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FERRALLITIC and PLINTHITIC SOILS

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Foreword

This is the second edition of lecture notes on Ferrallitic and Plinthitic soils. The first edition was made in 1968 by the first author. They have been revised and complemented by the second author when he took over lecturing on this subject for the graduates in tropical soil science, because of the appointment of Dr. Buringh to conrector and later-on to president of the Agricultural University.

For more details students are referred to the original publications, available in the library of the Soils Department.

The lectures have been illustrated by a great many colour slides of soil profiles and landtypes from many tropical countries. An album of selected colour photographs can be studied in the library.

Wageningen, April 1971.

Some abbreviations

CEC = cation exchange capacity

V = base saturation

S = sum of exchangeable metallic cations

K_i = SiO_2/Al_2O_3 molair ratio (of the clay fraction)

ORSTOM = Office de la Recherche Scientifique et Technique d'Outre-Mer (Paris-Bondy, Dakar, Fort Lamy etc)

INEAC = Institut National d'Etudes Agricoles au Congo (Belge)

CSIRO = Commonwealth Scientific and Industrial Research Organization (Australia)

ISSS = International Soil Science Society

ASEQUA = Association Sénégalaise pour l'Etude du Quarternaire de l'Ouest Africain (Dakar)

Chapter 1. HISTORY OF RESEARCH; EVOLUTION OF CONCEPTS; FERRALLITIZATION VERSUS PLINTHIZATION

These lecture notes deal with the zonal soils of the humid and hot tropical regions of Asia, Australia, Africa, and South and Middle America. It is expected that students have basic knowledge on tropical soils in general, as described in Buringh (1970).

The (non-plinthitic) ferrallitic soils are old, deep to very deep, normally well-drained, often bright reddish or yellowish coloured soils with indistinct horizon differentiation. Their clay-fraction is rich in oxides of iron and/or aluminium, and its silicate clay minerals belong to the group of kaolinites; this clay fraction has a low cation exchange capacity. Since the content of easily weatherable primary minerals in the soils is very low and the base saturation often low, the soils are poor from a chemical point of view. Physically however, because of their friability, low plasticity, high porosity and stable structure, the soils are of high quality.

The plinthitic soils, only part of which are ferrallitic, are characterized by the presence of iron concretions, iron hardpans or soft dense clayey material which is stained by iron-rich mottles and hardens on exposure. Chemically these soils are comparable with the (non-plinthitic) ferrallitic soils, but the drainage condition, the depth, and the other physical properties vary widely, normally being inferior to those of the non-plinthitic ferrallitic soils.

The study of both groups of soils started at the beginning of the 19th century, and has received much impetus during the last two decades. Unfortunately, the nomenclature and classifications are so varied, that misunderstandings on the subject have been common, and have not yet disappeared present-days. A short account on the history of research is therefore useful (cf. Mohr and van Baren 1964, Sombroek 1966, Sys 1967).

In 1807 Buchanan found, in Malabar-India, a reddish mottled soil material, apparently rich in iron, which was soft on excavation from its natural soft condition but became irreversibly stone hard when left to dry at the open air. The local population used to cut the soft material with a spade into blocks of brick-size, and to use the hardened units as building material for temples, houses etc, because of its resistance to the weathering action of the local climate. Buchanan called the material "laterite", after the Latin word for brick: "later".

The term was eagerly taken up by geographers and soon it became associated with red colour of earth in the tropics rather than with quality as building material. The meaning of the term narrowed again after chemical and mineralogical analysis started. Bauer (1898), for instance, studied hardened material chemically. Instead of iron, the presence of free aluminium oxihydrates (Tonerde hydrat, gibbsite) was taken as criterion. Van Bemmelen (1904), who worked in Indonesia, could relate the presence of such aluminium oxides with the ratio $SiO_2:Al_2O_3$ (K_i-value) of the quartz free soil material. Only if that value was lower than 2.0, a material should be called "lateritic". Also Harrassowitz (1926, 1930), a laboratory man who analysed materials from many tropical countries but never visited the tropics himself, adopted the criterion that "allitic" constituents should be present to call a soil lateritic. This obliged him to exclude from lateritic materials those iron-oxide crusts, apparently having no free aluminium, that occurred in "superficial" horizons of tropical savannah soils (Savannen-eisensteine). He envisaged various so-called "laterite profiles", and took it as proven that lateritic crusts develop at the surface of the soil by evaporation of sesquioxide-rich soil moisture (upward movement).

At this time it became generally accepted among earth scientists that weathering anywhere in the tropics would lead ultimately to only iron- and aluminium oxides, even silicate clay minerals like kaolinite not being stable. Substantial laboratory research on tropical weathering in relation to type of parent material was done by Harrison (1933), based on samples from British Guiana.

About the first soil scientist who studied extensively the conditions in the field was Marbut (1932). In Cuba he found a well-drained deep reddish soil ,Nipe series, which by all means was "lateritic" in the sense that K_i-values were below 2.0, but contained no brick-like material, did not harden on continued exposure and showed no indications for wandering of sesquioxides to the surface of the soil. In the Amazon valley, on the other hand, he found brick-like material and mottled soft material hardening on exposure, both rich in sesquioxides but below "normal" soil material. The sequence would originate under the influence of a shallow oscillating groundwater-table, giving a leached imperfectly drained soil where sesquioxides would accumulate locally, mainly by downward movement. Crusts on well-drained plateaux would be the relics of such a soil, after erosion of the surface layer. Marbut therefore could discard the Harrassowitz "laterite profiles" as incorrect and proposed to call the well-drained stone-free Cuba soil profile "laterite (soil)" and the imperfectly drained Amazon soil profile with a reddish mottled zone "groundwater laterite (soil)". Marbut's explanation and sub-division was taken over correctly by American soil scientists, who had been able to follow his lectures (e.g. Thorp and Baldwin 1940 for China; Roberts 1942 for Puerto Rico; Pendleton 1947 for India; Kellogg and Davol 1949 for Congo; Prescott and Pendleton 1952, worldwide). Because no separate name was given for the soils with a - relic - crust, and because Marbut's publications contained various writing and printing errors, the confusion in international soil literature became however still greater than before. Kellogg (1949) therefore proposed the following. The name "Laterite" should be confined to such ferruginous materials as harden on exposure and the relics of such materials (soft mottled clays that change irreversibly to hardpans or crusts when exposed; cellular and mottled hardpans and crusts; concretions; consolidated concretions). "Latosol" should comprise all the well-drