally, certain periods had a more favourable climate for lateritic weathering than others — see Fig. 13 (after Frakes 1979 and Haq et al. 1987).

This is an appropriate place to refer to an interesting paper by Tardy et al. (1988), in which a comparison is made between the extensive Laterite Formations in Brazil and South East Africa with those in West and Central Africa. Both Shields experienced — since Jurassic time — equatorial, humid, tropical or arid, tropical climates. However, age, nature and mineralogical composition of the laterites differ widely. In Brazil and S.E. Africa ferruginous cuirasses,
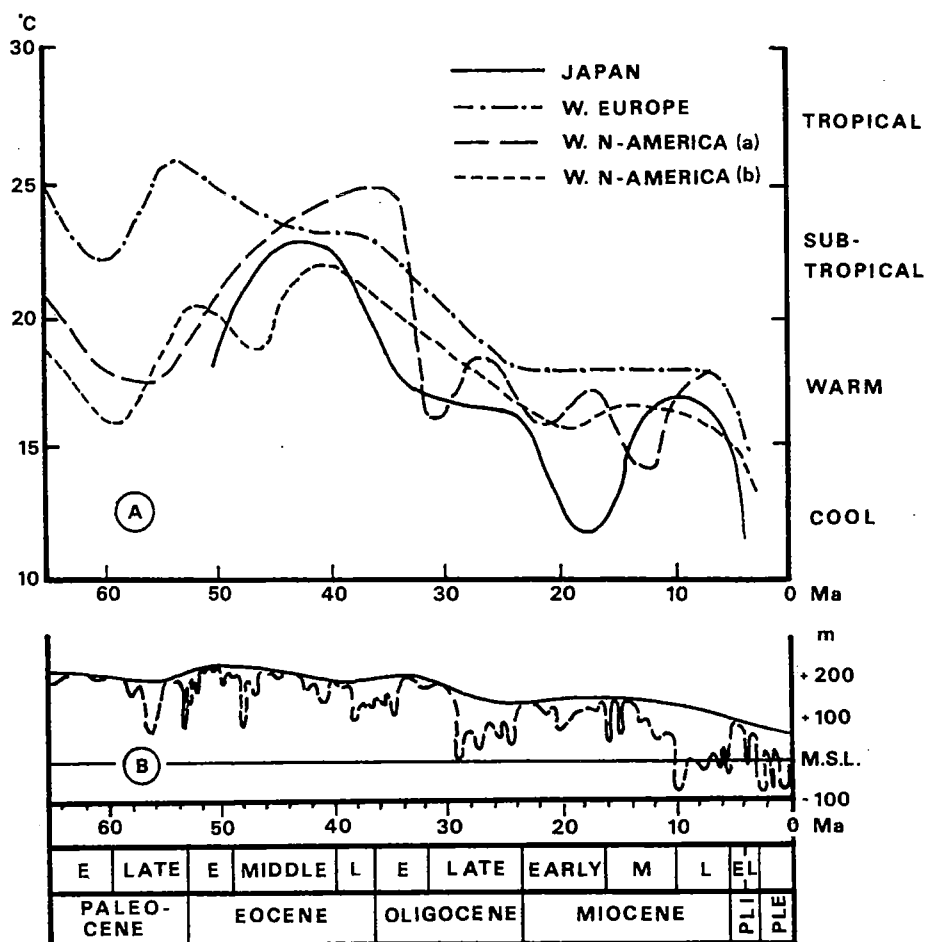
Fig. 13 - Charts illustrating the two world-wide fluctuations during the Cainozoic of the two features that contribute to the prevailing climate.

A. Changes in the mean ambient surface temperature in °C, after Frakes, 1979.

B. Changes in the average sea-level: the heavy line is the long term fluctuation, the broken line is the short term variation; after Haq et al., 1987.

covering the laterite, are scarce but bauxitic accumulation zones are generally massive, without pisoids, and essentially composed of gibbsite, with very little boehmite. This is distinctly different from the abundant, West and Central African laterites, composed of highly ferruginous (hematitic) cuirasses, while the gibbsitic bauxites often do contain pisoids and also contain boehmite.

The authors explain these differences on the basis of the thermodynamic conditions prevailing during the formation of these laterites. The dehydrated minerals hematite (Fe_2O_3) as compared to goethite (FeOOH) and boehmite (AlOOH) as compared to gibbsite ($Al(OH)_3$) are formed preferentially at higher temperatures and low water activity, i.e. when the climate becomes hotter and drier.

The spacial distribution and the mineralogical composition of the older lateritic cover of Brazil and South East Africa are determined by differences in climate at present and the recent past, but also — and in particular — reflect the past climatic evolution around the Atlantic Ocean during the last 150 Ma.

Tectonic plate movements must be taken into account when considering the time span available for the formation of certain laterite/bauxite profiles. The intensity and the duration of the processes will be mirrored in the thickness of the profile formed, and in the completeness of the mineral transformations, taking into account the different susceptibilities of the various parent rocks. Using the stratigraphic column with the estimated ages of the successive periods and epochs — e.g. the one by Van Eysinga (1975) — leads to the time spans available for the lateritic weathering processes in the northern part of South America as shown in Table X (the Guyana Shield, partly after McConnell, 1968 and Aleva, 1984).

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

Period	Age of lower boundary (Ma)	Observed average thickness of laterite/bauxite	Name of topographic surface	Estimated duration of favourable weathering period
Quaternary	1.8	< 2 m	Present surface with plinthite	< 1 Ma
Pliocene	5	~ 2 m	Pediplane level with laterite	~ 2 Ma
Miocene	22.5	< 5 m	Foothill level with laterite	~ 10 Ma
Eocene/Cretaceous	70	5-15 m	Main laterite-bauxite level	~ 25–50 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 an research on the Paragominas bauxite deposits in the Eastern Amazon region.

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

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

Parent rock composition and fabric are important factors in the lateritization process: feldspathoids weather more easily than feldspars, while very fine-grained igneous rocks and very coarse-grained pegmatitic rocks resist weathering compared with fine to medium grained rocks - see Plate F. At similar grain sizes, it can be stated that lateritization is realized fastest in alkaline rocks and arkoses, at decreasing rates through basalts, dolerites and anorthosites to the slower reacting granites and gneisses.

7 Laterites: use and routine description

7.1 Introduction

The complete description of a Laterite Formation is not only a difficult and time consuming task. In view of the very high variability of almost all the essential characteristics of laterites, it becomes even an endless task if not well managed — see Table II.

The interest in — and the uses of — laterite are highly varying, and hence it is common practice that a description is made to include particular facets that are of prime importance for a specific, potential user — or the person threatened by the presence of laterite, e.g. the local farmer. The following list names some persons and professionals that are interested in certain features of laterites:

— Farmer: how to prevent hardening of the soil they till.
— Building contractor: how to determine or to estimate the bearing strength of laterite 'bricks' as locally 'mined'.
— Civil engineer: where to find sufficient road metal or railway ballast, or materials to construct a durable dam or road. If found, how to test the quality for the purpose envisaged.
— Village dwellers requiring a new house or cow shed.
— Survey geologists: how to determine the nature of the parent rock when overlain by 5 - 50 m thick laterite.
— Geomorphologist: laterites of different type protect large parts of the landscape and may be used for correlation over considerable distances. Some characteristics, such as elevation, composition, nature of the crust, may provide a relative age which might be used to establish absolute ages. Certain laterite features may indicate the existence of different development phases, associated with specific palaeoclimates in the geological past.
— Economic geologist: is either interested in the laterite itself, in which case knowledge is required of the chemical or mineralogical composition and the total mass available, counted in millions of tons; or he is interested in what is hidden beneath the laterite, e.g. copper mineralization in the parent rock — Annex VI and VII.
— Mining engineer: requires technical information for mining, such as hardness and moisture content of the laterite, the presence of core boulders, etc.
— Ore trader & process engineer: data on the chemical and mineralogical composition in view of potential users (e.g. TiO_2 content, presence — even in traces — of Zn, Cu, etc.).

Several of these users are looking for only one or a few of the many characteristics of a laterite, and they will evaluate the laterite according to their own needs. Industrial users and entrepreneurs, as in all other capital intensive businesses, want to know at an early date what they may expect from a certain laterite deposit; they want to approach an investigation on the basis of a cost versus yield analysis. A usual approach therefore, is one in which the earlier stages are low cost, but applicable to larger areas (regional or reconnaissance exploration), while the costly, more detailed investigations are only applied to the smaller, more promising areas found during the earlier stages. The following five stages of exploration can be distinguished:

(i) *In the planning office*: this involves a 'desk study' which includes the collection of all data available from published sources such as reports and maps produced by the Geological Survey, aerial photographs, remote sensing data, reports on earlier mapping and exploration exercises, travel reports, Proceedings of Seminars on this or related subjects or on neighbouring areas, SOTER data (World Soils and Terrain Digital Database — a project of the International Society of Soil Science), etc..

(ii) *Regional reconnaissance*: during the first stage, the staff engaged in the project needs to obtain a feeling for their project, for which it is necessary to make one or a few short, but well-planned, visits to the area that looks to be of most importance. During such a first visit, the staff can obtain an impression about the logistics for a larger excursion or an expedition to the area, availability of local guides, possible transport routes, etc.

(iii) *Field mapping*: to collect the necessary data and samples to make possible decisions on the economic and technical feasibilities of the project envisaged, be it mineral exploration, road or railway building, dam site location, etc.

(iv) *Sampling procedures*: decide on the number and type of samples to be taken, in order to obtain sufficient and essential material for mechanical or chemical testing in the laboratory.

(v) *Analytical work*: decide on the technical, chemical and mineralogical data required for the ultimate decision on the viability of the project. Investigate the availability of suitable laboratories and their requirements with respect to the size of samples and sample batches.

(vi) *Selection of analytical procedures*: including the laboratories where such work can be performed on a contract basis. Usually, this will require small numbers of test samples to allow the contractor to make an economically attractive bid.

(vii) *Final office work*: this includes the bringing together of all the data collected, needed to prepare the recommendations for the instigators of the exercise, i.e. the company directors and the shareholders. This last report should be kept in mind while the work is in progress, in order that there is sufficient illustrative material available to make it interesting and informative.

7.2 The regional approach

"Field mapping (R.R.A. & R.E.S.) − an Australian perspective.

In lateritic terrains, the combined effects of prolonged deep weathering under humid conditions followed by differential erosion and chemical modification under arid and semi-arid conditions, have led to a great variety of materials exposed at the land surface and to intricate regolith-landform relationships. It is important for mineral exploration and assessment and for studies of genesis to establish an understanding of the various terrain types which have resulted from this complex regolith evolution. This can be achieved by mapping the regolith, to establish the regolith stratigraphy, and to study the mineralogy and geochemistry of the regolith to explain its origin and associations. Regolith mapping is more easy to do where vegetation is sparse than in forested areas.

In designing an approach to mapping the regolith, it is necessary to keep in mind the purpose of the mapping and the users of the resultant map. The mineral explorer needs information on the nature, distribution and genesis of various regolith types, correlations between various regolith units across the landscape and associations between the regolith and the underlying bedrock. Land-users will be concerned with those aspects that interest the mining industry as well as those aspects of the regolith that influence land usage, including degradation and environmental fragility.

The required regolith-landform control for mineral exploration is provided by carrying out regolith-landform mapping, establishing the regolith stratigraphy within the main mapped units and, through synthesis, building a regolith-landform model.

The area is mapped into regolith-landform units, based on field traverses and inspection and interpretation of aerial photographs, airborne radiometric surveys, where available, and satellite imagery such as LANDSAT TM. Mapping units are based on the laterite profile and its erosional modifications. For some regions or districts, the premise can be made that the

landscape was originally extensively mantled by a laterite profile and the present land surface is the result of long-continued differential stripping, movement and sorting of detritus, resulting in exposure of a variously weathered to unweathered substrate.

Air photo patterns form the basis of mapping. They are largely related to the variable influence and interaction of geology, soil, vegetation and landform. These pattern are referred to as *regolith-landform units**. These are defined as areas delineated from air-photo interpretation, represented on a map, and within which a chosen association of surface regolith materials and land forms occur. These can be distinguished in mapping, at the scale chosen, from adjacent areas which have been defined using the same principles. The scale of aerial photos being used will influence the choice and definitions of regolith-landform units because of the practicality of representing heterogeneous assemblages of regolith-landform associations. The more detailed the scale becomes, the more the mapping units become regolith-, rather than landform-based.

From a mineral exploration point of view, it can be useful to consider laterite landscapes in terms of residual, erosional and depositional regimes - where focus is on preservation and truncation of the laterite. These regimes are broader terms than the regolith-landform units described above. *Residual regimes** are broad mappable areas characterized by preservation of the laterite. *Erosional regimes** are those areas where erosion has removed the laterite to the level where the mottled zone, clay zone, saprolite, saprock or even fresh bedrock are either exposed, concealed beneath residual soils or beneath a veneer of locally-derived sediments. *Depositional regimes** are areas characterized by substantial accumulation of sediments."

7.3 The Laterite Formation described

There are three stages in the description:
— In the field, where the basic data for all further work is collected. An error or omission made here, can only be rectified by returning to the spot, which may be prohibitively expensive.
— In the laboratory there is often a broad choice of different tests and methods of analysis. It is economically important to select the minimum number of analyses to be made, but these should cover all the essential aspects required for the particular assignment and meet the terms of reference within which the work is taking place.
— In the office, the essential data and the outcome of the investigation must be summarized and presented in a concise and clear final report. This should preferably contain some photographs of the area and of the outcrops sampled, and include a good map of the investigated area (with an index map to show the location of the fieldwork area).

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

The book 'Field Geology', by F.H. Lahee, 5th edition in 1952, although old fashioned still might be of use where fieldwork has to be done in remote areas and modern electronic instrumental surveys are unavailable.

7.4 In the field (Annex VI)

The description starts with defining the geographical location of the object.
— Give X, Y, and Z of the outcrop studied, using the national geographical coordinate system.
— 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, the vegetation, and the climate. See e.g. the "Guidelines for Soil Description" (FAO, 1990) for descriptive terms for the landscape and the lay of the land. State the representativeness of the survey site for the surrounding district.

The laterite profile description may include the following tasks:
(i) Describe macroscopically the Laterite Formation, starting with an overview and proceed stepwise to more details:
— the profile as a whole;
— number, thickness and character of the discernable layers and zones, the presumed (weathered) parent rock to be considered as a layer as well;
— description of each separate layer with colour, structure, fabric, including voids (use hand-lens!), mineralogy as far as possible with the hand-lens only, nature of contact with the underlying layer and horizontal changes within the layer.
(ii) Next, it must be decided what samples should be collected for future use in the laboratory. This concerns specimens of all rock layers and zones described (each with its position within the layer, and the analytical work proposed).
(iii) Take photographs e.g. from the total vertical profile and from each of the layers separately; prepare the face of the outcrop for photography by placing a measuring staff (graduated in cm, dm and m) for scale, and place numbered cards or boards at the places where samples have been taken. If colour photography is being used, place also a standard colour reference chart or colour-striped tape to guarantee correctly coloured prints later.
(iv) Collect a monolith, if so desired and planned — see ISRIC publication: Technical Paper No. 1 (1979).
(v) Make a bore hole, or dig a pit or channel, in places where the lower layers are not exposed, either from the top of the Formation, or from a position at the foot of the outcrop slope.

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

There is one structural/textural unit that warrants specific mention: the pisoid* (or pisolith) which, when occurring in great abundance, forms the rock called pisolite* (PLate H and I). It is suggested in the laterite context to use the term pisoid (Simone, 1981), in order to prevent confusion from the calcite pisoliths found in many limestones. Pisoids may range in size from say 3 to 30 mm; they are generally well rounded, and contain a massive core or nucleus, surrounded by a cortex composed of many, thin, concentric and colour-banded layers. Cortex and nucleus range in colour from white to black, with in between all shades of yellow, pink, red and brown. Some pisoids have a more complex structure, with a core composed of a number of small pisoids or pisoid fragments, which are enveloped by the outer cortex. Diameter of core and thickness of cortex vary greatly: some pisoids are mostly nucleus, with a cortex not much

thicker than a coat of paint, while other pisoids are almost without core (See e.g. Bárdossy & Aleva, 1990, from which Annex II-c is borrowed). Well rounded nodules without a core-cortex structure should not be described as pisoids. The frequency of occurrence of pisoids is also highly variable: there are large deposits without pisoids like the bauxite deposits of Onverdacht, Suriname, South America (Aleva, 1965), and the deposits of the Eastern Ghats, India. But there are also huge deposits that consist entirely of pisoids such as the bauxite of Weipa, Queensland, Australia. The chemical and mineralogical composition of pisoids is highly variable, from mainly gibbsite to mainly hematite and/or goethite. In some deposits the majority of pisoids have a nucleus with a septarian type of cracks, generally filled with gibbsite.

7.5 Sampling: from field to laboratory (Annex VI)

A sample has been defined as: "part of a whole taken to show what the rest is like" (Concise Oxford Dictionary). When this definition is compared with the characteristics of laterite — see Table II — it is obvious that sampling laterite is a very risky business. This risk can be reduced in several ways:

(i) Take relatively few large samples, crush and mix the material thoroughly, and take in a technical correct way (see P. Gy, 1982) a much smaller sub-sample from the ground material.

(ii) Take many smaller samples, but in a systematic way to ensure that any larger part of the laterite deposit is represented in this sample. Again crush, mix and sample this mass as above.

(iii) Take systematically placed samples, i.e. place an imaginary geometric grid over the deposit to be sampled, and take a sample of standard size/weight from each grid point.

Industrial sampling generally employs an adapted form of (iii), i.e. make bore holes, with the holes situated according to a rectangular grid, and sample the material produced from each hole in a systematic way, e.g. by separating the material obtained from each successive metre or 6-feet penetration, crush to less than 5 mm grain size, and thoroughly mix this material (use e.g. a small, motor-driven cement mixer), and take a fixed part from this mixture as the sample representing that part of the hole. In a similar way a small sample can be produced that represents the complete drill hole.

At each step of the sampling procedure, care must be taken that no *systematic* errors are being made. During resampling of a large bauxite deposit in the Eastern Ghats, India, an interesting systematic error occurred. For the purpose of a final feasibility study, the samples were taken by core drilling — probably the best way to sample a hard laterite in a statistically correct way. The first results gave unexpectedly low iron contents, which led to a detailed inspection of the procedures. It appeared that moving a piece of the, by then, dry core from one core box to the next — or to the sample treatment instrumentation — left a distinctly visible amount of iron oxide powder in the original core box! The core, when taken from the core barrel, was still in a moist state and hence no losses occurred, but after some time the core dried out, whereafter the very fine iron-oxide powder would fall out of the porous core to such an extend that a serious sampling error was created.

7.6 In the chemical/mineralogical laboratory (see Annex V and VII)

The technical literature on chemical and mineralogical investigation is extensive, while the progress in the various mineralogical and chemical methods and procedures is rapid. Annex V gives an overview of some of the analytical methods that are available. Annex VII contains expert technical advise and suggestions, from scientists active in SW Australia in the study of laterites in the widest sense.

The following remarks may seem superfluous, but . . .

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

Chemical analysis used during exploration activities for mineral deposits (bauxite) should adhere to the specific requirements and conventions of the relevant industry. For all lateritic rocks this includes careful drying at a temperature not higher than 105°C — and not longer than necessary — in order not to destroy the OH-group contained in the Al and Fe minerals (gibbsite and goethite).

In case of bauxite, this includes mainly the necessity of a double silica determination, i.e. separate determinations of the silica contained in kaolinite (= reactive silica), and that present as quartz and unweathered or only partly weathered silicates, e.g. staurolite. This is generally realized by using a tri-acid solution to digest the sample aliquot (instead of using a melting procedure with aggressive agents such as Na_2O_2, caustic soda or Na-K-pyrosulphate). In this solution the kaolinite mineral is decomposed while quartz and remaining rock silicate minerals are not attacked. The quartz SiO_2 is determined afterwards through weighing before and after an HF treatment of the precipitate to remove the quartz present, while the original rock silicates are reported as insoluble rest. Total silica is determined by physical analytical methods and the reactive silica is subtracted.

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

temperatures are approx. 150°C and approx. 250°C, depending on the presence or absence of boehmite.

Before a laterite — or any other rock — sample can be chemically analyzed, it must be crushed and ground to a sufficiently small grain size so that complete chemical reactions can take place within a relatively short time span, i.e. the material must be ground to minus 150 μm = 0.150 mm = 100 mesh. This fine grinding is a job that requires specialist experience. If a choice is available, the sample preparation in the field should not go further than circa 1 mm ∅. The final fine grinding can generally be done on contract by the analytical laboratory — but check their procedures! A source of information for alumina-related analyses, etc., is the annual Light Metals Yearbook of AIME, USA.

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

Truckenbrodt et al. (1991) studied in detail the laterite/bauxite deposits of the Lower Amazon area in Brazil, trying to establish the origin of the 5-10 m thick clay layer covering the accumulation zone. They did not succeed in arriving at a definite answer to this question, but they established that the parent rock, the laterite/bauxite accumulation layer and the overlying Belterra clay are geochemically clearly related, but differing from place to place. Geographical trends in the geochemical composition of the parent rocks recur in the geochemical composition of the accumulation layer and in particular in the covering Belterra clay. This vertical correlation is so close that the authors suggest that geochemical analysis of the top layer can be used for the prospecting of (metallic) mineral deposits in the saprolite and in the parent rock, circa 15-20 m below the present surface. Hence, they suggest that the above relation could be employed as a mineral exploration method to "look through" the laterite cover. See also examples in Butt & Zeegers (1992).

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

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

When a translation of the chemical composition into the mineral composition would facilitate the understanding of the rock forming process, mineralogical analyses can be substituted by petrochemical computations (norm* computation), provided that reliable chemical analyses are available and a differentiation has been made between total silica and free silica (=quartz) (Van der Plas & Van Schuylenborgh, 1970, Bárdossy & Aleva, 1990). It must be realized, however, that e.g. the irregular distribution of aluminium, as traces in other minerals such as aluminous goethite, may confuse the computational results.

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

Sampling required for the density determination of laterite has its special problems. 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. Therefore the moisture condensed upon the walls of the containers must also be collected.

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

When more detailed information, e.g. layer by layer, is required, one sample should be taken from each layer, and where layers are thicker then 1 metre, a sample should be taken from each successive metre. The sampling slits preferably have a rectangular isosceles triangular cross section (with the 90° angle digging into the laterite wall; use a metal or plywood template to check the cross-section on shape and size — see Chapter 8, fig 14). The *in situ* density figure of each sample must be accompanied by a figure for its moisture content. The (dry) density may vary between 1 (Fe-poor bauxite) and 3 (for iron-rich laterite), average values (dry) will vary between 1.3 and 1.8.

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

7.7 In the office

A summary report should be prepared which must include the objectives of the exercise, the duration of preparatory work in the office and of the actual field work, and the staff and labour force employed. The technical part deals with the mapping and sampling procedures, techniques employed, sample treatment and analyses (including methods used).

The report must be accompanied by topographic and geological maps of the area, and by at least some drill hole sections to illustrate the laterite profile. Be sure to mention the way and the location where all the primary data and the samples are stored for safekeeping, including the key words by which the detailed data can be reclaimed from the files, and the location - with box or drawer number - where any duplicate samples are stored. All data and duplicate or character samples must be safely kept, at least until exploitation of the laterite reserve has been completed.

8 Artificial exposures for geological and engineering purposes

8.1 Pitting and sampling

The highly variable nature of laterite is such, that closely spaced sites of observation and data collection are needed when considering mineral exploration, planning excavations, or executing civil engineering work. Depending on the intended purpose, this may require digging of pits and trenches, the excavation of shafts, or drilling a borehole, to produce artificial outcrops. There are many successful methods available for creating such exposures — see Annex VI — 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 relating to local situations. Before deciding on the use of artificial exposures, the following points should be considered.

Sampling geometry

Generally, artificial outcrops will be small in size or volume, as they are expensive to produce. An advantage over natural exposures, however, is that their location may be chosen, e.g.:

— *Grid sampling* is advantageous for larger areas: the sample sites can be arranged on a square or other type of geometric grid, which allows systematic sampling and, by decreasing the size of the grid mesh, increasing the sample density in accordance to the results required. The Geostatistics theory may assist in the correct determination of optimal sample density, at least for that one deposit, as optimal sample density depends on the value distribution within each specific deposit.

— *Corridor sampling*: following a proposed trace for a road or rail, either by sampling short cross lines at fixed or variable distances, or by sampling along the axis of the proposed construction.

— *Site sampling*: one or a few preferred locations for a major building are tested by grid sampling or a few excavations or drill holes to determine the most advantageous of the sites contemplated.

The number and type of samples

These must be related to the questions posed. A bauxite mine may require several hundreds of sample sites, as the chemical composition is the characteristic to be sampled, and in laterites the chemical variation is usually very high. Where construction work is concerned for a house or a larger structure, the characteristic to be sampled may be e.g. bearing strength, which could be determined with a much smaller number of sample sites (but do not rely on one sample site only!). The type of sample required — undisturbed or disturbed — depends on the analytical methods to be employed:

— For geological descriptions, micromorphological investigations and genetic considerations undisturbed samples are essential.

— For chemical or mineralogical testing any type of representative sample can be used, as long as no extreme heating and drying occurs during sampling.

— For determination of the physical characteristics of the material, undisturbed samples are necessary, without changing the grain size, structure, natural moisture content, permeability, etc.

— The total size of the samples depends on the tests envisaged.

The depth from which the samples are taken and the total sample volume needed is critical. The need for one sample of 1 dm^3 from 10 m depth or of 50 samples of 10 dm^3 from 1 m depth,

makes a considerable difference to the method of sampling and the cost involved per sample. See Annex IV, after Bárdossy & Aleva (1990).

The equipment required at the site

— Pitting can be done in any place that can be reached by a geologist or engineer: on foot, by boat or truck, or even by helicopter and fixed wing airplane. The equipment required is minimal: bush knife, spade, pickaxe, crowbar and a pail or wicker basket will suffice. The air-tight containers for storing and shipping of the samples required for the determination of density and moisture content should not be forgotten.

— Trenching is essentially no more than a pit extended horizontally to many metres. Hence it can be used just as universally as simple pitting. A mechanical backhow is an ideal instrument for trenching, and such machines are generally available and in variable sizes.

— Drilling machinery varies from hand powered auger and sand pump drills (Banka, Empire drills) to highly sophisticated diesel engine driven equipment, with hole diameter varying from 4 cm upward to at least 15 cm, and samples in the shape of irregular cuttings (rock chips) in particles of several millimetres diameter, to solid cores of up to 15 cm and more in diameter. Removal of cuttings can be effected by compressed air, foam or just plain water, but the latter is not advisable for laterite, as this is a material often quickly dispersed into clay particles that are easily lost with the circulating cooling and flushing water.

— Augers come in a very large number of sizes and models, depending on the material to be sampled, the depth to be reached, the requirements of the ultimate sample, and the type of sample to be obtained. As to the latter, there are almost as many auger designs as there are types of materials to be sampled by auger.

Shaft sinking and tunnelling

These are extreme examples of artificial outcrops; they also may provide a superior quality of outcrops for study and sampling. However, shafts and tunnels are expensive to produce (lining of the walls, roof support, hoisting of excavated material) and require constant supervision by a qualified (mining) engineer. Government regulations must be followed to the letter to safeguard the lives of the labour force and the capital investment of the enterprise.

In respect to sampling, shafts are very similar to pits, particularly when it can be done between the drilling, blasting and mucking shifts of the mining crew, especially when the wall to be sampled can be reached by short ladder from the shaft bottom. Otherwise, the sampling has to be done at a later stage by a geologist to mark the sample sites and by — preferably at least two — samplers. These men or women have then to be lowered from the surface, sitting on a boatswain's chair, by a competent hoisting crew. The sampling of an existing shaft is a notoriously difficult job.

The actual taking of the sample

The size and number of samples to be taken is directly related to the purpose of the sampling exercise:
— ore reserve estimation;
— chemical or mineralogical analysis;
— rock mechanical tests for mine development, etc.

During the early stages of an investigation, the number of outcrops is limited, hence most sampling will be through pits, shafts and drill holes, and such openings have relative small surface areas. By using the full length of the artificial opening, the two main objectives of the

sampling can be achieved: the best possible representativeness of the samples and sufficient sample material to perform the mineralogical and chemical tests envisaged.

The total amount of sample material obtained may need to be reduced to manageable quantities. This can be done by using a small part of the surface area or cross section of the opening. For this purpose drill cores are often split lengthwise in two or four parts, of which only one part is used for further study. Pits and shafts usually are sampled by cutting a groove along the full length of the wall, collecting the cuttings from this groove as sample — see fig 14A.

Formations thicker than say one metre are usually sampled over successive distances of one metre or less, depending on the required accuracy and the average thickness of the layering. Sampling theory requires that all samples have the same 'support' (Gy, 1982), which generally translates in a similar cross-section and length for samples employed in the same computation. This theory also states that successive layers of different composition should — as much as possible — be sampled separately.

Nature does not adhere to any measuring system, hence, systematic sampling will always result in a number of samples that are not conform to the sample length selected — which is often 1 metre. Fig. 14B illustrates a number of sample strategies for a layered laterite deposit. The choices to be made will depend on the costs of analysis per sample, the accuracy required, and the inherent variability of the deposit in horizontal and vertical direction.

Technical and professional advice

This should be sought before embarking on any larger scale programme of creating artificial outcrops. In particular for larger (and deeper) programmes, it is essential to establish the minimum requirements needed for number, size, type and depth of samples to be taken, and to estimate the material characteristics of the soil/rock to be sampled. A literature search will show that for the most varying characteristics of soils, rocks and related material, somebody will have designed the ideal sampling tool (soil sciences, geology, material characterization, soil engineering, etc.). Annex IV provides an introductory summary of some different types of artificial exposures, including six types of drilling procedures.

Additionally many countries have laws which control pitting, trenching and shaft sinking. Adherence to these regulations is essential for any enterprise and its supervising professionals, as legal actions after a breach of the law can be severe.

It is a commendable practice — even where not required by law — to fill in any artificial opening made in the country side, before leaving the area and giving nature the chance to hide pits and open shaft collars by new under or overgrowths.

8.2 Geotechnical aspects of laterite

"In civil engineering the confusion regarding laterite has been caused largely by the tendency to apply the term to any red soil or rock in the tropics. The numerous attempts made at defining and classification to enable engineering behaviour to be predicted, have been less than satisfactory because the term has been so loosely applied. Equally, the concept of self hardening has persisted even though the granular lateritic materials most useful for pavement construction rarely display this characteristic" (Charman, 1988). Additionally, in civil engineering practice soil is any naturally occurring mineral material that can be excavated without use of artificially induced fragmentation (i.e. blasting). Hence, this practice could exclude an important, and probably in the engineering context, the most useful part of a true laterite deposit.

Finally, the confusion between true, i.e. residual, laterites and any other more or less reddish, more or less hard and/or nodular 'soil' material of non-residual nature aggravates the
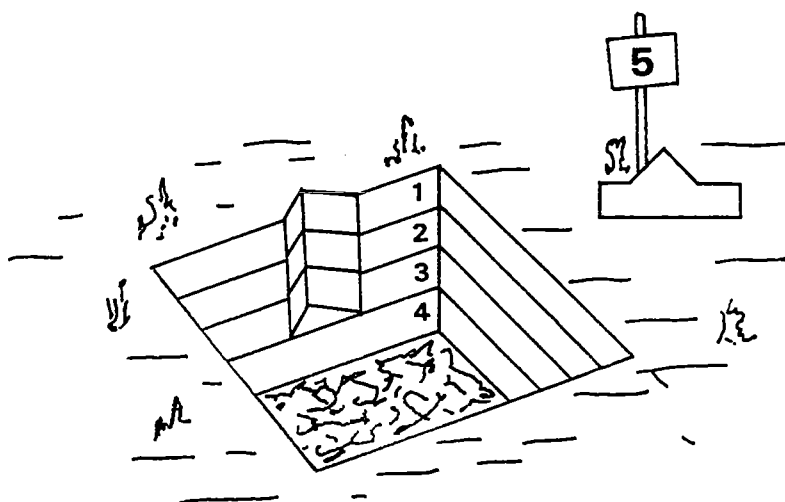
Fig 14A - Sketch of pit number 5 being excavated and sampled at 25 cm interval. The samples 1, 2, and 3 have been taken. The channel shape — and hence the sample volume — has been checked with the template standing against the number peg.

The next action is deepening the pit with another 25 cm, followed by taking sample 4. A piece of board or a tarpaulin is spread on the pit floor to collect all the loosened material of the sample 4, without mixing it with material from the pit floor.
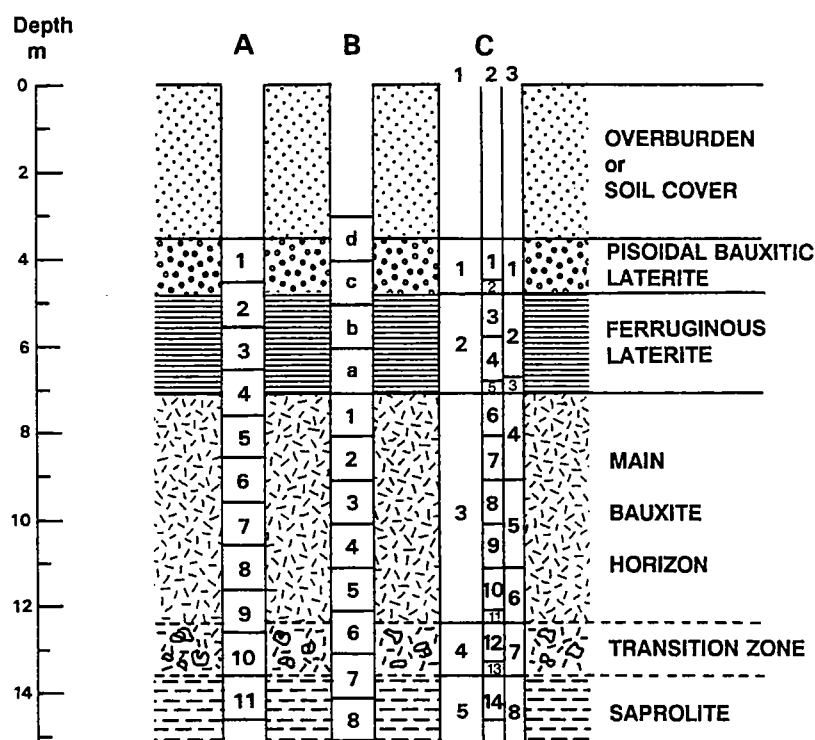
Fig 14B - Chart of a hypothetical Laterite Formation, sampled with three pits, shafts or drillholes A, B and C. For each of these holes different sampling strategies have been used.

A: Metre by metre throughout, starting directly below the soil; a number of samples straddle the boundary between two different layers.

B: Sampling done after the hole was completed, hence the sampling could start — upward and downward — from the top of the main laterite bed.

C: Sampling based on lithology, layer by layer, and three different strategies are shown:

   C1: Just one sample for each lithological unit.

   C2: Again sampled by lithological unit, but with 1 metre samples, resulting in short rest samples for each unit.

   C3: As before, only the sampling unit has been taken twice as large, hence less samples in total.

difficulties for the civil engineer. The correct differentiation between laterite, plinthite, ferricrete, petro-plinthite, petroferric phases, skeletal phases etc. is essential for an understanding of the material characteristics.

"The general problem facing engineers dealing with any type of soil in the tropics is that we are working in darkness. We have brought down "temperate zone soil tests" and are applying them blindly to tropical soils of which lateritic materials constitute a major one" (M.D. Gidigasu, pers. comm., 1992).

Some recent publications on the engineering uses and practices concerning laterites are the following:

— Tropical Residual Soils, Report prepared by the Geol. Soc. Engineering Group Working Part (EGWP, 1990, 101 pp);
— Laterite in road pavement (Charman, 1988), a publication of the Construction Industry Research and Information Association (CIRIA), spec. publ. 47 (71 pp).
— Several conferences on the mechanical aspects of residual soil in tropical terrain have been held (see references to the Proceedings Honolulu, 1982, Brasilia, 1985, and Singapore, 1988).

The following paragraphs are contributed by A.M. Kruse, Delft Geotechnics, Delft, The Netherlands.

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

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

Characteristics of the excavated material are many; notable characteristics are:

— bulk density
— compaction and densification behaviour
— abrasion and erosion behaviour
— permeability of reworked material
— lateral and vertical variation of properties at the borrow site.

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

The engineering properties of laterites are generally understood to be determined to a large extent by:
  (i) cementation within and between aggregates and particles by various agents, and
  (ii) by the pore-system in the material.

For the strongly deformed and excavated material, the properties are also determined by the properties of the individual particles and aggregates. The properties of the mineral phases present in laterites are notably those of iron and aluminium oxides and hydroxides, and of kaolinite.

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

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

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

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

The vertical variation found in a laterite profile requires detailed sampling to establish its mechanical properties. This is the more so in polycyclic landscape environments. The properties of laterites will change as ambient conditions change since water content and mineralogical changes will occur. These short and long term changes will have to be considered in designing constructions upon and with laterite. When using excavated material attention must be paid to the variability at the borrow site and to changes upon excavation. See also Charman (1988)".

9 Suggestions for further research

There are a number of points that emerge for further research; studies that could increase the understanding of the processes and environmental parameters that lead to the formation of a laterite profile:

1. The feature of *self-hardening* of laterite that occurs in certain laterites, and that through the ages has proven to be so beneficial to the living standards of a wide range of people: houses for farmers, village people, etc. but that also led to the construction of palaces and in particular of fortresses, e.g. the fort São João at Macapá, Brazil, built in the 17/18th century to protect the Brazilian coast against incursions by the Dutch, French and British. Alexander & Cady (1962; see also Chapter 2) report that 15 years of wetting and drying produce a hard crust of 2 cm thickness, but thirty years later the cause of such hardening is still not fully understood. Sivarajasingham et al. (1962) include this characteristic in their description of a typical laterite − see Chapter 2.

2. The relation between *laterites and soils*. Laterites are not soils in the present-day meaning of a soil. However, the processes of soil formation could be similar in kind to those of laterite formation, if not in results expressed in the minerals formed. If so, what are the differences that produced materials with such highly different characteristics? Long exposure to a more extreme climate, a flatter landscape that prevented near-horizontal transport of weathering products, other types of organisms and vegetation are a few possibilities which can be mentioned.

3. *Absolute dating* of the Laterite Formation or the formation of laterites. Bird & Chivas (1988), have done some work on isotope ratios ($^{18}O/^{16}O$ and D/H) to determine the age of formation of the kaolinite and gibbsite in laterites, but no positive results of those studies are mentioned, other than the difficulties in correlating oxygen ratios with other time markers, in particular climate.

4. Many major thick and of very extensive occurrences of laterite (bauxite) deposits were formed on *stable, old cratonic areas*: Peninsular India, Central Africa, NW Australia (Mitchell Plateau), the Brazilian and Guyana Shields in South America. Before the lateritization processes started, these areas had been reduced to extensive planation surfaces on which little horizontal transport of matter could occur. The bauxite deposits in the centre of the Amazon valley, however, are formed on a thick sedimentary succession, within an area of long continued subsidence!

Johnson (1992) proposed a multi-tiered slope development as the universal profile for sloping areas, resulting in denudation and horizontal transport of weathering products. Laterites could be the counterpart of surface development, related to areas without sufficient slope to allow horizontal movement of particulate matter.

5. *Pisoids**. This term proposed by Simone (1981) is here used to differentiate these spherical bodies with concentric banding clearly from the radial fabric of $CaCO_3$ pisoliths of marine derivation.

Any study will have to address the following points:

    I - The different type of spherical bodies:
        − massive spheres with very thin outer skin;
        − spherical bodies with a fine, 'sandy' fabric, surrounded by a thin outer skin;

— a massive nucleus surrounded by a finely banded cortex, with a highly variable ratio of nucleus radius to cortex thickness;

— multiple or "mother" pisoids (MacGeehan, 1972).

II - The place of occurrence of pisoids within the laterite formation:

— The total laterite is made up of pisoids (loose in Weipa, Australia, cemented together elsewhere);

— pisoids occur in certain zones, e.g. the upper, reworked zone;

— pisoids occur throughout the total mass of the laterite, independent of relict fabric or structure, e.g. Mitchell Plateau, NW Australia;

— pisoids occur irregularly and often widely spaced within a more or less massive laterite: Gujarat, NW India, Arkansas, USA.

III - Frequency of occurrence within a laterite formation:

— Less than one pisoid per Mt of laterite/bauxite (e.g. Coastal Plain of Suriname);

— 100% of the laterite formation is made up of pisoids (e.g. Weipa in NE Australia);

— pisoids occur in certain zones, e.g. in the reworked, upper crust of the laterite formation (Boulangé, 1984).

IV - Origin:

— The formation of pisoid bodies is the result of reworking at or near the surface of the laterite formation (Boulangé);

— the formation of pisoids is in one way or the other comparable with the formation of e.g. silica nodules in a limestone; but see also MacGeehan (1972).

6. Polycyclic profiles: this term is frequently used but it is often not clear what is exactly meant. There are at least two scenarios:

— An existing laterite profile is, after a certain period with a climate unsuitable for lateritization - too dry, too cold - again subjected to environmental conditions that promote the formation of laterites: for example the successive lateritization periods in the Guyana Shield, each later period - at intervals of 20 to 40 Ma - produced on a lower topographic surface a newly formed laterite zone. What has been the influence of these changes on the already existing laterites at higher levels? Presumably, the earlier laterite zones were again subjected to lateritization processes, but these are difficult to distinguish. The effect could well have been a continuation of the process of lateritization, resulting in an increased thickness of the already existing laterite profile. Could it be that the bauxite vein crosscutting bedded bauxite from Onverdacht, Suriname, has been formed as result of such repeated lateritization (pers. comm. P.K. Banerjee, 1992) — Plate B: 1 & 2.

— A laterite profile is in the process of development, and a laterite zone of - say - 6 m thickness has been created. The environmental parameters for lateritization deteriorate strongly, the process of lateritization halts, and alteration processes start in an opposite direction (e.g. gibbsite —> kaolinite). After some time, the environmental conditions return to the original, lateritization promoting situation. It would be interesting to know how the original and retrograde mineralogy react on this return to lateritization promoting conditions.

However, the retrograde mineral transformations (e.g. gibbsite —> kaolinite) could well be proceeding much slower (low temperature, dryer atmosphere) than the prograding changes. In this case the reversal is actually no more than a relatively short period of standstill, without actual production of a retrograde mineral paragenesis so that the relatively short period with an adverse environment would not be clearly recorded in the present day laterite profile.

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The question then is how much time is needed - and how severe must the environment be - to produce a retrograde mineralogy that can still be observed or determined after the next period of lateritization has had its chance to repair the damage inflicted.

In Onverdacht, Suriname, the retrograde changes (veining of bauxite by kaolinite with metahalloysite, Plates G and J) are clearly visible, but these profiles have been covered by younger sediments or the ocean, before the next laterite producing conditions returned.

A note of caution must be given: what is known as pedogenetic laterite is not a true laterite, but a ferricrete*, i.e. a gravel (an unconsolidated, natural accumulation of rounded rock fragments - of any composition - resulting from erosion, consisting predominantly of particles larger than sand - GG) cemented by iron derived from uphill sources (topographical higher levels), the iron of which could have been - but not necessarily has - derived from an older laterite in the process of (chemical) break down.

Postscript

The compiler has tried to be neutral and even-handed in discussing the many views regarding laterite, lateritization, plinthite, soils and associated rocks, and their processes of formation. As a result there is no consensus about laterites, what they are or represent, or how they could be incorporated in a more general scheme of earth history. The following remarks give a purely personal opinion on some outstanding points of discussion.

A short history of laterite as a rock name: the corruption of a scientific idea.

1807 — The medical doctor Buchanan reported — on a few pages of his 1500+ page long report on a journey along the West Coast of Peninsular India — on the occurrence of a strange rock, locally called itch-stone because its surface may look as a seriously diseased human skin. It was quarried for building stone, so he suggested the name 'laterite'. His description links the occurrence of laterite to the granites in the area.

1844 — The Captain (J.T.) Newbold, MNI, FRS, Assistant Commissioner at Kurnool, reported on an E-W journey through the northern part of Peninsular India. He observed massive laterite beds, which he compared with the Old Red Sandstones of Scotland. The laterite, occurring as a 100 - 200 ft thick blanket, caps all the hills and mountains in the area around Bedar (Bidar); this table land is at an elevation of circa 2400 ft (730 m). Newbold also described laterite talus at the foot of the hills, loose or reconsolidated, and which is difficult to distinguish from true laterite. He treats laterite as a common feature that does not require any introduction.

1889 — J. Walter, in an oral report on his journey to "Ost-indien" (i.e. India) to the Gesellschaft für Erdkunde, Berlin (1889), stated that laterites are the weathering products of Deccan basalt (brick red) and granite gneisses (pale red to whitish yellow in colour). The *in situ* process of the product is clear, the process starts along cracks and fractures. After erosion and denudation the origin is more difficult to establish, as the material is further weathered and leached, it becomes cellular while also 'bean ores' (concretions) are formed.

1897 — G.P. Merrill, in his 'Treatise on rocks, rock weathering and soils', discussed the regolith and its components, which he divided into Sedimentary and Transported. The sedimentary forms encompass Residual and Cummulose deposits, the Residual deposits include gravels, sands and clays, wacke, laterite, terra rossa, etc. He then distinguished High level laterite, overlying the Deccan traps, and the Low level laterite overlying gneisses and granites [hence following the Indian descriptions]. He then stated "Origin of both high and low level forms of laterite has been the subject of much speculation. It is probable that all of it is of residual nature, i.e. represents the loss of soluble portions of pre-existing rock masses." And also "a part of the material, however, has the appearance and structure of a clastic rock of sedimentary origin, and so it is considered by the best authorities to be".

1898 — G.C. Dubois reported in 1903 on a visit to Suriname, where he observed laterites. He distinguished two groups of laterites: Eluvial and Alluvial. He states that free silica (or quartz) is not a product of the lateritization process, and that only the silica bound to metal oxides should be taken into account.

1915 — J. Walther described laterite profiles observed in Australia: the basement rock, with their folded schists, are overlain by white clays with greenish and yellowish partly weathered patches; relict structures are abundant. Higher in the profile relict structures appeared in a white clayey mass, a 4-8 m thick 'bleach zone'. This gradually changes upward into a 'Fleckenzone' with red, brown, yellow, blue and violet patches the size of a human head, and with the same hardness as the surrounding white clay; locally they are somewhat harder and then appear in relief. Starting from these concretions the iron crust is formed, the loose concretions coalesce in upward direction to a continuous mantle of red to reddish brown iron oxides, the 'iron crust', which covers the profile as a continuous hard crust or plate. Walter called this process in its

totality lateritisation.

1962 — Alexander & Cady reported on their fact-finding mission through West Africa and summarized their findings in a short statement, which included the sentence "laterites are an end product .....of processes taking place over large parts of the earths surface". They then mentioned four types of crusts, based on their geomorphological position:

(1) High level or peneplain Iron crusts;

(2) Foot slope or colluvial Fe crusts;

(3) High water table or low-level Fe crusts;

(4) Residual crusts other than the old-peneplain type.

At this time, corroborated by the description provided by Sivarajasingham et al.(1962), laterite was equated with its iron crust and the significance of its residual nature became lost.

1964 — De Swart formalized the existence of two features in the earth sciences, both called laterite but which were of completely different genetic nature: laterite ≠ laterite. This was caused by the use of non specific terms such as 'iron crust', for distinctly different features, while sound geological fieldwork always could have separated a 'laterite' from a 'secondary iron crust' or 'ferricrete' (Lamplugh, 1902).

It would be appropriate if this CORLAT Handbook would contribute to a return of the correct usage of the term laterite.

GLOSSARY

Definitions or explanations are given for all terms marked in the text with an asterisk (*). In addition, all terms occurring in the appendices and figures are presented, as well as several other related terms. Several relatively common English words, occuring in the Annexes, have been included on the specific request of some not English oriented scientists, who perused an earlier draft of the Handbook.

The derivation or author of each term is given between brackets at the end of each entry: COD stands for Concise Oxford Dictionary; GG indicates the Glossary of Geology by Bates & Jackson (1980); GN refers to the Geological Nomenclator by Visser (1980); B&Z refers to Butt & Zeegers (1992), and Acs refers to contributions by R.R. Anand, C.R.M. Butt, R.E. Smith and I.D.M. Robertson, 1992. Drs R. Anand and I.D.M. Robertson (CSIRO, West Australia) have checked and updated the Glossary with numerous terms (marked RA), coined during the last few years as result of intensive research work by a CSIRO study group (R. Anand, C.R.M. Butt, I.D.M. Robertson and R.E. Smith). Several of these terms, not further discussed in the Handbook, are marked with '<' in front of the term given.

Most of the unmarked terms are derived from Bárdossy & Aleva (1990): Lateritic bauxites. If terms are used in several sub-disciplines, the name of the relevant discipline is added in brackets.

The choice of terms included in the Glossary may be somewhat biased through the working experience of the contributors. The Australian contributions are based on modern research — using all available instrumental, chemical and mineralogical methods — and extensive field work in West Australia. The working experience of the compiler is restricted to the macroscopic study of, mainly bauxitic, laterite, more or less world-wide. Hence laterites with a relative low content in iron minerals, however, the exposures studied were often very good and deep, due to extensive mining operations.

< **Accretion:** a mesoscopic or microscopic mass/body produced by overgrowth upon a pre-existing nucleus (Acs).

< **Accretionary:** tending to increase by external additions or accumulations (Acs).

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

Acicular: a particle that is needle-like in shape (high aspect ratio).

Alcrete: a term analogous to Lamplugh's calcrete (1902) for a conglomerated gravel, hardened by aluminium hydroxides derived from infiltrating waters. Hence not applicable to an aluminous lateritic accumulation zone in view of its residual origin.

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

Allophane: an amorphous weathering product with the composition $Al_2O_3.SiO_2.nH_2O$.

Alterite: (i) laterite) a surface or near-surface rock characterized by its complete mineral re-equilibration to the physio-chemical environment of the reining or fossil climate. The main components are kaolinite and/or gibbsite, with Fe compounds and weathering resistant minerals such as quartz. A French term, usually synonymous with saprolite. (B&Z).
(ii - sediment petrology) a general term for altered, microscopically unrecognizable grains of (heavy) minerals.

Alveole: the smallest of the interstices* distinguished (<16 mm), usually equant to tri-axial in shape. Their shape, frequency and distribution pattern is highly variable, from a few openings to making up >50% of the rock surface or volume, in which case they determine the rock

texture (alveolar, spongy*); see Annex III. Alveolar weathering = Honeycomb weathering; see also boxwork.

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

Arkose: a sedimentary rock largely composed of grains of feldspar and quartz; a feldspathic sandstone. Generally derived from the rapid disintegration of granitic rocks or pre-existing arkose (RA). French: arène.

Armour: a possible translation of the French term cuirasse; when rich in iron: iron crust. In Australia: desert armour = lag.

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

Authigenic: formed or generated in place; said of rock constituents or minerals that have not been transported but have crystallized in situ subsequent to the formation of the rock in which they now are found (Acs).

Azonal soils: soils that are too young to reflect the influence of site-specific conditions in their profile characteristics; see also zonal and intrazonal soils (Driessen & Dudal, 1989). Hence lacking well-developed horizons and resembling their parent material (Acs).

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

Banded Iron Formation: (BIF) a metamorphosed rock composed of iron minerals and chert or fine-grained quartz, showing a marked banding (GG).

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

Bauxite: (i) Economic term: a lateritic ore of aluminium.

(ii) Lateritic bauxite is a highly aluminous layer in the upper part of the laterite regolith. It may form on any parent rock but most typically on basalts, syenites, granites, arkoses, marls and shales in freely drained, strongly leached environments. They contain abundant aluminium hydroxides (gibbsite, less commonly boehmite, diaspore) and Al-substituted Fe oxides.

(iii) Karst bauxite is a variant, formed in karstic caves and hollows in limestones; the Fe and Al are presumably derived from common erosion products, transported by flowing water as denudation products and trapped in the karstic caves.

Bedded/bedding: formed, arranged or deposited in layers or beds; also applied to non-sedimentary material such as lava and volcanoclastic rocks, and weathering materials; also a mineral deposit that follows a bedding plane in a sedimentary rock (RA).

Bedrock: the solid rock at the surface of the earth or at some depth beneath the beneath the regolith which has been unaffected by weathering or soil forming processes. (RA)

Bioturbation: the churning and stirring of a sediment by organisms (GG).

<**Birbirite:** the prominent outcrops produced by highly weathering resistant silicification, resulting from the lateritization of dunite in tropical terrain.

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

Bog iron: ironstone developed in bogs, swamps or footslopes by the chemical or biochemical oxidation of iron carried in solution. Generally goethite-rich, in places locally massive, also

vesicular; it can develop as Fe-oxide concentrations in previously unconsolidated sediments (RA). Often erroneously named 'slope bottom laterite'.

Botryoidal: groups of globular structures resembling clusters of grapes - of any size; the globular structure consists generally of acicular crystals in radiating clusters.

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

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

Boudinage or Roll-shaped: structure produced by the stretching of a competent layer between less competent layers, resulting in a series of bodies resembling boudins or sausages, surrounded by the less competent material.

Boxwork: in the laterite context: a construction of angular interstices* or chambers, separated by thin sheets of hard, lateritic matter (gibbsite and/or iron oxyhydroxides) intersecting in three or more directions in space, the whole enclosed in lateritic rock or saprolite*. See Annex III.

< **Breakaway:** upper or mid slope cliffs, generally comprising both a very short scarp (free face) that is generally bare rock, and a stony scarp - foot slope (debris slope); generally above a pediment. An Australian term (Acs).

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

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

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

Carapace: (weathering) a French term used for the lower part of the laterite accumulation zone of the laterite profile; it is generally less indurated than the upper zone or cuirass. See also 'duricrust'.

Catena: a sequence of regolith units (e.g. soils) developed from similar parent materials under similar climatic conditions but whose characteristics differ because of variations in relief and drainage (RA).

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

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

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

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

Cellular: a fabric consisting of rounded bladder, cell or buble-shaped voids, especially in the lateritic accumulation zone (B&Z).

< **Cellular duricrust:** lateritic duricrust characterized by irregular to rounded, bladder, cell or buble-shaped voids. It may contain pisoliths [pisois], nodules and a motled fabric. (Acs).

Cementation front: A transformation front resulting in cementation by components such as oxides and oxyhydroxides of Al, Fe and Mn, silica and Ca or Mg carbonates. (B&Z).

Clay (geol): (i) rock fragment, mineral fragment, detrital particle or crystal of any composition < 1/256 mm (or < 0.004mm = < 4μm);

(ii) loose, earthy, extremely fine-grained natural particles, or a soft rock composed primarily of clay-sized or colloidal particles and characterized by high plasticity and by a considerable content of minerals from the group of clay minerals (GG).

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

Coated grain: in the laterite context: a rock or mineral particle of any composition or size, that is surrounded by a layer of any thickness and composed of Fe-oxides, clays or carbonates. (RA).

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

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

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

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

Collapsed saprolite: a collapse breccia in which saprolite has been fragmented during the weathering process and part of the interclastic material has been removed by leaching and/or eluviation, resulting in downward volume collapse of the saprolitic material (RA).

Colloform: a fabric composed of rounded, finely banded* kidney-shaped mineral matter.

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

Columnar (geol): a structure composed of solid prisms or cylindrical elements that are close together in parallel position, usually with the long axes arranged vertically; the spaces between the columns may be void* or filled with mineral matter.

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

Concretion: a hard, compact mass or aggregate of mineral matter, spherical to oblate, dish-shaped or irregular in shape and usually with complex outlines, supposedly formed by precipitation from an aquous solution.

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

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

Congruent solution: dissolution of solid without change in composition, e.g. salt (NaCl) dissolves congruently.

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

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

Core boulder, core stone: the rounded, ellipsoidal or broadly rectangular and hard blocks, composed of virtually fresh parent rock, locally occurring in the saprolite or in the accumulation zone of the lateritic weathering profile; the residual unweathered remnant of a joint block, originating from any massive type of parent rock, e.g. granite, gabbro, dolerite, etc., but separated from it.

Cortex: the outer, concentric shell or envelop of a pisoid*, ooid, pisolith, oolith, or concretion; it may vary in thickness. This thickness may be expressed as the ratio between the diameter of the particle and the thickness of the cortex; see Annex III.

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

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

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

Cuirass: (weathering) the hard, upper layer of the accumulation zone in the laterite profile, particularly enriched in iron oxide minerals; a type of duricrust*. Originally a French term for the harder, upper part of the accumulation zone.

Cutan: (soil) an outer layer or surface coating or skin found on the surface of voids, grains and aggregates (Bullock et al. 1985).

Degradation: reduction to lower rank, to simpler molecular structure or the wearing down of the Earth's surface through weathering and erosion (COD); de polygenetic nature of lateritization processes may cause successive or alternating periods of desilication (gibbsite) or resilication (kaolinite), for which the unidirectional term degradation seems incorrect. The succession of the newly formed minerals may show inversions and reversals, with respect to the order in which the new minerals are formed.

Dense: a not recommended synonym for aphanitic* because it may also mean high density.

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

< Depositional regime: an area characterized by widespread sediments with thicknesses greatly in excess of 2m.

Detritus: a collective term for loose rock and regolith material that is worn off or removed by mechanical means, as by disintegration of abrasion (Acs); esp. fragmental material, such as gravel, sand, silt and clay, derived from older rocks or regolith and moved from their place of origin (GG).

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

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

Diapir: structure resulting from rupturing and piercing of a relatively brittle rock layer by underlying plastic material, through geostatic loading.

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

Duricrust: (i) 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) or SiO_2 (silcrete) 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). (ii) Indurated material at or just below the surface. The material may be ferruginous, aluminous, siliceous or calcareous, or a combination of these. Siliceous and calcareous materials are normally referred to as silcrete and calcrete respectively (B&Z).

Epi-norm: theoretical calculation of minerals in a metamorphic rock of the epizone, as indicated by chemical analysis (GG).

Epizone: the uppermost depth zone of metamorphism, characterized by low to moderate temperature (<300°C), hydrostatic pressure and unspecified shearing stress; it includes the weathering environment.

< Erosional regime: an area where erosion has removed the laterite to the level where the mottled zone, clay zone or fresh bedrock is either exposed, concealed beneath soil or beneath loccaly derived, associated sediments (Acs).

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

Fabric: the physical nature of a regolith unit or component according to the spatial arrangement, orientation (or lack of it) and mutual relationships of the discrete elements such as particles, crystals, cements and voids of wich it is composed. Fabric refers to the smaller (microscopic and mesoscopic) features. The term structure is used for larger features. Used in preference to 'texture'(B&Z).

Facies: the aspect, appearance and characteristics of a rock unit, usually reflecting the conditions of its origin; especially as differentiating the unit from adjacent or associated units (GG).

False laterite: surface or near-surface materials that look similar but are not the residual weathering products of the local parent rock (or bedrock). They are mostly transported erosion products of laterites - i.e. exolaterites - occurring in the neighbourhood, cemented by mainly ferruginous matter derived from circulating (ground)water, and found on lower topographical levels than the true laterite.

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

< Fe-rich massive duricrust: a dense, Fe-rich crust with a uniform fabric in hand specimens. Commonly occurs in topographically prominent positions, such as ridges and mesas, closely associated with other forms of lateritic duricrusts (Acs).

< Fe-rich pebbly duricrust: a dense, black, Fe-rich crust with a pebbly fabric. Commonly occurs in topographically prominent positions, such as on ridges and mesas (Acs).

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

(ii) A humid tropical soil characterized by a high Fe-oxide content, formed by the leaching of silica and bases. Commonly used synonymously for laterite, latosol, oxisol (B&Z); a not recommended usage.

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 alkalis and alkaline earth elements; 3/ partial or total leaching of silica; leaving a residue of Fe, Al and Ti, as hydroxides and oxides and remaining silica as unaltered, residual quartz or newly formed kaolinite (after Delvigne, 1965).

Ferricrete: a conglomerate composed of iron oxide cemented gravel (G.W.Lamplugh, 1902); hence an allochthonous rock, incompatable with the laterite scene (Aleva, 1991). Recently (and confusingly according to the compiler) used to indicate indurated material formed by the *in situ* cementation or replacement, or both, of pre-existing regolith by Fe-oxides and oxyhydroxides precipitated from soil water or groundwater. The fabric, mineralogy and composition of such ferricretes may reflect those of the parent (regolith) material and hence, if residual, the underlying lithology (B&Z). Some authors restrict the term to the ferruginous horizon of laterite

regoliths (synonymous with cuirasse, laterite duricrust) but the more general definition is preferred (B&Z).

Ferrite: an older and confusing term for a lateritic rock in which the iron minerals represent ≥80% of the lateritic weathering minerals; as such it is used in older versions of Fig. 1B: the iron apex of the triangular compositional diagram. It should be replaced by "sum of Fe minerals".

Ferruginous saprolite: generally a yellowish brown to reddish brown, low-Fe material (relative to most laterites), typically with a relict fabric and may have diffuse mottling and incipient nodular structures (Acs).

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

Fissure: fracture or crack in a rock along which there is a distinct separation, i.e. a displacement normal to the fracture surface; in the laterite context: an interstice* with one axis much shorter than both other axes; the walls of the fissures may be coated* or fissures may be completely filled in with lateritic constituants.

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

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

< **Fragmental duricrust:** a lateritic duricrust which has a fragmental of blocky fabric in outcrop and/or hand specimen. The interstices between fragments are commonly occupied by a clayey, ferruginous and in places a sandy matrix. The fabric of the parent rock is in places preserved within the fragments. Dissolution cavities may be common in the fragments (Acs).

Garnierite: nickel-bearing serpentinite [$Mg_3[Si_2O_5](OH)_4$] in which part of the magnesium is substituted by nickel.

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

Gondite: metamorphic rock consisting of spessartine (a manganese-aluminium garnet) and quartz, probably derived from Mn-bearing sediments (GG).

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

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

Granular: rock texture in which the crystalline components may be distinguished by the unaided eye and are of approximately equal size, i.e. >0.06mm in diameter.

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

< (ii) Fragments ranging in dimensions from 2 mm to 60 mm. 'Gravel' is a size fraction commonly used colloquially in Australia to refer to pisoliths, nodules and hardened mottles, and includes fragments that are of irregular shape. Recommended use only with qualifier, e.g. lateritic gravel, lithic gravels (B&Z).

Ground-water laterite: not a laterite in the sense of the laterite definition (Schellmann, 1982). It is used in two ways:

(i) an imperfectly drained soil profile composed of a leached A horizon and a slowly permeable B horizon with soft plinthite formed by accumulation of sesquioxides derived from overlying horizon(s), and usually found in the Tropics (Sombroek, 1966).

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

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

Grus: A fragmental desintegration product of largely unweathered granitic rocks. Commonly applied to surface products, but also present as a porous zone ranging a few centimetres to 10 m or more in thickness at the base of saprolite. In the French literature, grus or "arène" are used to designate such horizons over any lithology. Grus differs from saprock in that it is friable rather than compact (B&Z).

< Hardened mottles: Ferruginous (hematite, goethite) irregular-shaped lateritic mottles, occurring as surface lag on truncated landscapes from which the laterite has been stripped exposing the mottled zone. Commonly occurring in the pebble-size range (4-64 mm). (Acs).

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

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

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

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

(ii) A layer within the regolith approximately parallel to the landsurface and differing from adjacent, genetically related, layers in physical, chemical and/or biological properties, or in characteristics such as colour, pH, structure, fabric, texture, consistency and types and number of organisms (B&Z).

Hyallite: equals opal, formula $SiO_2.nH_2O$.

Impregnated lateritoid: lateritoid* rock composed of epigenetically and pervasively deposited lateritic matter in a permeable, mostly not lateritic host rock below the topographical level of residual weathering. Often a more correct term than the frequently misused term ferricrete in its original meaning.

Incongruent solution: dissolution accompanied by decomposition or by reaction with the liquid so that one solid phase is converted into another; dissolution to give dissolved material in different proportions from those in the original solid (GG).

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

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

Intrazonal soils: see zonality of soils.

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

Iron crust: a substantial concentration of iron oxides and oxyhydroxides, covering an already existing substrate, forming an overlaying, hard layer or armour.

Ironstone: any rock containing a substantial proportion of an iron compound; more specific an iron-rich sedimentary rock, either deposited directly as a ferruginous sediment or resulting from chemical replacement (GG).

Isalterite: a residual weathering product in which the parent rock fabric is distinctly conserved, as well as the main chemical component(s); in the laterite context this is generally aluminium and/or iron.

Itabirite: a laminated, metamorphosed oxide facies Iron Formation in which the original chert or jasper bands have been recrystallized into megascopically distinguishable grains of quartz and in which the iron is present as thin layers of hematite, magnetite or martite [= hematite derived from alteration of magnetite or pyrite] (GG).

Kaolin: (i) the unconsolidated rock in which the minerals of the kaolinite group represent $\geq 80\%$ of the weathering minerals; see Fig. 1B. It is usually a soft, fine, white, earthy, non-plastic material. (ii) Kandites: a group of clay minerals with a two-layer structure with the approximate composition $Al_2Si_2O_5OH_4$, including kaolinite, halloysite, endellite, nacrite, dickite and anauxite.

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

Khondalite: a group of metamorphosed aluminous sediments consisting of garnet-quartz-sillimanite rocks with garnetiferous quartzites, graphite schists, and marbles (GG).

Lag (laterite): a general term for surface accumulations of clasts of diverse origin, such as regolith, rock and mineral particles. Most clasts are in the granule to cobble range (2-256 mm). They result from removal of finer material by pluvial and aeolian processes or by removal of the matrix by differential weathering. The type of lag is related to the local regolith-landform-bedrock environment (Acs).

Laterite: a term coined by Buchanan, 1807, for the weathering material from which blocks are cut, that after drying are used as building bricks (Latin 'later' = brick, tile); 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. Redescribed many times, e.g. by Alexander & Cady (1962): see Chapter 2.2. Defined by W. Schellmann (1982): Laterites are products of intense rock weathering. They consist predominantly of mineral assemblages of goethite, hematite, aluminium hydroxides, kaolinite minerals and quartz. The $SiO_2 : (Al_2O_3 + Fe_2O_3)$ ratio of a laterite must be lower than that of the kaolinized parent rock in which all the alumina of the parent rock is present in the form of kaolinite, all the iron in the form of iron oxides, and which contains no more silica than is fixed in the kaolinite plus the primary quartz. See Chapter 2.2.

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

Laterite Derivative Facies (LDF): generally. an allochthonous lithofacies composed of detritus derived from a pre-existing laterite formation, parts of which may still be in existence (Goldbery, 1979).

Laterite profile: refers to the whole laterite weathering profile: laterite gravel, accumulation zone or duricrust, mottled zone and saprock (Acs).

Laterite sensu lato: the less strictly defined use of the term laterite, where the emphasis is on the process of weathering under humid, tropical conditions — see Ch. 2.2.

Laterite, specialized: a lateritic rock of uncommon chemical composition due to the original content in uncommon metal elements in the parent rock, e.g. Ni, Mn.

Laterite, false: a rock that on surficial inspection looks like laterite, but is not the product of intense in situ weathering.

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

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

Lateritic duricrust: a hard, ferruginous crust which is also commonly aluminous and silicic, developed in the upper part of a lateritic weathering profile. It is formed by accumulation of secondary oxides and oxyhydroxides of Fe, Al and Si and by accumulation of insoluble mineral grains and aggregates, resistant mineral grains - of which quartz is the most common - and weathered rock debris. It may occur at the surface or below the surface when the weathering profile has been buried (Acs).

Lateritic gravel: a loose accumulation of lateritic oolith, pisolith and/or nodules and hardened mottles in the 2-64 mm size range. It includes residual gravels and transported gravels and this distinction should be noted where possible (Acs).

Lateritic residuum: a collective term for units of the ferruginous zone of the laterite profile. It includes units of loose lateritic pisoliths and nodules and lateritic duricrust (Acs).

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

Lateritization (laterization) : the process of transformation of a (near) surface layer (rock or soil) into a laterite.

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

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

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

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

Limonite: a common alteration product of iron-bearing minerals, usually composed of a cryptocrystalline mixture of goethite, lepidocrocite, and with adsorbed water and other elements. Colour: yellow-brown, orange-brown, brownish black. Approximate composition $FeO.OH.nH_2O$.

Lithofacies: a lateral, mappable subdivision of a designated stratigraphical unit, distinguished from adjacent subdivisions on the basis of lithology, including all mineralogical, petrographical and paleontological characters that influence appearance, composition or texture (= fabric) of the rock (shortened after GG).

Lithomarge: the amorphous compound, found directly overlying the bedrock (which is generally its parent rock) of composition $2H_2O.Al_2O_3.2SiO_2$, i.e. kaolinite (Dana, 1858; Fermor, 1911); a smooth, indurated variety of common kaolin, consisting at least in part of a mixture of kaolinite and halloysite (GG); an older, not well defined term with the meaning of china clay; see saprolite.

< **Loose nodules:** a loose accumulation of lateritic nodules. These commonly form a blanket deposit up to a few metres in thickness. They may also occur as lag. They may outcrop or occur within or underlie soil. colluvium or calcrete (Acs).

< **Loose ooliths:** a loose accumulation of lateritic ooliths which may occur in soil or as surface lag. They do not generally form a blanket deposit (Acs).

< **Loose pisoliths:** a loose accumulation of lateritic pisoliths which commonly forms a blanket deposit of 1-2 m in thickness. It may also occur as a lag. It may outcrop but also may occur within or underlie a soil, colluvium or calcrete units (Acs).

Massive: homogeneous, without visible internal fabric (B&Z).

< **Massive duricrust:** A lateritic duricrust having an homogeneous fabric on a hand-specimen scale. In places it is completely massive but generally contains minor vesicles and tubules which may be filled or partly filled with clay and/or other sediment. It may be either uniformly

coloured or multicoloured due to segregation of secondary minerals or the selective ferruginisation. It commonly underlies nodular duricrust (Acs).

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

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

Microtubular: a void* structure consisting of sinuous tubes with a diameter of <0.5 mm, occurring in otherwise more or less massive* and aphanitic* rock or soil.

Mottles: spots, blotches or streaks of subdominant colours from the matrix colour. Mottles commonly have diffuse boundaries and differ in mineralogical composition from their matrix (B&Z).

< **Mottled duricrust:** lateritic duricrust containing abundant mottles (see above). Incipient nodules, pisoliths and irregular voids also occur in mottled duricrust. In places rock fabric and structure may be apparent (Acs).

Mottled zone: a zone or layer characterized by mottles that, with further mobilization and concentration, become reorganized into secondary structures. Nodule growth progressively destroys pre-existing fabrics, although microfabrics may be preserved in the nucleus (after B&Z).

Nodule (lateritic): irregularly shaped rounded knot, mass or lump, or a mineral or mineral aggregate, normally having a warty or knobby surface and no internal structure, and essentially exhibiting a contrasting composition from the surrounding matrix* or rock in which it is embedded; generally they can be separated as discrete masses from the host material. Hence **Nodular:** the texture of a rock composed of a relatively structureless matrix* enclosing numerous nodules. The composition of a lateritic nodule may vary from essentially Fe-oxides and oxyhydroxides to almost pure gibbsite in bauxitic laterites. The spherical shape and the presence of a distincy concentric, internal structure separates the pisoid (pisolith) from a nodule.

< **Nodular duricrust:** predominantly consisting of lateritic nodules which are separated from one another by hardened, ferruginous, and in places sandy, clayey matrix. It may also contain a few lateritic pisoliths and voids. It commonly forms a blanket deposit up to a few metres in thickness (Acs).

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

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

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

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

< **Oolitic (ooidal) duricrust:** ferruginous lateritic duricrust predominantly consisting of lateritic ooliths which are spaced within a cemented ferruginous-clayey matrix. Pisolithic duricrust is more common (Acs).

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

< **Packed pisolitic duricrust:** it consists of lateritic pisoliths which are cemented as a grain-supported mass. The interstices between pisoliths commonly are cavities or are partly filled with clay or sandy clay. The degree of cementation is variable. Depending upon the fabric, the duricrust may be classified as packed nodular, packed oolitic or packed pisolitic-nodular. Some

packed duricrusts have formed through fluvial processes, others appear to have formed through breakdown and removal of the matrix in pisolitic duricrust (Acs).

Paragenesis: a characteristic association or occurrence of minerals or mineral assemblages in ore deposits, connoting contemporaneous formation (GG).

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

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

Pedogenesis: soil formation. Adjective: pedogenic (B&Z).

Pedogenetic laterite: see chapter 2.2 (iv).

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

< **Pedolith:** upper part of the regolith, above the pedoplasmation front, that has been subjected to soil forming processes resulting in the loss of the fabric of the parent material and the development of new fabrics, including secondary structures such as pisolith and nodules. The pedolith may develop from residuum, i.e. from saprolite, saprock or bedrock, or from transported overburden (B&Z).

Pedoplasmation front: transformation front at which the lithic fabric is destroyed, although commonly with little chemical reworking (pedoplasmation, Flach et al.,1968). It forms the upper boundary of the saprolite in deeply weathered profiles (B&Z).

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

Petroferric or skeletic phase: see text, chapter 3.4 (FAO-Unesco Revised Legend, 1988).

Petroplinthite: iron [and/or aluminium] oxide individualizations, which have hardened irreversibly. When moist it can not be cut with a spade. It appears as hard concretions in a clayey matrix, or as a hard crust or sheet (Sys, 1969). This term has been superceded by the 'petroferric phase', see text, chapter 3.4.

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

Pipe: tubular cavity with a diameter larger than 1/4 metre (256 mm), which may be filled with clastic or other material.

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

Pisoid: (weathering) non-generic term for a more or less sphaeroidal textural or structural element, between 3 and 30 mm in diameter, consisting mostly of an homogeneous core or 'nucleus' and an outer, concentrically layered rind or 'cortex' of lateritic matter; see Annex III.

Pisoidal: texture of a rock composed of pisoids.

Pisolite: a sedimentary rock, usually a limestone, made up chiefly of pisoliths cemented together.

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

(ii - laterite) ferruginous or aluminous lateritic particle resembling a pea in shape and limited in size to bodies over 2 mm diameter. It can have a concentric internal structure but concentric lamination is not diagnostic; however, most pisoliths have an outer cortex or cutan (Acs).

< **Pisolitic duricrust:** it consists predominantly of lateritic pisoliths cemented by a ferruginous-clayey matrix. It may also contain a few voids and lateritic nodules (Acs).

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

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

Plasma: that part of a soil material which is capable of being or has been moved, reorganised, and/or concentrated by the processes of soil formation. It includes all the material, mineral or organic, of colloidal size and relatively soluble material which is not bound up in skeleton grains (Brewer, 1964). The plasma/skeleton distinction in soils has been replaced by Bullock et al. (1985) by the concept of fine/coarse material, with the concept of plasmic fabric replaced by birefringince fabric.

Plasmic horizon: the horizon in which the lithic fabric of the saprolite (or saprock) has been replaced by a new, mesoscopic homogeneous, plasmic fabric, above the pedoplasmation front. The loss of lithic fabric is caused by solution and authigenesis of minerals and the mechanical processes such as shrink and swell of clays and settling of resistant primary and secondary minerals through instability induced by leaching. It consists of massive clays or silty clays over rocks poor in quartz; a sandy arenose zone forms over quartz-rich rocks. Major structural features, such as quartz veins and lithological contacts, may be preserved, possibly with change in orientation (dip) (B&Z).

Playa: a dry, vegetation-free, flat area at the lowest part of an undrained desert basin, underlain by stratified clay, silt, or sand, and commonly by soluble salts (GG).

Plinthite: see text, chapter 3.3. The revised Legend of the FAO-UNESCO Soil Map of the World (1988) gives the following definition: an iron-rich, humus-poor mixture of clay with quartz and other diluents. It commonly occurs as red mottles, usually in platy, polygonal or reticulate patterns, and changes irreversibly to a hardpan or to irregular aggregations on exposure to repeated wetting and drying. In a moist soil, plinthite is usually firm but it can be cut by a spade. When irreversibly hardened the material is no longer considered plithite. Such hardened material is shown as a petroferric or a skeletic phase.

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

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

Protore: the rock below the sulphide zone of supergene enrichment; the primary, subeconomic material (GG); in a more general meaning: the rock that became an ore through subsequent enrichment by ore minerals, independant of the proceses involved.

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

Pseudomorph, -ic, -ism, -osis: a mineral or mineral aggregate formed by alteration that has the outward shape of another mineral species or aggregate that has been replaced through alteration, e.g. goethite with the shape of pyrite. Hence 'pseudomorphic' - the state of showing pseudomorphosis (GN). A pseudomorph is described as being "after" the mineral whose outward form it has, e.g. goethite with the shape of pyrite.

< **Pyroaurite:** a possible MnO containing, golden yellow or brownish mineral of the composition $Mg_6Fe_2(CO_3)(OH)_{16}.4H_2O$ (GG).

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

Reactive silica: see under silica, below.

Regolith: the entire unconsolidated and possibly secundary recemented cover that overlies the more coherent bedrock and that has formed by the weathering, erosion, transport and/or deposition of older material (Merrill, 1897). The regolith thus includes fractured and weathered

basement rocks, saprolites, soils, organic accumulations, glacial deposits, colluvium, alluvium, evaporitic sediments, loess and aeolian deposits (B&Z).

< **Regolith-landform unit:** an area, delineated by air-photo interpretation, that can be represented on a map, within which a chosen association of surface regolith materials and landforms occurs. This may be distinguished by mapping, at the appropriate scale, from adjacent areas which have been defined using similar principles (Acs).

Relic: a memorial. Commonly applied to original fabrics or textures that remain visible after the replacement of pre-existing minerals (B&Z).

Relict: (i) remnant of a mineral, structure*, texture* or other feature of an earlier rock that has persisted in a later rock, in spite of processes such as metamorphism or weathering which tend to destroy it. Also used for the elements of an older landscape still present in a younger landscape. A survivor. (ii) A species (plant, animal, mineral) in a changed environment; e.g. a primary mineral, especially a weatherable one, present within a predominantly secondary mineral assemblage (B&Z).

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

< **Residual regime:** a mappable area characterized by widespread preservation of laterite (Acs).

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

Rock: an aggregate - hardened or not - of one or more minerals, e.g. granite, shale, sand, marble; or a body of undifferentiated mineral matter, e.g. obsidian, clay or of organic material, e.g. peat, coal. A natural aggregate of minerals connected by strong and permanent cohesive forces.

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

Roll-shaped: see Boudinage.

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

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

Rotten rock: imprecise term used to indicate the transition between fresh rock and its more fully weathered state, saprolite (see below); saprock is preferred.

Sample: small separate part of something illustrating the qualities of the mass etc. it is taken from (COD).

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

Saprolite: (derived from Greek for 'rotten rock') (i) a soft, earthy, typically clay-rich and thoroughly decomposed rock, formed in place by chemical weathering of igneous, sedimentary and metamorphic rocks, and mainly composed of kaolinite. It is characterized by preservation of structures that were present in the unweathered rock (after Becker, 1895).

(ii) Weathered bedrock in which fine fabric, originally expressed by the arrangement of the primary mineral constituents of the rock (e.g. crystals, grains), are retained. Compared to saprock, material with more than 20% of weatherable minerals altered. Saprolite may be extended to include weathered rocks in which only larger structures such as bedding, schistosity,

veining or lithological contacts are preserved. The presence of saprolite implies that weathering has been essentially nearly isovolumetric (B&Z).

Serpentine: a mineral of the serpentine group, having the general formula $(Mg,Fe)_3Si_2O_5(OH)_4$; a secondary mineral derived by alteration of Mg-rich silicate minerals such as olivine, and found in both igneous and metamorphic rocks. After GG.

Siallitic: an old term for a weathering product characterized by Al-silicate minerals, e.g. kaolinite, and leached of alkalis and alkaline earths.

Silica: dioxide of silicon or SiO_2. In the weathering context two varieties are commonly recognized, i.e. *reactive* silica: which in the laterite/bauxite context is the silica present in the clay minerals, in particular kaolinite and halloysite or in a very fine-grained state, which is soluble in hot sodium hydroxide solutions; and *total* silica, which is all SiO_2 present including clay minerals and quartz.

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

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

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

(ii) Engineering: all unconsolidated material above bedrock, hence synonymous with regolith.

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

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

(v) Upper part of the regolith, commonly defined as that which supports plant life. In particular, refers to those surface horizons reacting to the present environment; paleosols are soils that formed under past weathering conditions (B&Z).

Specialized laterite: see Chapter 2.3 - a laterite derived from a parent rock of relatively uncommon chemical composition, e.g. rich in manganese or nickel.

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

< Stichtite: a lilac-coloured rhombohedral mineral of the composition $Mg_6Cr_2(CO_3)(OH)_{16}.4H_2O$; it may contain some iron.

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

Structure/texture: see Chapter 1.1.

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

Talc: a common secondary mineral derived by hydration of non-aluminous Mg silicates (olivine, enstatite, tremolite) in basic igneous rocks or by metamorphism of Mg-Ca-carbonate rocks (dolomite). It is very soft, light green, and has a greasy to soapy feel. After GG.

Ternary compositional diagram: see Fig. 1 and Chapter 2.2.

Texture: see Chapter 2.1. Also (petrology) a term applied to the smaller, megascopic features of a rock; the general appearance of a rock, including geometric aspects and the mutual relations among its component particles (after GG).
See also 'fabric'.

Total silica: see under silica above.

Trap: a dark-coloured fine-grained hypabyssal to extrusive rock, such as basalt, diabase, fine-grained gabbro or peridotite. After GG.

True laterite: an intentional pleonasm to stress that the rock in question is without doubt of lateritic origin.

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

Tubular: rock or structure composed of one or more tubes. The individual tubes may contain fill in* structures of secondary nature (Valeton, 1971).

Tubule: tube* with diameter <2 mm.

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

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

Vermicular, vermiform: like a worm in form or movement (COD).

Vermiculate: as preceding but also 'worm eaten' (COD).

< Vermiform duricrust: lateritic duricrust characterized by tubular, pipe or worm-shaped voids. Usually contains a few mottles, pisoliths and nodules. Tubules or cavities may be filled or partly filled with clays, sandy sediments or Fe-oxides. Generally underlies pisolitic-nodular duricrust (Acs).

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

Vug, Vuggy: irregularly shaped voids* ≥4 mm which may be lined with mineral matter, differing in composition from the rock in which they occur; vuggy structure characterized by numerous, irregularly distributed vugs.

Weathering: (i) the adjustment of the mineral assemblage of a given rock to the conditions reigning at the surface of the earth. (ii) The destructive process or group of processes by which earthy and rocky materials on exposure to atmospheric agents at or near the Earth's surface are changed in color, texture, composition, firmness, or form, with little or no transport of the loosened or altered material; specifically the physical desintegration and chemical decomposition of rock that produce an in-situ mantle of waste and prepare sediments for transportation - some include biologic changes and the corrosive action of wind, water and ice; others restrict weathering to the distinctive processes of surface waters below 100°C and 1 kbar (GG).

Weathering front: (Mabbutt, 1961): the transformation front marking the commencement of weathering at the base of the regolith. The rock-saprock interface (B&Z).

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

Zonality of soils: soils are characterized by their formative environment; three types are distinguished:
(i) azonal: soils that are too young to reflect site-specific conditions; generally very young soils;
(ii) intrazonal: soils whose characteristics result from strong local dominance of soil forming factors, other than climate;
(iii) zonal: soils mainly occuring in specific climatic zones (Driessen & Dudal, 1989).

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

Zoned, zoning: (i - soil) structure characterized by a succession of lithostratigraphic zones or horizons, parallel to the earth surface and differing from overlying and underlying horizons in one or more features such as mineralogy, chemistry, texture, colour, etc.;
(ii - geol.) any regular pattern in the spatial distribution of minerals or elements in the Earth's crust (GG).

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Annex I

Analysis of Malabar Laterite (Fox, 1963)

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

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

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

Mr Raoult used a gentle agent to take up the sample in solution, in order to be able to distinguish between quartz and silica bound to kaolinite. In the analytical procedures for the alumina/bauxite industry a tri-acid mix of the following composition has been used for this purpose:

$$485.1 \, ml \; H_2O \qquad\qquad 242.2 \, ml \; concentrated \; H_2SO_4$$
$$181.8 \, ml \; concentrated \; HCl \qquad 90.0 \, ml \; concentrated \; HNO_3$$

N.B. Be aware of strong heat development during the mixing process.

The following norm* computation (see Table A and B) is based on the hypothesis that the parent rock has been fully weathered, resulting in a mineral paragenesis composed of only laterite* minerals plus quartz and anatase. All insoluble material, remaining after the tri-acid treatment, is counted as free silica (quartz), but could contain unweathered parent rock silicates.

The computation starts with assigning sufficient LOI (water as loss on ignition; Fox states "loss at red hot") to the free silica present to form − with the required amount of Al_2O_3 − the mineral kaolinite. The remaining LOI is distributed among the remaining aluminium oxide and all the iron oxide to form the minerals kaolinite, gibbsite and/or boehmite and hematite and/or goethite. Three common, actually occurring parageneses are computed: gibbsite + hematite (a 'dry' combination), gibbsite + goethite (a 'wet' combination) and gibbsite + hematite + goethite. A paragenesis resulting in a negative mineral phase indicates a wrong hypothesis.

The table shows that the gibbsite-hematite norm always produces negative amounts of certain minerals, hence this 'dry' hypothetical paragenesis is wrong and must be rejected.

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

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

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

References: Bárdossy & Aleva, 1990
               Fox, 1963

Annex I — Table A

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)

Sample No	1		2		3	
	original	recomputed	original	recomputed	original	recomputed
Insol.	6.67	6.86	12.45	12.68	13.64	14.06
R.SiO$_2$	17.08	17.56	20.90	21.28	21.08	21.72
Al$_2$O$_3$	20.83	21.42	18.64	18.98	21.40	22.06
Fe$_2$O$_3$	39.09		33.23		26.30	
Σ iron [*]		40.65		33.64		26.78
FeO	0.98		0.92		1.07	
CaO	0.30	0.31	0.28	0.29	0.56	0.57
P$_2$O$_5$	0.07	0.7	0.09	0.09	0.09	0.09
TiO$_2$	1.72	1.77	2.00	2.04	2.44	2.51
L.O.I.	11.05	11.36	10.19	10.38	11.04	11.38
Sum	97.25	100.00	98.19	100.00	97.03	100.00

Annex I — Table B

Mineralogical norm composition[++]

	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$_2$O$_3$ + 2.2 × % FeO
[++] Anatase, quartz and kaolinite are independent of the norm hypothesis used.

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

Annex I — Table C

BAUXITE NORM COMPUTATION

Sample identification number 1

Total Al_2O_3	21.42	Fe_2O_3	40.65
Reactive SiO_2	17.56	Free SiO_2	6.86
L.O.I.	11.36	TiO_2	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	hematite		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	99.61

Sample identification number 2

Total Al_2O_3	18.64	Fe_2O_3	33.64
Reactive SiO_2	20.90	Free SiO_2	12.68
L.O.I.	10.19	TiO_2	2.04

gibbsite-hematite norm		gibbsite-goethite norm			gibbsite-htt/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		98.08	total	98.09

Sample identification number 3

Total Al_2O_3	22.06	Fe_2O_3	26.78
Reactive SiO_2	21.72	Free SiO_2	14.06
L.O.I.	11.38	TiO_2	2.51

gibbsite-hematite norm		gibbsite-goethite norm			gibbsite-htt/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	35.18	sum is		35.22	sum is	35.24
anatase			2.51			
quartz			14.06			
kaolinite			46.70			
total	98.45	total		98.49	total	98.51

Sample identification number 4

Total Al_2O_3	16.89	Fe_2O_3	18.71
Reactive SiO_2	27.08	Free SiO_2	26.16
L.O.I.	8.61	TiO_2	2.55

gibbsite-hematite norm		gibbsite-goethite norm			gibbsite-htt/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

Deviation from 100 % is rounding-off error.

ROCK TYPE / RANK	LATERITES and LATERITIOUS ROCKS					
CLASS Relation of laterite vs. substratum	I Autochthonous LATERITE (s.s., residual, true)	II — Allochthonous — EXOLATERITE				
SUBCLASS Transport mechanism		A In ionic and collodial solution LATERITOID	B In particulate form, derived from I and IIA LATERITOID and LATERITOID-CONTAINING SEDIMENTS			C In particulate form onto a carbonate substrutum
ORDER Based on parent rock 1. Sediment– 2. Metamorphite– 3. Granitoid– .. .. n. Ultramafitite– –DERIVED LATERITE		Based on depositional environment				
		1 ≥ 50% LATERITOID Sandstone- Conglomerate- Pyroclastic- etc. If pervasive: IMPREGNATED LATERITE If in veins: INVADED LATERITE	2 < 50% LATERITOID LATERITOID-INFILTRATED -sand(stone) -conglomerate -pyroclastic etc.	1 ≥ 50 % clastic matter LATERITOID SEDIMENT Talus, scree, colluvium, alluvium, etc.	2 < 50 % clastic matter LATERITOID-CONTAINING -sandstone -conglomerate -argillite, etc.	Related to karst depressions KARST BAUXITE LATERITE
EXAMPLES OF ROCK NAMES See ternary diagram of Fe-Al-kaolin minerals Fig 1B.	Arkose-derived ferriferrous bauxite Gabroid-derived aluminous Fe-(hydr)oxides	Sandstone-impregnated kaolinitic lateritoid Anorthosite invaded ferruginous lateritoid	Aluminous lateritoid-infiltrated sandstone Ferruginous lateritoid-infiltrated pyroclastic rock	Bauxitic lateritoid talus Kaolinitic lateritoid colluvium	Ferruginous lateritoid-containing gravel Bauxitic lateritoid-containing sandstone	Kaolinitic karst bauxite Ferruginous karst bauxite

Annex IIIA

Shape nomenclature for the description of laterites of homogeneous and inhomogeneous composition

Shapes / Size groups	Homogeneous	Inhomogeneous — Equi-dimensional	Cylindrical — Long dimension vertical	Cylindrical — Long dimension horizontal	Tabular — Short dimension vertical	Tabular — Short dimension horizontal
A STRUC-TURES	Massive	Bouldery Blocky Spheroidal	Columnar[+] Diapyric[+]	Roll- Boudinage- shaped	Banded Bedded[+] Layered[+] Stratiform[+] Lens-shaped[+] Zonal Pillow[++]	Dike[+]
	Pore Interstice	*Cave Cavernous*	*Tube Tubular*	*Pipe*	*Fissure*	*Fissure*
B SMALLER SCALE STRUC-TURES AND LARGER ROCK FABRICS	Massive	As above plus Breccia-like Coated grains Concretionary Geode Pisoidal Matrix and grain-supported	Root-shaped Rod-shaped Columnar[+]	As above plus Rod-shaped	As above plus Platy[+] Laminated Heavy mineral streaks[++]	Dike Fissure filling
			Root channel Tubule Tubular	*Pipe Root channel*	*Fissure Slit*	*Fissure Slit*
	Pore Interstices	*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 FABRICS	Massive Crystalline Aphanitic	Crystalline[+] Granular[+] Ophitic[++] Nodular Concretionary Pisoidal Ooidal				
	Interstice Pore	*As above plus crystal mesh* *Interstice Pore*	*Alveolar Cavity Contorted tubule Microtube Tubule/tubular*		*Boxwork Crystal mesh Cellular Fissure Internal hollow Slit*	

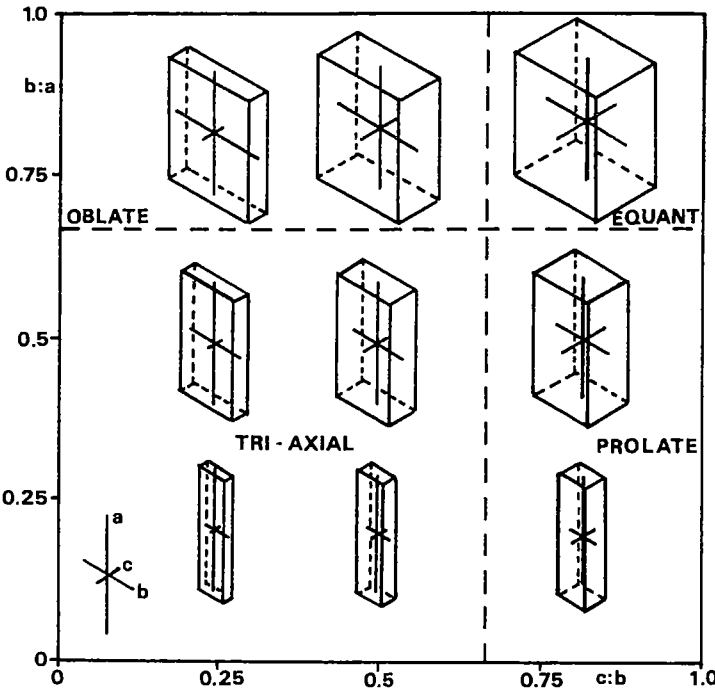[+] Frequently as parent rock relict. [++] As parent rock relict only. *Italics* indicate void terms.

Example of grain size nomenclature based on the Wentworth Scale.

^{1}) $\phi = - \log 2$ grain diameter in mm.

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

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 usually are subrounded to irregular, whereas the axes will not intersect in one point.

Annex IIIC — Proposed nomenclature for pisoids (pisoliths), based on their internal structure (nucleus-cortex relationship)

NUCLEUS CORTEX	Composition of the nucleus				
	Foreign matter			Lateritic matter	
				Homogranular and massive	
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	–

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: –

Annex IIID

Semi-quantitative relative abundance terminology

Abundance (%)	Code	Designation
100–50	d	dominant
50–25	p	plentiful
25–10	c	common
10–5	m	minor
5–1	a	accessory
1–0.1	r	rare
0.1–0	t	traces
	o	looked for but not identified
	x	not looked for

Annex IIIE — Proposed classification of voids

Definition: 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: INTERCRYSTALINE PORE
	    b: INTERGRANULAR PORE
		1 - With sharply defined walls
		    a: ALVEOLAR-CAVITY-CAVE-CAVERN
		    b: TUBE-TUBULE-PIPE
		    c: FISSURE-SLIT
		    d: INTERNAL HOLLOW
		    e: BOXWORK
		    f: CELL
		    g: RATTLE ROCK

	2 - Intraparticle pore
	    a: INTRACRYSTALINE PORE
	    b: INTRAGRANULAR PORE
		2 - With diffuse, gradual walls
		    a: FENESTRA
		    b: CRYSTAL MESH

Size terminology		Shape terminology, based on ratio of three perpendicular axes a, b and c	
< 4 mm	small alveole	$a{\geq}b{\geq}c$:	equant
4-16 mm	large alveole	$a{>}b{>}c$:	tri-axial
16-64 mm	small cavity	$a{\geq}b{>}c$:	oblate, lensoid mold
64-256 mm	large cavity	$a{\geq}b{>}{>}c$:	fissure
> 256 mm	cave	$a{>}b{\geq}c$:	prolate, spindle shaped mold
	if large cavern	$a{>}{>}b{\geq}c$:	tubular

Annex IIIF — Terminology for the description of the consistency of lateritic materials

STATE of the rock	RESPONSE[1]) to deformation (pressure, shear)
Consolidated	
Hard	Tough, brittle, splintery
Dense, medium hard	Conchoidal (fracture)
Soft	Brittle, sectile, doughy
Unconsolidated	
Hard	Tough, sectile, doughy
Soft	Plastic, sectile, sticky
Earthy	Friable, crumbly
Dense	Tough, brittle, sectile
Granular	⎫
Powdery	⎬ by definition loose
Disintegrated	⎭

[1]) to be used as modifiers to the terms listed in column at left.

Annex IV — Soil horizon designations: the Master Horizons according to FAO

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

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

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

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

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

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

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

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

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

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

Reference: FAO (1990)

Annex V - A

Characteristics of analytical methods for the investigation of lateritic rocks

Parameter	Analytical method							
	LOI	TG	BD	NA	XRF	DTA	WC	XRD
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 determination	xx	xx	x	=	x	x	=	x
- 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
- 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 costs	x	x	xx	x	xx	xx	xxx	xx
Capital costs	x	x	xx	xxx	xxxx	xx	xx	xx
Suitability for remote areas	xx	xx	xx	x	x	x	xx	x
Cost of duplicate analysis				80$		100$		200$

Codes

LOI Loss on ignition	# possible method	x acceptable, low
TG Thermogravity	− possible but low accuracy	xx good, medium
BD Bomb digest analysis	#/ possible with special arrangements	xxx excellent, high
NA Neutron activation analysis	* DTA peaks may overlap partly or completely	= not feasible
XRF X-ray fluorescent spectroscopy	. not aplicable	o absent
DTA Differential thermal analysis		$ immaginary monitary unit
WC Wet chemical analysis		
XRD X-ray diffraction analysis		

Epi-norm computation to transform chemical oxide data into epi-norm mineralogical data[1)]

Code	Mineral	A = Al$_2$O$_3$ %	H = L.O.I. %	S = R.SiO$_2$ %	Q = F.SiO$_2$ %	Fe = Fe$_2$O$_3$ %	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 remains amounts of loss on ignition (H') and alumina (A') that have to be divided over gibbsite and boehmite. This gives two equations with two unknows to solve. In the following equations a multiplication is indicated by the symbol * as used in 'Basic' programming; all percentage signs have been left out, an oxide or mineral code means its amount.

$$\text{KLT} = 2.151 * \text{R.SiO}_2 \dotfill 1/$$

This is a summation of three equations:

$$H_{KLT} = 0.301 * \text{R.SiO}_2 \dotfill 1a/$$
$$A_{KLT} = 0.850 * \text{R.SiO}_2 \dotfill 1b/$$
$$S_{KLT} = 1.000 * \text{R.SiO}_2 \dotfill 1c/$$

Remains for further assignment:

$$A' = A - A_{KLT} \dotfill 2/$$
$$H' = H - H_{KLT} \dotfill 3/$$

From the above mineral compositions it follows that:

$$H' = 0.176 * A_{BMT} + 0.529 * A_{GBS} \dotfill 4/$$
$$A' = A_{BMT} + A_{GBS}, \quad \text{or} \quad A_{BMT} = A' - A_{GBS}$$
$$\text{and} \quad A_{GBS} = A' - A_{BMT} \dotfill 5/$$

The two equations are solved as follows:

$$H' = 0.176 * (A' - A_{GBS}) + 0.529 * A_{GBS}$$
$$= 0.176 * A' - 0.176 * A_{GBS} + 0.529 * A_{GBS}$$
$$= 0.176 A' + 0.353 A_{GBS}$$

or

$$A_{GBS} = (H' - 0.176 * A') : 0.353 = 2.833 * (H' - 0.176 * A') \dotfill 6/$$
$$\text{in which } 0.176 * A' = X \text{ and } A_{GBS} = Y$$

[1)] The chemical data must include a differentiation between reactive silica and total free silica.

Type of artificial outcrop	Size of outcrop	Type of sample	Transport of sample to surface	Influence of laterite consistency on sample	Geologic informa-tion	Visibility of contact relations	Remarks	Examples	Suitability of methods
EXCAVATIONS									
1. PIT, hand-dug	minimum 0.8×1.2or 0.8 m cicular	channel in pit wall or bulk sample	by bucket on rope	free-standing walls required; hard beds may require blasting	very good	very good	efficient method in area with little infrastructure	Amazonas, BRA; Bintan, IND 15-30 m deep	geological observations in unaccessible terrain
2. TRENCH, by 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. AUS; Amazonas, BRA	geological observations, providing bulk samples for pilot plant testing
CASED DRILLHOLE									
3. EMPIRE/BANKA DRILL	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	reasona-ble to absent	useful to pentrate thick soil or overburden up to 80 m thick	Arkansas, USA; Nassau, SME; Onverdacht, SME with motor driven auger inside	most effective in unconsolidated rocks and/or remote unaccessible 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, or continuous: see text	almost any laterite; hard aphanitic iron-oxide bands may prevent further progress	limited	reasona-ble to absent	simple, fast and accurate when correctly used	Guinea, Pijiguaos, VEN	not for very hard laterite; independent of moisture, even below water-table reasonable recovery
5. CHEMCO BAILER DRILL, engine driven	Ø 10-25 cm	crumbs or loose nodules	lift out bailer at set intervals	only feasible in loose, granular to nodular laterite	limited	limited	excellent for fragile pisoids	Aurukun, AUS	mainly for unconsolidated fragile nodules or pisoids
6. VACUUM or SUCTION DRILL, engine driven	Ø 5 cm	crushed laterite	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 laterite	Mitchell Plat. AUS; Worsley, AUS	mounted on 4-wheel 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 Ø 5-10 cm	chips of all sizes	by air or foam pressure through anulus around drill stem	best in hard and brittle laterite; unsuitable below water-table	limited	limited	fast and efficient in massive, hard laterite; accuracy locally uncertain		only above water-table; requires heavy air compressor which consumes much fuel
8. CORE DRILLING, dry, water or mud flushing or by compressed air	Ø 5-25 cm	solid cylinder of laterite in compact core	hoisted out in core barrel	suitable in almost all circumstances, except loose, dry, small pisoids'	good	good	high degree of sampling accuracy; requires good roads	Amazonas ABMP, BRA; Lelydorp, SME, Mitchell Plateau, AUS	effective in almost any type of laterite; below water-table use triple core barrel

Annex VII

EXPLORATION, SAMPLE PREPARATION AND ANALYTICAL PROCEDURES
in an Australian perspective

Contributed by R.R. Anand, C.R.M. Butt, R.E. Smith and I.D.M. Robertson
The references follow directly after each section

1. Mineral exploration - an Australian perspective (IDMR, CRMB, RES)

Extensive areas of laterite and other deeply weathered regolith cover much of Australia and this has caused difficulties for the explorationist. One of the more economically significant regions, the Yilgarn Block of Western Australia, is a complex granite-greenstone terrain which is rich in metalliferous mineral deposits, particularly nickel and gold. The lateritic regoliths of the granites are covered in sand plains and those of the greenstones (metasedimentary and felsic to mafic and ultramafic metavolcanic rocks) are mantled by red soil. Depths to fresh rock are 40-100 m, even where the regolith is partly eroded to the saprolite level. This weathered blanket has hindered mapping and prospecting by weakening geochemical signatures and making recognition of rock types and gossans extraordinarily difficult. In many areas the residual weathered material is buried beneath accumulations of transported overburden. Recent research and developments in exploration technology have addressed some of these problems and improved the situation considerably (see Mazzucchelli, 1989).

Exploration Procedures

Knowledge of the geochemical and mineralogical characteristics of lateritic regoliths and an appreciation of the landform-regolith relationships are essential to successful exploration in these terrains. These factors dictate the nature of the geophysical and geochemical expressions of mineralization and hence the most important investigation and interpretative techniques. Such an understanding allows: (i) appropriate exploration methods to be chosen, (ii) design and execution of optimum geochemical programs, (iii) sensible data interpretation, and (iv) soundly-based integration of exploration findings. Effective procedures for identifying and evaluating gossans, use of lateritic nodules, duricrusts and lags as sampling media and recognition of the importance of geomorphology in planning and interpreting geochemical surveys have been the most significant advances.

Idealized dispersion models integrating this information have been developed for Australia (Butt and Smith, 1980) and similar models apply to related terrain elsewhere (Butt, 1987). Numerous examples of the geochemical expression of mineralization in lateritic terrains in different climates (rainforest, savanna, semi-arid) are given in Butt and Zeegers (1992).

Geophysics

Geophysical exploration procedures are hindered in areas of deep weathering, especially at the prospect scale. The low resistivity of the regolith screen the target from electromagnetic and induced polarization techniques and superimpose spurious signals. Concentration of magnetic minerals and density contrasts mask or attenuate magnetic and gravity signals and radiometric responses may be suppressed by overburden or overprinted by false anomalies from concentrated resistate minerals or secondarily mobilized uranium and its daughter products.

Refinement of time-domain electromagnetic instrumentation permits detection of signals from sulphide targets beneath conductive regolith, whereas the use of image processing techniques applied to remote sensing, gravity surveys and, in particular, airborne magnetic and radiometric surveys have been of great benefit for regional appraisal and area selection.

Laterite Geochemistry

Laterite geochemical techniques are widely used in Australia for initial mineral exploration and for follow-up work. Laterites have been found to contain relatively low-order anomalies of kilometre scale which are far greater in area than the equivalent anomalies found in fresh rock or saprolite. The act of hydromorphic and mechanical dispersion has tended to smooth much of the local chemical and mineralogical variation, making recognition of these low-order haloes generally easier (Smith, 1989). Laterite samples taken at a low sampling density (3 km) are suitable for deposits sited within plutons and stocks (Smith et al., 1986; Smith, 1989), polymetallic sulphide deposits of 10-20 Mt are amenable to exploration using 1 km spacing (Smith, 1989; Smith and Perdrix, 1983). Subvertical metamorphogenic Au deposits with target sizes as small as 200 x 5 m may be detected by laterite sampling at 400-1000 m intervals by not only Au analysis but by determination of a suite of associated chalcophile elements (Glasson et al., 1988).

Elements that have been found forming geochemical haloes in laterites are Ag, As, Au, B, Ba, Be, Bi, Cd, Co, Cr, Cu, Ga, Ge, In, Li, Mo, Ni, Nb, Pb, Sb, Se, Sn, Ta, Te, W and Zn (Mazzucchelli and James, 1966; Smith and Perdrix, 1983; Smith, 1989; Freyssinet et al., 1989). These lateritic geochemical haloes are formed around a wide variety of mineral deposits, including vein Au, base metal sulphide, rare metal, granite associated deposits etc.

Lag Geochemistry

Ferruginous (goethite, hematite, maghemite) nodules and fragments which form a lag, particularly over mafic and ultramafic rocks, have been used effectively as a geochemical sampling medium for some years (Carver et al., 1987). Because of the fine crystallinity and hence high surface area of goethite, these materials have considerable trace element absorptive powers, giving stronger anomalies and wider dispersions than their co-located fine, kaolinitic soil fractions. Hence lag has been shown to be effective in exploration for Au and base metals (Cu, Ni, Pb and Zn). Lag has the advantage of lying on the surface and so it is easy to collect. It occurs both over laterite and over eroded saprolitic zones.

Bedrock Identification

The fabric, colour and major element geochemistry of the bedrock have undergone considerable change in their transition to laterite, which makes identification difficult. Ferruginised relics of saprolite and even rare bedrock fabrics may be recognised but these are generally Fe-oxide pseudomorphs, need skill in their identification and considerable search. These may be found in the laterite and particularly in the lag derived from saprolite.

Typical signatures related to elements generally stable in the lateritic environment may be used to identify the bedrock but much depends on the stability of the minerals that contain them. Early work by Hallberg (1984) using Ti, Zr and Cr was able to distinguish the major igneous rock groupings in the saprolithic and the plasmic zones but this became in part unreliable in the mottled zone and above. Generally more sophisticated discriminant statistical procedures using reference groups and a broader suite of elements is necessary. Birrell (1985) showed that the main bedrock types in the Saddleback Greenstone Belt could be discriminated from each other using cannonical variate analysis of multi-element laterite geochemistry.

Secondary Mineral Deposits

The solubility and hence mobility of gold within the weathering environment is now well documented (Krauskopf, 1951; Cloke and Kelly, 1964; Mann, 1984; Webster and Mann, 1984; Webster, 1986). This has caused considerable redistribution of gold in the weathered zone over primary ore and led to the development of substantial (0.2-2.0 Mt) low-grade (1-3 ppm) secondary gold deposits in the saprolite and laterite (Davy and El-Ansary, 1986; Anand et al., 1990; Smith & Anand, 1992). These deposits are readily mined by open pit methods and the Au extracted by carbon-in-pulp processes.

In Australia, laterite development probably occurred under a seasonally humid climate (Au concentrated in the laterite) which later changed to an arid climate (Au partly redistributed in the saprolite (Butt, 1987; Butt,

1989)). In addition to gold, the process of lateritization has lead to secondary concentrations of bauxite (discussed elsewhere), manganese oxides, kaolinite, rare earth elements, phosphates and nickel (Nahon et al., 1992).

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2. Sample preparation (IDMR)

The complete analytical scheme should be decided upon before any sample preparation is commenced. Contamination is inherent in crushing and pulverising (Smith and Butt, 1983); there are two ways to minimise its impact. Pulverising implements, made of elements not sought in the analytical scheme, may be used, or implements may be used which are made of elements already present in excess. In the first case the contamination is ignored, in the second it is camouflaged. Comparatively little contamination is introduced by crushing to the 1-5 mm size range; by far the most comes from milling to 75 μm. The crushing and milling implements (jaw crusher, disc grinder, ring mill) should be constructed of hard materials, to minimise contamination. They should never be over-filled and milling time should be kept as short as possible to reach 95% <75 μm. Reduction of the sample size (1 kg field sample to 50-100 g laboratory aliquot) is necessary and must be done with care, using a variety of techniques, including the riffle splitter, mat roll, cone-and-quarter etc; again use of materials that will not contaminate the sample (e.g. PVC plastic, polythene etc) or introduce sample bias is essential (Gy, 1982). Representativeness must be preserved throughout the size reduction and preparation processes according to the principles set out by Gy (1982).

Although it is time-consuming, thorough cleaning of equipment between samples is necessary if cross-contamination is to be avoided. Many Fe- and Mn-rich materials leave a smeared coating on the grinding surface and this must be removed before loading a new sample. Two brief millings of clean quartz, with an ethanol wipe of mill parts between samples is recommended, alternately a wash with an aliquot of the next sample may be used. Crushers are cleaned with an air blast and zirconia press parts should be peened with glass shot.

For bauxite analysis, almost any milling materials, including tungsten carbide, are generally satisfactory. Multi-element trace geochemistry restricts the choice considerably; specialised low trace element Mn steels and agate are the most satisfactory. The zirconia press and alumina disc grinder may be used in some circumstances. There is little Zr contamination from a press but there is much from a zirconia mill. The disc grinder is difficult to clean properly and the agate mill is very slow.

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3. Mineralogical analyses (RRA)

The quantitative mineralogy of laterite samples is estimated using a combination of X-ray diffraction (XRD) and chemical analysis as follows. X-ray diffraction patterns of finely ground samples containing 10% CaF_2 as an internal standard are obtained using Cu or Co Ka radiation with a diffractometer and graphite diffracted beam monochromator. Amounts of secondary minerals (e.g. gibbsite, goethite, hematite, maghemite, quartz, boehmite, kaolinite, anatase, ilmenite and corundum) are determined by reference to patterns of mixtures of standard minerals also containing CaF_2 (Klug and Alexander, 1974). The main limitation to the accurate quantitative determination of minerals of variable crystallinity such as goethite and hematite by XRD lies in obtaining standard samples of goethite and hematite identical to the minerals in soil or laterite. To minimise this source of error, goethite and hematite standards may be isolated from laterites using a boiling 5M NaOH solution, to remove clays, followed by particle size fractionation (Kampf and Schwertmann, 1982).
    Iron oxides may also be separated for detailed mineralogical analysis and these are concentrated from the bulk samples by treating the soil with boiling 5M NaOH containing 0.2M Si, to prevent modification of the Fe oxides (Kampf and Schwertmann, 1982). For all Al substitution and XRD line broadening measurements, a halite internal standard should be added. A halite standard is used because it is easy to

wash out of the samples so that the sample may be used for other measurements. A diffractometer scanning speed of 0.25° 2Q/min is generally used and paper speed of 10 mm/min. Aluminium substitution in goethite is determined from the 111 reflection of goethite measured in units using the relation mole % Al = 2086 - 850.7d(111) (Schulze, 1984). Aluminium substitution in hematite is calculated from the a dimension of the hematite unit cell as obtained from d(110) using the relation mole % Al = 3109 - 617.1a (Schwertmann et al., 1979). The spacings and widths of reflections at half height are determined graphically after correcting for minor peak displacement and broadening by reference to reflections of the halite internal standard (Klug and Alexander, 1974).

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4. Geochemical analysis (IDMR)

Since the mid 1970's, several geochemical techniques have allowed reliable determination of chalcophile target and pathfinder trace elements to the low ppm levels and for Au and a few other elements even to the low ppb level. Laterites and other ferruginous materials have a matrix of highly variable Fe content that may severely disturb many instrumental techniques. Pathfinder and target elements are largely contained in resistant hematite and goethite, with lesser amounts adsorbed on clay particles and amorphous oxides, so analysis of the "total" content is generally preferable to partial extraction. If partial extraction is to be used, it should accompany the "total" analysis.

Laterites are enriched in highly refractory, insoluble minerals (chromite, zircon, rutile, ilmenite etc). Any technique involving dissolution of the sample must ensure that all these minerals are completely broken down and this may be difficult (e.g. Maqueda et al., 1986; Chao & Sanzolone, 1992). Colorimetry, Atomic Absorption Spectrometry (AAS)(Viets & O'Leary, 1992), Inductively Coupled Plasma Spectrometry (ICP)(Jarvis & Jarvis, 1992) and its mass spectrometry variant (ICP-MS)(Hall, 1992), require the sample to be presented in solution. Sample dissolution is a crucial step and should be carried out with care. In general $HF-HClO_4$ gives the best dissolution, with HNO_3-HClO_4 being better than $HClO_4$ alone (Gedeon et al., 1977). All three dissolutions may be unsatisfactory for Cr and V. ICP analysis (Hughes, 1988) is moderately reliable, particularly if fusion precedes dissolution, and is capable of simultaneous, and therefore cheap, multi-elemental analysis. ICP-MS analysis is very sensitive (ppb range).

The best and most reliable analytical schemes currently available are the non-destructive techniques of X-ray Fluorescence Analysis (XRF)(Potts & Webb, 1992) and Instrumental Neutron Activation Analysis (INAA)(Hoffman, 1992). Many trace elements may be quickly determined on pressed discs (Norrish and Chappell, 1977; Hart, 1989) and major elements on fused discs (Norrish and Hutton, 1969) by XRF. Recent work employes a "12:22" flux (12 parts $Li_2B_4O_7$, 22 parts $LiBO_2$: Sigma Chemicals) and a 1:4 sample to flux ratio. Minor difficulties may be encountered in making fused discs from Fe- and Cr-rich laterites; the degree of dilution and the fusion time may have to be increased. Instrumental Neutron Activation Analysis provides an excellent range of trace elements (Hoffman, 1989), including Au, and a 30 g sample vial is generally sufficient. It is particularly effective for As, Au, Sb, Mo and W. It has the minor disadvantage of a two week turnaround, dictated by the physics of radioactive decay, but this is generally outweighed by its sensitivity for some elements and its reliability.

Analysis of bauxites is a specialised and particularly complex case of laterite geochemistry. Major element analysis for at least Si, Al, Fe^{2+}, Fe^{3+}, Ti, H_2O^+ and H_2O^- with some trace constituents (Ca, Mg, Na, K, Zr, REE, Ga, V, As, P, Mn, Cr, CO_2, Cl, S and organic matter) is usual. Estimates of extractable alumina, reactive silica and the kaolinite, gibbsite and boehmite contents need to be made to determine the viability of bauxite. This involves pressurised extraction of the bauxite in a solution of hot NaOH (bomb digestion), coupled with X-ray diffractometry and other techniques (Bardossy, 1975). Standards should be used to monitor the analysis (LaBrecque and Schorin (1992). The bauxite composition is only one factor, among many, on which economic viability depends (e.g., Zambo and Osvald, 1975; Solymar, 1975).

Ultimately an analytical and sample preparation scheme will be a compromise between effectiveness and cost to successfully achieve the purpose for which the analysis is required. The increased use of large amounts of multi-element geochemistry is necessitating the use of sophisticated mathematical treatment of the data by computer to distinguish subtle anomalies (e.g. Smith et al., 1983; 1984).

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5. Laterite micromorphology investigation techniques (IDMR)

Selection of material for micromorphological study must be done with care as, by its nature, laterite is very inhomogeneous. The material may be broken off or sectioned with a diamond saw. Opaque minerals and structures (chiefly hematite, goethite and maghemite), are best studied by polished section. These are prepared by cutting a slab, setting it in epoxy or polyester resin (Cent and Brewer, 19**), grinding one surface flat in a diamond or carborundum lap and polishing it with progressively finer polishing powders (Burkart, 1981; Samuels, 1982). Initial study may be in oblique light, under a binocular microscope, where the gross fabric and true colours should be noted. For further fabric detail and mineral identification, normally reflected light (ore microscope) should be used in air, or possibly even using oil immersion, for high magnification. Here colours are related to reflectance and other optical properties such as anisotropism.

Study in transmitted light is only possible where the minerals are translucent, (e.g. kaolinite, gibbsite). A thin section (20 μm) should be prepared (Allman and Lawrence, 1972) which may be covered with a glass coverslip or left uncovered, in which case it may be polished on the top surface, allowing study in both transmitted and reflected light (mixture of opaque and translucent minerals) and access by electron optical techniques and microbeam analysis.

Detailed examination of a rough block, a polished or polished thin section may be made using a scanning electron microscope (SEM) in either backscattered electron mode (where the intensity of the image is related to the average atomic number of the material) or in secondary electron mode, where the topography of the image is emphasised (Reimer, 1985). Backscatter electron mode is most effective on flat surfaces. Qualitative chemical analyses, by energy dispersive X-ray analysis, of recognisable phases may be readily and quickly made using the SEM. For quantitative chemical analysis, a microprobe is necessary, using either energy dispersive or wavelength dispersive X-ray analysis of targets in excess of 5 μm in diameter of polished surfaces (Reed, 1975). Carbon coatings have to be applied for microprobe analysis, but some SEMs (Robinson and Nickel, 1979) do not require coating, which makes alternate microbeam analysis and conventional optical study very convenient.

Detailed study of particular mineral phases may be made using the transmission electron microscope (TEM). Here the area to be studied ($\varnothing$ 2-3 mm) is selected from a specially-prepared thin section. A small copper grid is glued to it and the study area detatched from the slide. The grid and its attached sample is subjected to argon-beam milling to produce a hole in the section with a feathered edge. Study using electrons transmitted through this very thin feathered edge achieve magnifications of over 1×10^6, and crystal orientations and defects as well as electron diffraction experiments may be carried out and the nature of the junction between reacting minerals may be resolved almost on the atomic scale. The analytical transmitted electron microscope (ATEM) is capable of semiquantitative chemical analysis of smaller targets than the microprobe. TEM work is very tedious.

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Annex VIII

Comparison table for the new and old international units

Unit	SI	cgs	Technical
length l	metre (m) $= 1$ m	centimetre (cm) $= 0.01$ m	metre $= 100$ cm
mass m	kilogram (kg) $= 1$kg	gram (g)	kgf $s^2 m^{-2}$
time t	second (s) $= 1$ s	second (s) $= 1$ s	second (s) 1 sec
force F	newton (N) $= 1$kg m s^{-2}	dyne (dyn) $= 10^{-5}$N	kgf [1] $= 9.807$ N
pressure p	pascal (Pa) $= Nm^{-1} =$ 1 kgm^{-1} s^{-2}	bar $= 10^{-1}$Pa s	kgf m^{-2} $= 9.807$ Pa
energy E	Joule (J) $= Nm$	erg $= 10^{-7}$ J	kg m^2 s^{-2} $= kgf$ m $=$ $= 9.807$ J
density ρ	kg m^{-3}	Spec. Grav. $= g$ cm^{-3}	kgf s^{-2} m^{-4} $= 9807$ kg m^{-3}

[1] $=$ kilogram force

The above gives a summary and comparison of the successive metric systems of measurements.

Prefixes

exa	E	10^{18}	deci	d	10^{-1}
peta	P	10^{15}	centi	c	10^{-2}
tera	T	10^{12}	milli	m	10^{-3}
giga	G	10^{9}	micro	μ	10^{-6}
mega	M	10^{6}	nano	n	10^{-9}
kilo	k	10^{3}	pico	p	10^{-12}
hecto	h	10^{2}	femto	f	10^{-15}
deca	da	10^{1}	atto	a	10^{-18}

Annex IX

Conversion table for selected units

gallon UK	0.004546	m³
gallon US	0.003785	m³
quart UK	1.1365	dm³ (=*l*)
quart US	0.9464	dm³ (=*l*)
ton, long	1016.0469	kg
ton, short	907.1847	kg
ton, metric	1000.0000	kg
ton, register	2.8317	m³
inch	0.0254	m
foot	30.48	cm
yard	0.9144	m
chain	20.12	m
ounce, avoir dupois	28.3495	g
ounce, apoth. or troy	31.1035	g
ounce, fluid UK	28.41	cm³
ounce, fluid US	29.57	cm³
mile, nautical/international	1852	m
mile, nautical UK	1853.18	m
mile, statue	1609.3	m
knot	1852	m/hour
square foot	0.0929	m²
square yard	0.8361	m²
acre	4046.9	m²
hectare (ha)	10 000.0	m²
cubic inch	0.0006	dm³ (=*l*)
cubic foot	28.3168	dm³ (=*l*)
cubic yard	0.7646	m³
cubic dm = 1 liter	0.001	m³
pound per cubic foot	16.0185	kg/m³
pound (mass) per square foot	4.8824	kg/m²
pound (mass) per square inch	703.0696	kg/m²
millimetre mercury	0.1333	kPa
foot per second	0.3048	ms⁻¹
joule (J)	1.0	newton metre = Nm
micrometre (μm)	10⁻⁶	m
10⁶ gallons per day	4546.09	m³/day
°C + 273.15	°K(elvin)	
°C × 9/5 + 32	°F(ahrenheit)	
(°F − 32) × 5/9	°C	

List of some low-pressure and/or low temperature minerals

Albite: Sodium feldspar, $Na(Si_3Al)O_8$, with less than 3% anorthite, $CaAl_2Si_2O_8$.

Calcite: A common carbonate, $CaCO_3$. Most calcite is relatively free from other ions and is fairly close in composition to $CaCO_3$.

Chlorite: A sheet silicate $(Mg,Fe^{2+},Fe^{3+},Mn,Al)_{12}[(Si,Al)_8O_{20}](OH)_{16}$. A group of minerals with layered structure, resembling mica's.

Clinozoisite: A silicate, $Ca_2Al \cdot Al_2O \cdot OH[SiO_7][SiO_4$ related to **Epidote:** $Ca_2Al_2O \cdot (Al,Fe^{3+})OH[Si_2O_7][SiO_4]$.

Glaucophane: A chain silicate, $Na_2Mg_3Al_2[Si_8O_{22}](OH)2$, with grey to lavender blue colour.

Laumontite: A framework silicate of the zeolite group, $Ca_4[Al_8Si_{16}O_{48}].16H_2O$.

Lawsonite: An ortho- and ring silicate, $CaAl_2[Si_2O_7](OH)_2.H_2O$

Prehnite: A sheet silicate, $Ca_2(Al, Fe^{3+})[AlSi_3O_{10}](OH)_2$.

Pumpellyite: An ortho- and ring silicate, $Ca_2Al_2(Al,Fe^{3+},Fe^{2+},Mg)_{1.0}[Si_2(O,OH)_7][SiO_4](OH,O)_3$.

Quartz: A framework silicate, SiO_2, varieties: α-Quartz, α-Tridymite, α-cristobalite. Chalcedony is a group name for the compact varieties of silica composed of minute crystals of quartz with submicroscopic pores.

Tremolite –
Ferro-actinolite: Chain silicate, $Ca_2(Mg,Fe^{2+})_5[Si_8O_{22}](OH,F)_2$. Amphibole group with Mg partly replaced by Fe^{2+} and, rarely, Mg and Zn. Within the Mg – Fe series the names **tremolite, actinolite** and **ferro-actinolite** are used for the ranges of Mg:(Mg+Fe) = 1.0–0.9, 0.9–0.5 and 0.5–0.0, respectively.

(from: Deer, Howie & Zussman, 2nd edition, 1992)

Annex XI

List of the rock forming minerals

List of minerals mentioned in the Handbook, with their chemical formulae, density (D), hardness (H), cleavage (#) and colours. For more detailed information the reader is refered to W.A. Deer, R.A. Howie & J. Zussman, An Introduction to The Rock-Forming Minerals, 2nd edition, Longman, 1992 (696 pp), from which the following summary data have been mainly derived.

Anatase TiO_2 D 3.8–4.0 H 5½-6 # {001} and {111} perfect
Brown, yellow, greenish blue, black; insoluble in acids. Low temperature polymorph of TiO_2. Accessory mineral in igneous and metamorphic rocks, pegmatites and as alteration product of other Ti minerals; common detrital mineral where it is often of authigenic origin.

Boehmite γ-AlO(OH) D ~3.0 H 3½-4 # {010} very good, {010} good
White when pure. Usually very fine-grained.

Biotite-Phlogopite $K_2(Mg,Fe^{2+})_{6-4}(Fe^{3+},Al,Ti)_{0-2}$ $[Si_{6.5}Al_{2-3}O_{20}](OH,F)_4$
D 2.7-3.3 H 2-3 # {001} perfect
Black, dark to reddish brown, yellow. Iron rich, tri-octahedral mica. Biotite has Mg:Fe < 2:1; phlogopite has Mg:Fe > 2:1.

Brucite $Mg(OH)_2$ D 2.4 H 2½ # (0001) perfect, may be fibrous
White, greenish, brownish. Alteration product of periclase in dolomite; also in low temperature hydrothermal veins in serpentinite and chlorite schists.

Chalcophile (GG), said of a chemical element concentrated in the sulphide rather than the metallic or silicate phases (of meteorites); essentially mantle-derived elements.

Chromite $FeCr_2O_4$ D 5.1 H: 5.5 # none
Black, grey. Mostly with considerable amounts of Mg, appreciable Al and some ferric iron; may contain zink. Insoluble in acids.

Corundum α-Al_2O_3 D 4.0 H 9 # none
White, grey, blue, red, yellow, green. Insoluble in all acids.

Diaspore α-AlO(OH) D 3.3-3.5 H 6½-7 # {010} p, {110}, {210}, {100} less common

White, grey-white, colourless. Fe & Mn containing varieties green, brown, yellow, pink. In certain bauxites.

Feldspar

    Alkali Feldspar: (K, Na)[AlSi₃O₈]
        D 2.5-2.6 H: 6-6½ # {001}, {010} perfect
    Colourless, white, sometimes pink, yellow, white or green

    Plagioclase: Na[AlSi₃O₈] - Ca[Al₂Si₂O₈]
        D 2.6-2.8 H 6-6½ # {001} perfect, {010} good, {110} poor
    The plagioclase series includes six minerals in a Na → Ca series: albite, oligoclase, andesine, labradorite, bytownite, anorthite.

Feldspathoids - a group of common rock-forming minerals consisting of Na, K or Ca aluminosilicates; related to feldspars but formed in igneous rocks undersaturated in silica. Includes leucite, nepheline, sodalite, nosean, haüyne, lazurite, cancrinite and melilite (GG).

Garnet $R^{2+}_3Al_2[SiO_4]_3$ D: 3.2 - 4.3   H: 6-7½   # none, sometimes parting {110}
Red, brown, black, green, yellow, pink, colourless.
A group of cubic aluminous silicates of metamorphic origin but also found in some igneous rocks and as detrital grains in sediments. R may be Mg^{2+} (= **pyrope**), Fe^{2+} (= **almandine**), Ca^{2+} (= **grossular**), Mn^{2+} (= **spessartine**), Ca^{2+}, Fe^{2+} + some Ti^{2+} (= **andradite**), or Ca^{2+} and Cr^{2+} (= **uvarovite**).

Garnierite = Ni serpentine.

Gibbsite $Al(OH)_3$ D ~2.4   H: 2½-3½   # {001} perfect
White, pale pink, green, grey, light brown.

Goethite α-FeO.OH   D ~4.3   H 5-5½   # {010} perfect, {100} moderate
Yellowish brown to red; yellow streak

Halite   NaCl   D: 2.16   H: 2½   # {100} perfect
Colourless, white, orange, red, grey, yellow, blue. Soluble in water; salty taste.

Halloysite - see Annex XII for summary of clay minerals.

Hematite α-Fe$_2$O$_3$ D 5.25   H 5-6   # none, parting {0001} & {1011}
Black, steel-grey, and bright to dull red; distinctive cherry-red streak.
Red ochre = earthy hematite
Martite = hematite in dodecahedral or octahedral crystals pseudomorphous after magnetite or pyrite.

Hornblende $(Ca, Mg, Fe, Al)[Si_6Al_2O_{22}](OH)_2$ with little Na, K and OH, F.
                D 3.0-3.6   H 5-6   # {110} good, parting {110} and {110}
Very dark to pale green, brown, yellow-brown.

Ilmenite $FeTiO_3$ D 4.7-4.8   H 5-6   # none
Black. Common accessory mineral in igneous and metamorphic rocks, also in veins; associated with gabbro, norite, anorthosite; ubiquitous detrital mineral.

Kaolinite - see Annex XII for summary of clay minerals.

Low pressure minerals - minerals that are formed or are stable under low pressure conditions, i.e. near the surface.

Maghemite γ-Fe$^{3+}_2$O$_3$ D 4.88   H 7.5-8   # none, parting {111} may occur
Opaque. Metastable, inverts on heating to hematite.

Magnesite $MgCO_3$ D 2.98-3.5   H 3½-4½   # {1011} perfect
White, colourless, Fe-bearing varieties may be yellow or brown.
Member of solid solution series $MgCO_3$ — $FeCO_3$
Alteration products of Mg-rich igneous and metamorhic rocks.

Magnetite $Fe^{2+}Fe^{3+}_2O_4$ D 5.2   H 5.5-6.5   # none, parting {111}
Opaque; abundant and ubiquitous in igneous and metamorphic rocks; the principle magnetic ore.

Metahalloysite - see Annex XII for summary of clay minerals.

Mica - see biotite, muscovite.

Montmorillonite - see Annex XII for summary of clay minerals.

Muscovite $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$
                    D 2.77-2.88   H 2½-3   # {001} perfect
Colourless, light shades of green, red or brown.
One of the most common mica's; occurs in a wide variety of geological environments, including regionally metamorphosed sediments.

Olivine $(Mg,Fe)_2[SiO_4]$ D 3.22-4.39   H 7-6½   # {010} moderate, {100} imperfect
Green, yellow. Common mineral in basic and ultrabasic rocks; susceptible to hydrothermal alteration and weathering, producing serpentine, chlorite, amphibolite, talc, carbonates and Fe oxides.

Pyroaurite - see Glossary.

Pyrite FeS_2 D 4.95-5.03   H 6-6½   # {001} poor
Pale brassy yellow, black when fine-grained, metallic lustre.
The most abundant sulphide mineral with widespread occurrence. It occurs as masses, and veins of hydrothermal origin, both primary and secondary minerals in igneous and in sedimentary rocks.

Pyroxenes - A group of chain silicates, essentially a mixture of the end members, $MgSiO_3$ and $FeSiO_2$ (the orthorhombic group) and of $CaMgSi_2O_6$, $CaFeSi_2O_6$, $Mg_2Si_2O_6$, and $Fe_2Si_2O_6$ (the monoclinic group).

Enstatite $(Mg,Fe^{2+})SiO_3$ (orthorhombic)
                    D 3.1-3.3   H 5.5   # {210} good, parting {010}

Colourless, grey, green, yellow, brown. Common in some ultra-basic
rocks: pyroxinites, etc., associated with olivine, augite and spinel.

Ferrosilite (= Hyperstene) $(Fe^{2+},Mg)SiO_3$ (orthorhombic)
                    D 3.4-3.5   H 5-6   # {210} good, parting {101}
Green, dark brown.

Diopside - hedenbergite $CaMgSi_2O_6$ — $CaFeSi_2O_6$
                    D 3.22-3.56   H: 5½-6½   # {110} good, {100} & {001} partings
White, pale-dark green (diopside) - brownish green, dark green, black (hedenbergite)
Typical for a variety of metamorphic rocks, the Mg-rich varieties in particular characteristic for metamorphosed Ca-rich sediments.

Augite $(Ca,Mg,Fe^{2+}Fe,^{2+},Ti,Al)_2[(Si,Al)_2O_6]$ monoclinic
                    D 3.19-3.56   H: 5-6   # {110} good, {100} & {010} parting
Pale brown, brown, purplish brown, green, black.
Occurs mainly in igneous rocks: gabbro, dolerite, basalt.

Pyrophyllite $Al_4[Si_3O_{20}](OH)_4$
                    D: 2.65-2.90   H: 1-2   # {001} perfect
White, yellow, pale blue, greyish or brownish green, pearly lustre
Occurs in fine-grained, foliated lamellae, radiating granular larger crystals and needles, and in massive aggregates of smaller crystals; comparatively uncommon mineral formed by hydrothermal alteration of feldspar.

Quartz SiO_2 D 2.65   H 7   # none
Colourless, white and variable: black, purple, green, etc. Second most abundant mineral next to feldspar.

Rhodochrosite $MnCO_3$ D 3.2-4.1   H 3½-4   # {1011} perfect
       Rose-pink, pink, red, brown, brownish-yellow
       Occurs in high temperature, metasomatic deposits, associated with other Mn minerals.

Rutile TiO_2 D 4.23-5.5   H 6-6½   # {110} good
       Reddish brown, black, violet, yellow, green

       The high temperature polymorph and most common form of TiO_2 in nature; very well distributed in minute grains in many igneous rocks and as secondary mineral in metamorphic rocks. Often as inclusions in other minerals such as quartz and biotite.

Sericite : a fine-grained, white mica (muscovite) or paragonite, often with a relative high SiO_2, MgO and H_2O content and low in K_2O. Monoclinic.

Serpentine $Mg_3[Si_2O_5](OH)_4$ D 2.55-2.6   H 2½-3½   # {001} perfect
       White, yellow, grey, colourless.
       Varieties:
       Chrysotile: fibrous // X,   D 2.55   H 2½
       Lizardite: # {100} perfect   D 2.55   H 2½
       Antigorite: # {001} perfect   D 2.6   H 2½-3½
       Principal occurrence in altered ultra-basic rocks; alteration − presumably − may be due to the rise of ultrabasic rocks from their original deep-seated place of origin to their present day surface position.

Sillimanite Al_2SiO_5 D 3.23-3.27   H 6½-7½   # {010} good
       Colourless, white, also yellow, brown, green, bluish. A high temperature polymorph of Al_2SiO_5, fond in higher grade metamorphic argillaceous rocks (gneisses, hornfels).

Smectite - see Annex XII for summary of clay minerals.

Spinel - cubic mineral; see magnetite, maghemite, chromite.

Stichtite - see Glossary.

Staurolite $(Fe^{2+},Mg,Zn)_2(Al,Fe^{3+},Ti)_9O_6[(Si,Al)O_4]_4(O,OH)_2$
                         D 3.74-3.83   H 7   # {010} moderate
       Dark brown, reddish brown, yellow-brown;
       Common in medium grade, regionally metamorphosed argillaceous sediments, in particular in those rich in aluminium.

Talc $Mg_6[Si_8O_{20}](OH)_4$ D 2.58-2.83   H 1   # {001} perfect
       Colourless, white, pale green, dark green, brown
       Common product of hydrothermal alteration of ultrabasic rocks and of low grade thermal metamorphism of silicious dolomites (Ca-Mg carbonates).

Tourmaline $(Na,Ca)(Mg,Fe,Mn,Li,Al)_3(Al_6,Mg,Fe^{3+})_6[Si_6O_{18}](BO_3)_3(OH,F)_4$
                         D 3.03-3.22   H 7   # {1120} and (1011), very poor
       Colour extremely variable: black, blue, green, pink, red
       Characteristic for granite pegmatites, pneumatolitic veins, some granites and in metamorphic rocks; in columnar to needle shaped grains, often in radial arrangements.

Vermiculite - see Annex XII for summary of clay minerals

Zircon $Zr[SiO_4]$ D 4.6-4.7   H: 7½ # 110 imp, 111 poor
       Reddish brown, yellow, grey, green. Common accessory mineral of igneous rocks and sediments, often surviving several cycles of weathering, erosion, transport and sedimentation.

Summary of Clay Minerals

Clay minerals are formed by decomposition of rocks through weathering, alteration or hydrothermal action. They generally occur as fine (< 2 µm) platy particles, mostly in fine-grained aggregates. Chemically they are hydrous silicates of aluminium in which part of the Si or Al may have been replaced by other cations. On heating they loose their adsorbed and their constitutional water. With some exceptions they are considered to be phyllosilicates (sheet silicates). Their structure is based on composite sheets either consisting of: (1) one layer of tetrahedrally coordinated $[(SiO_4O_{10}).(OH)_2]^{6-}$ linked with one layer of octahedrally coordinated $[Al_4(OH)_6]^{6+}$ (1:1 minerals) or (2) two layers of tetrahedrally coordinated $[(SiO_4O_{10}).(OH)_2]^{6-}$, with a central layer of octahedrally coordinated Al, Mg or Fe and OH ions sandwiched between the two tetrahedral layers (2:1 minerals). Si in the tetrahedron layer may be replaced by Al; Al in the octahedron layer may be replaced by Mg or Fe.

In the 1:1 minerals the successive composite sheets are directly superimposed except that in halloysite the space between the composite sheets contains a single layer of H_2O molecules. In the 2:1 minerals the sheets have a net negative charge which is balanced by cations such as such as K, Mg, Ca and Na that are located between the sheets; in smectite and vermiculite water and certain organic cations may penetrate into the spaces. As a result of the intercalated ions and molecules the repeat distance perpendicular to the sheets ranges from 7 Å (1:1 minerals) to 15 Å or more, depending on the water content (2:1 minerals).

Sheet-spacing	Mineral	Inter-sheet cations	CEC[1]	Remarks on genesis
7 Å	Kandite Group [1:1] kaolinite dickite nacrite halloysite metahalloysite	nil	3–15	Alteration of acid rocks, feldspars, etc; acidic conditions.
10 Å	Illite Group [2:1] illite hydro-mica phengite brammallite glauconite celadonite	K	10–40	Alteration of micas, feldspars etc. Alkaline conditions. High Al and K concentrations.
15 Å	Smectite Group [2:1] montmorillonite nontronite hectorite saponite sauconite	Ca, Na	60–150	Alteration of basic rocks, volcanic materials. Alkaline conditions. Availability of Mg and Ca; deficiency of K.
14.5 Å	Vermiculite Group [2:1]	Mg	100–150	Alteration of biotite, or of volcanic material, chlorites, hornblende, etc.
	Palygorskite Group palygorskite attapulgite sepiolite			Alkaline conditions and high activity of Si and Mg in solution
	Allophane		25–50	Amorphous $Al_2O_3.SiO_2nH_2O$. Alteration of volcanic ash

[1] Cation Exchange Capacity in c(+)mol/kg (= meq/100g)

After Deer et al. (1992)

Data on some common minerals from the weathering zone

Name	Formula Crystal system	Density Hardness	Cleavage	Colour
Boehmite	γ-AlO(OH) orthorhombic	3 3.5–4	{010} very good {100} good	white
Gibbsite	Al(OH)$_3$ monoclinic	2.4 2.5–3.5	{001} perfect	White, green, grey, brown
Goethite	α-FeO.OH orthorhombic	4.3 5–5.5	{001} perfect {100} moderate	yellow-brown, red
Hematite	α-Fe$_2$O$_3$ trigonal	5.25 or less 5–6	parting	black, grey, red
Maghemite	γ-Fe$_2$O$_3$ cubic	4.9 7.5–8	none	black
Magnetite	Fe^{2+}Fe^{3+}$_2$O$_4$ cubic	5.2 7.5–8	none	black
Montmorillonite	[1])	2–3, variable 1–2	{001} perfect	white, yellow, green
Olivine	(Mg,Fe)$_2$[SiO$_4$] orthorhombic	3.2–4.4 7–6.5	{001} imperfect to moderate, {100} imperfect to weak	green, yellow
Serpentine	Mg$_3$[Si$_2$O$_5$](OH)$_4$ trigonal, monoclinic or orthorhombic	2.6 2.5	{001} perfect to fibrous	green, yellow, white, grey
Talc	Mg$_6$[Si$_8$O$_{20}$](OH)$_4$ triclinic or monoclinic	2.6–2.8 1	{001} perfect	colourless, green,white, brown

[1]) (½Ca,Na)$_{0.7}$(Al,Mg,Fe)$_4$[(Si,Al)$_{0.8}$O$_{20}$](OH)$_4$.nH$_2$O, monoclinic.

After Deer et al. (1992)

Iron compounds in soil environments

Mineral	Chemical composition
Hematite	α-Fe$_2$O$_3$
Maghemite	γ-Fe$_2$O$_3$
Magnetite	Fe$_3$O$_4$
Goethite	α-FeOOH
Lepidocrocite	γ-FeOOH
Ferrihydrite	Fe$_2$O$_3 \cdot$ 2FeOOH $\cdot$ 2.6H$_2$O
Feroxyhite	δ-FeOOH

After: Schwertman & Taylor (1989)

PRINCIPAL GEOCHEMICAL TYPES OF SURFICIAL ALTERATION

Place of ferrallitization

After Pedro & Melfi (1983)

Evolution of alumino-silcates	Degree of hydrolysis	Total hydrolysis	Partial hydrolysis	
	Silica chemistry	Total desilicification	Partial desilicification	
	Minerals of neoformation Characteristics	Al hydroxides ALLITES	Clay silicates SIALLITES	
	Mineralogical types	Gibbsite Al(OH)$_3$ Boehmite γAlO.OH	Kaolinite (1/1 = KLT)	Smectite (2/1)
	Geochemical process	ALLITIZATION	MONO-SIALLITIZATION	BI-SIALLITIZATION
	Geochemistry of alkaline & earth alkaline cations	Total desalkalinization		Partial desalkalinization
Evolution of Fe & Mg minerals	Mineralogical types	Ferric hydrates amorphous & crystalline compounds αFe_2O_3 = HMT & $\alpha FeOOH$ = GTT		Ferric smectite (nontronite)
General evolution of rocks	Geochemical processes	FERRALLITIZATION		Sialferritization
		Sensu stricto (ultraferrallitization)	Sensu lato	
	Characteristic paragenesis	GBS + ferric hydrates (oxidic type)	KLT + ferric hydrates (kaolinitic type)	Smectite (Al-Fe)

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

CHART I

THE GREAT WAYS OF SUPERFICIAL EVOLUTION UNDER FERRALLITIZING TROPICAL CONDITIONS

After Pedro & Melfi (1983)

Ways of Evolution	Characteritic mechanisms	Corresponding phenomenon	Genetic conditions		Relations with the pedoclimate
I Homogeneous ways	Clay-iron association. Maintained skeleton-plasma bonding	Ferrallitic pedogenesis	Humid medium permanently drained		Zonal evolution
II Heterogeneous ways with segregation	Separation of clay versus iron and/or skeleton versus plasma	Lateritization sensu lato	Alternating pedoclimates	Alternation of humid and dry seasons	
				Alternation of humid drained periods and waterlogged periods (free groundwater)	Seasonal evolution

CHART II

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.

The following extended abstract of the above invited paper is added because of the concise way it explains the different environmental requirements and restrictions for the formation of either plinthite, ferrallite or laterite. The paper is summarized by the authors in the attached charts I & II.
N.B.: Between [...]synonymous terms added by the compiler; 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-siallitisation and bi-siallitisation (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, the weathering is **selective**:

a. the most vulnerable minerals are attacked before the Al silicates; weathering is diachronic, the levels (zones) under evolution always contain primary, not yet decomposed minerals; the newly formed minerals are the result of discrete, crystallo-chemically 'transformed' constituents, 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 **non selective**; it develops as follows:

a. all weatherable minerals are effected simultaneously (synchronous) and generally disappear from the horizon (zone) under attack; the process of neoformation is dominant and evolves into a level essentially composed of secondary minerals with no weatherable primary minerals present;
b. weathering reaches to great depth, so much so that only the upper, surficial layer shows a characteristic pedological evolution. In some instances the weathering profile is composed of two levels: an upper one which is the pedological solum, and a deeper one composed of alterites.

Type of alteration/weathering. See Chart I.

Ferrallitisation* (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 separately and independently individualized from the clay minerals (kaolinite).

There are two parageneses:

a. Al-hydroxide + Fe^{+++}hydrate $\rightarrow$ Ferrallitization *sensu stricto* = ultra-ferrallitization = oxidic ferrallitization.
b. Fe^{+++}hydrate + kaolinite $\rightarrow$ ferrallitization *sensu lato* = kaolinitic ferrallitization.

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

The 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. Oscillating water-table: concerns the temporarily flooded part of the profile (common names used: mottled clay, argile tachetée, 'groundwater laterite', retichron). The results of successive reduction and oxidation zones is the separation of clays and ferruginous components → heterogenous levels of grey, 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 ultra-dry 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 ferrallitization, Leprun, 1979).

Captions to colour plates

Plate A:

Laterite of the East Coast and in Kerala State, West Coast of India.

1 — The photograph shows the lower bench of a bauxititic laterite profile over khondalite parent rock. The upper two benches of 6 m thickness each, have been removed by mining. The lower bench shown includes a white kaolinite layer within the laterite profile, a not infrequent occurrence in places with gently dipping khondalite. Panchpatmali bauxite mine, NALCO, Orissa State, Easter Ghats bauxite district, India; photograph by Dr A.K. Nandi, Nagpur, India.

2 — Artisanal 'brick' quarry; cutting of laterite 'bricks' with steel tools, Palayangadi near Angadipuran, Kerala State, West Coast of India.

3 — Typical non-directional fabric of laterite from near Palayangadi. Scale is 0.7 of true size.

4 — Pile of laterite 'bricks', waiting to be used at a building site. Average thickness of bricks 15 cm, length 40 cm. Kerala State, India.

Plate B:

1 — Bauxite vein crosscutting stratified highly aluminous laterite (sediment derived bauxite); little or no kaolinite is present. Scale: hammer head is 17 cm, handle is 28 cm long. From: St. Helena Hill, Onoribo, Suriname.

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

3 — Quartz-rich ferriferous bauxite, representing the upper part of the accumulation layer over a granite-derived laterite/bauxite. The photograph shows abundant granite-derived quartz in a ferruginous cement showing concentric deposition around the quartz grains. From: ALCOA mine, Darling Ranges, Western Australia. Scale: ca. 3.5 times enlarged.

4 — Same, with a distinct pisoidal fabric. Note the variable relations between nucleus (variable composition, even within one pisoid) and cortex. The outer cortex may envelop more than one nucleus. Scale ca. 3.5 times enlarged. From same locality as photograph 3.

Plate C:

1 — Direct contact between fine-grained, fresh, dark green and quartz free foyalite (the parent rock) and its lateritic weathering rim (bauxite). Scale in mm and cm. From: Poços de Caldas, Minas Gerais, Brazil.

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

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

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

Plate D:

See block diagram I (Fig. 12) — the border of the 'Iron Quadrangle' along the road Ouro Prêto - Bela Horizonte, Minas Gerais, Brazil. Photographs S.B. de Rezende.

a — Laterite profile at site A, showing detrital accumulation of itabirite*; the laterites show a strong magnetic susceptibility.
b — Heap of laterite chunks; seen from the inward of the block toward the East - the most remote bushes are at the edge of the cliff.

See block diagram II - at the top of the 'Iron Quadrangle', inside a small sedimentary, clayey basin (palaeoplaya), along the road Bela Horizonte - Rio de Janeiro.

c — Clay and bauxite; below the cutting edge of the spade is hardened bauxite ore. Many of the white spots are giant, vertical pedotubules - see next plate.
d — Border of the sedimentary basin, seen from the inward of the block toward the East. The most remote bushes are at the edge of the cliff.

Plate E:

See Block diagram III (Fig. 12) — overview of laterite/bauxite on the uppermost geomorphological surface, close to the City of Cataguazes, MG. Site E. Photographs S.B. de Rezende.

a — Detail of the bauxite profile. A dashed line marks the bottom of the oxisol, and a solid line the boundary between the concretionary B horizon and the C horizon - both B and C horizon are bauxite ore.
b — Boulder of bauxite with white "palaeoworm" effect, i.e. giant pedotubules.

Block diagram IV: showing the upland close to the town of Realeza, MG., Site F.

c — A shovel full of bauxite chunks with worm activity and isolated pedotubules.
d — two pictures from the same horizontal surface:
Below: the large white, rounded spots are vertically continuous into the subsurface. Iron oxide (hematite) along the large, white pedotubules; see also the smaller pedotubules.
Above: multiple red rings, most of them centred around a white pedotubule.

PLate F:

1 — Bauxitization of medium-grained granite; the mica flakes from the granite are still visible as such. Scale in mm. From: Bintan Island, Indonesia.
2 — Lateritized dolerite with distinct relict fabric. Enlargement circa 3.75x. From: Kartkloof, Natal, South Africa.
3 — Pegmatitic dolerite, partly converted to aluminous laterite; the bluish grey fresh dolerite - outcropping in an extensive bauxite mine pit - illustrates the weathering resistance of a very coarse-grained rock. Scale: hammer head is 17 cm., handle is 28 cm long. From: Alcoa bauxite mine, Darling Ranges, West Australia.
4 — Bauxitized basaltic pillow lava with pillow structure perfectly preserved (with frequent pisoids within the pillows!). Scale as in photograph 3. From: Mitchell Plateau, NW Australia.

Plate G:

1 — Upper part of a 6 - 10 m thick bauxite bed of Palaeocene age, covered by Miocene and younger sediments. The bauxite is transected by kaolinitic veins representing the destructive action of Oligocene and later climatic conditions.
2 — Detail of one of the low iron veins, with a pink, bauxitic selvage along the ferruginous main mass, and a white centre composed of kaolinite with some metahalloysite. Scale: width of vein circa 25 cm. From: Onverdacht bauxite mine, Suriname, South America.

3 — The ferriginous bauxite deposit of Mineração Rio Norte, Trombetas area, Brazil. The bauxite bed is overlain by a circa 8 — 10 m thick pure kaolinitic layer, which is covered by an Amazonian type tropical forest.

4 — Detail of a sliced piece of low iron bauxite from the Rio Norte mine, showing the highly porous nature of the bauxite. Scale circa 3x enlarged. From: as above.

Plate H:

1 — Slice through a hematite-kaolinite-rich (1) duricrust showing vermiform voids (2). From: Lawlers Mine, near Leinster, West Australia. Photo RRA.

2 — Slice through a fragmental duricrust developed from mica schist showing slightly schistose hematite-kaolinite-rich fragments (1) set in a kaolinite matrix (2). Fragments in thin sections show a mica fabric. From: Mt Gibson Mine, Western Australia. Photo RRA.

3 — A slice through a pisolitic duricrust, developed from dolerite, showing black hematite-maghemite-rich pisoliths (1) set in a gibbsite-rich matrix (2). From: Darling Ranges, Western Australia. Photo RRA.

4 — Packed pisolitic duricrust. Hematite-rich pisoliths are cemented together where they touch, due to packing, by an outer layer of goethite. From: Darling Ranges, Western Australia. Photo RRA.

Plate I:

1 — A breakaway on granite. A thin armour of brown laterite duricrust (DRC), which resists erosion, overlies a deep mottled zone (MTZ) on granitic saprolite. Both mottled zone and duricrust are cut by a quartz vein [Q]. From: East of Davyhurst, Western Australia. Photo IDMR.

2 — A breakaway (erosion scarp) developed on a granite. Caverns have developed in the saprolite, undercutting the silcrete and cemented arenose horizon. Below this are a debris slope and pediment. From: Dalgaranga, Western Australia. Photo CRMB, taken from an extension of the same duricrust.

3 — A degraded pisolitic duricrust. Pisolithic duricrust showing dissolution of gibbsitic matrix, leaving a packed duricrust. From: Darling Ranges, Western Australia. Photo RRA.

4 — A cementation front [CF] showing the sharp transition from upper saprolite to mottled zone. The mottled zone has large, vertical mottles developed in a quartz-kaolinite deposit, filling a channel eroded into lateritic terrain. It shows that weathering and redistribution of elements has been an on-going process for some time. Scale: see CRMB, who is 1.9 m tall. From: Kanowna, Western Australia. Photo IDMR.

Plate J:

An example of laterite degradation resulting from post-laterite adverse environmental conditions.

The photographs show the abrupt, planar contact between low-iron laterite (bauxite; total thickness 7-11 m) and its irregularly bedded sandy sedimentary cover. The contact plane between bauxite and sand is remarkably flat and sharp, suggesting a marine abrasion surface. It is overlain by Oligocene-Miocene fluvial sands of the Lower Coesewijne Formation, the oldest member of the sediments covering the bauxite. The photograph shows this contact in a mine face at ~20 m below the present surface, which is just above the present sea level, and ~60 km South of the present ocean shore. The unconformity and the relict bedding in the bauxite are dipping away from the observer, i.e. to the North and toward the ocean. The low iron, 'bleached' bauxite contains veins and irregularly shaped masses of mainly kaolinite with some metahalloysite (Montagne, 1964) and fragments of bauxite - see also Fig. 11. Veining and bleaching are considered retrograde processes resulting from lower ambient temperatures and a less humid climate (Krook, 1979). Scale: hammer handle is 28 cm long. Photograph by courtesy of H. Morroy, 1977.
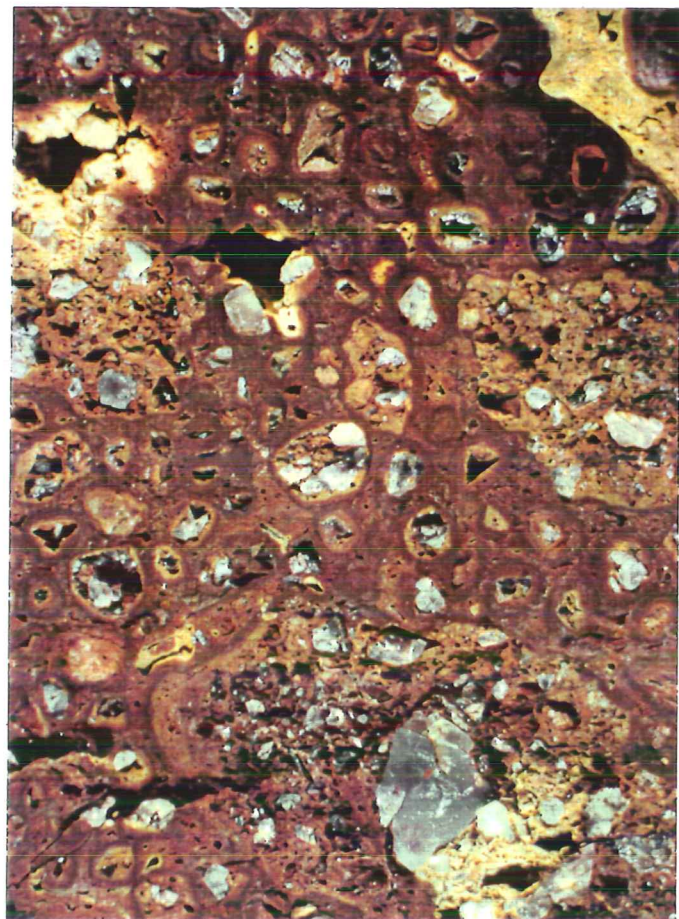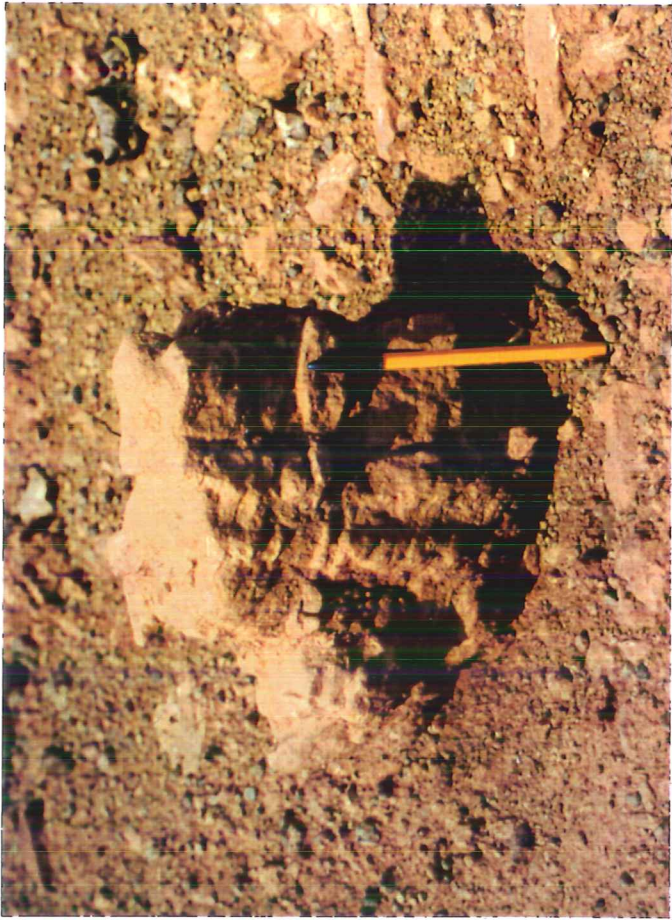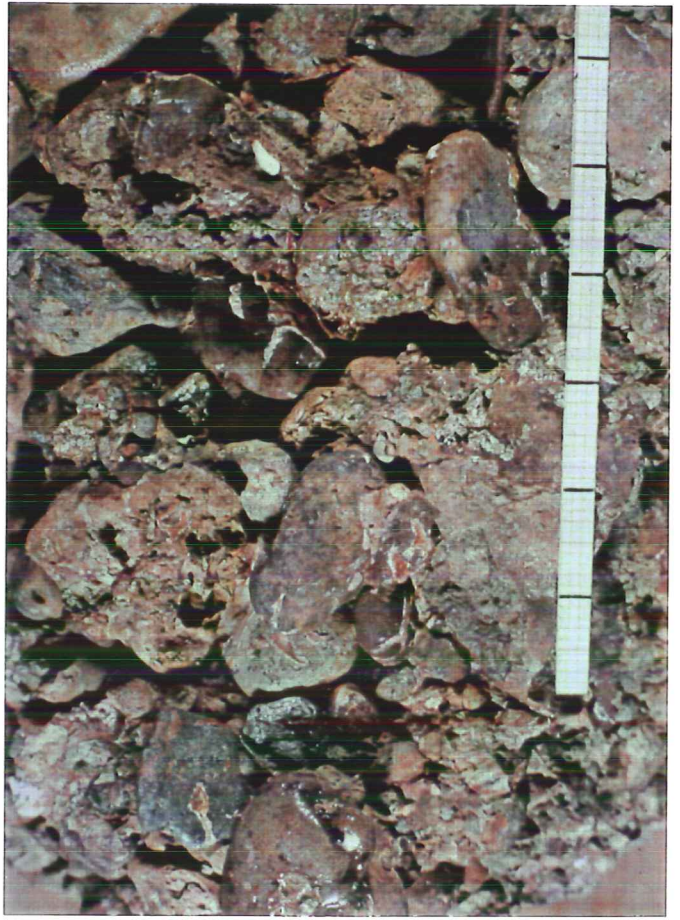
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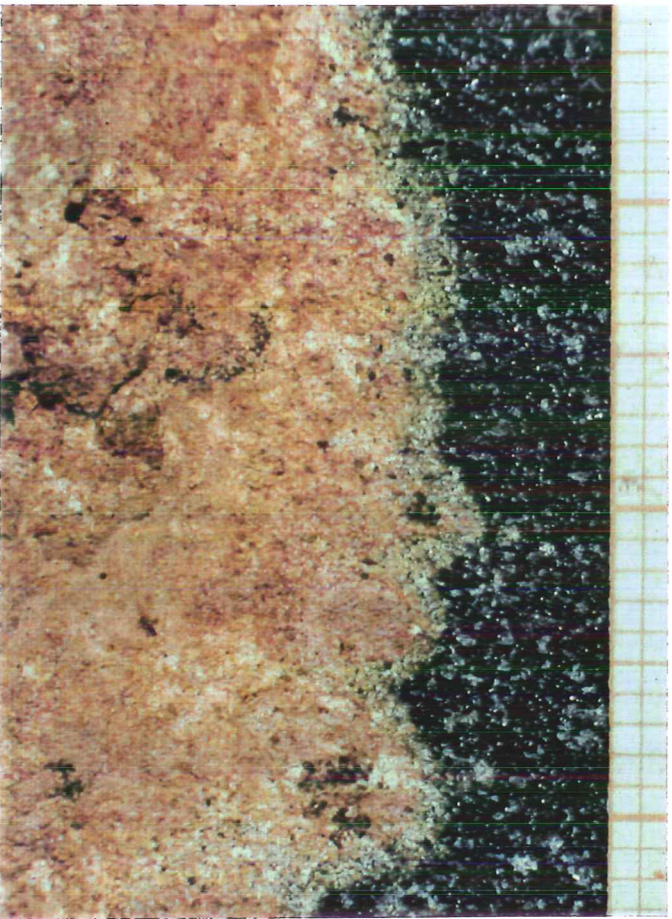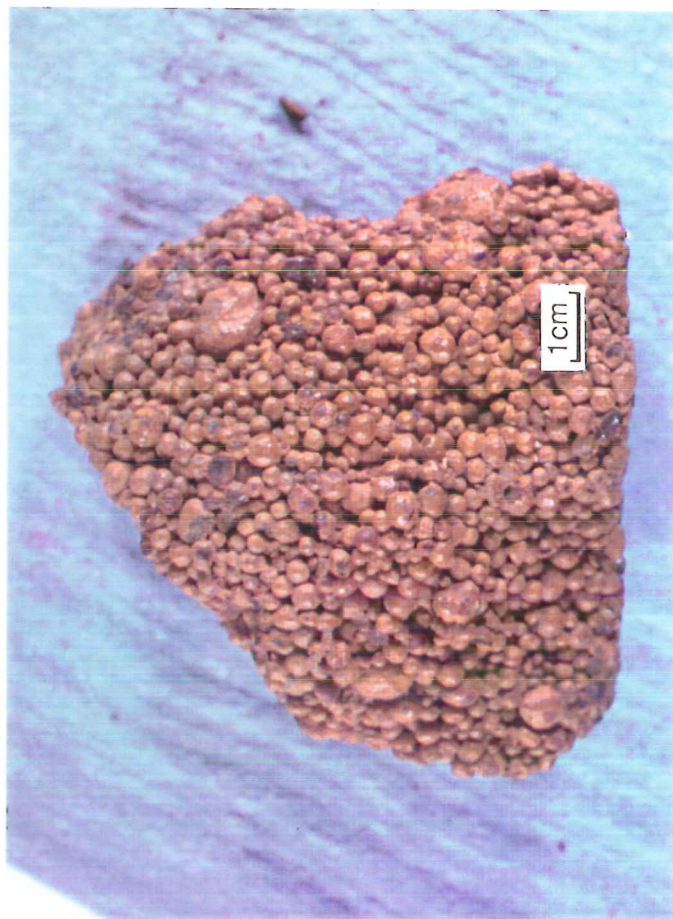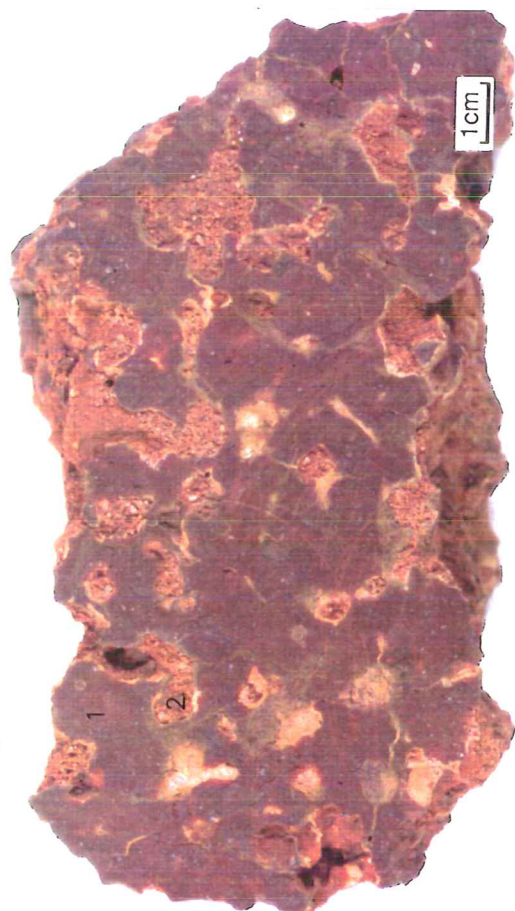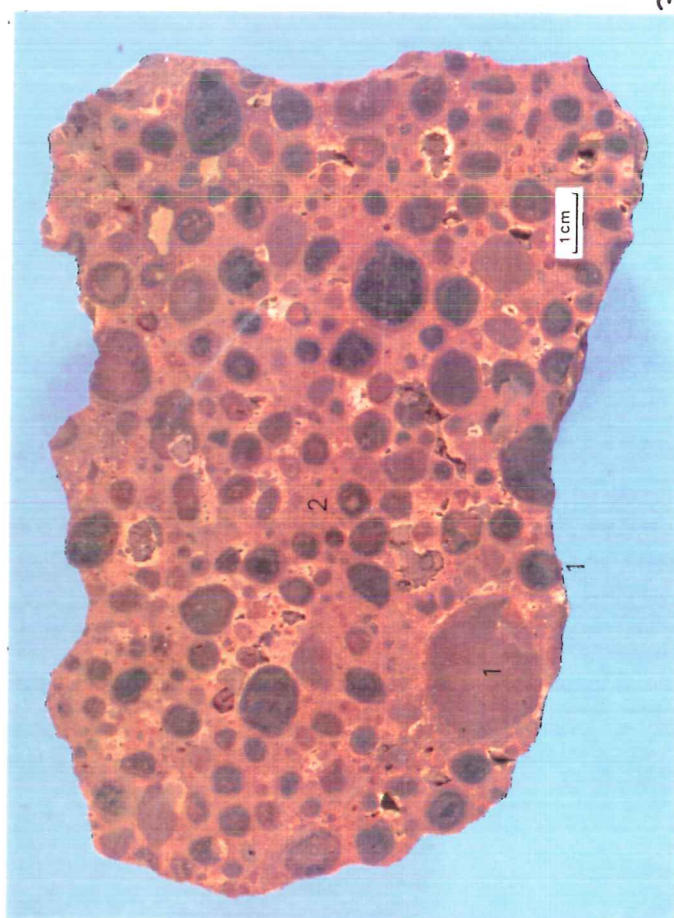

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PLATE C

PLATE G

1 2

3 4

DRC

MTZ

Q

1

3

2

CF

PLATE I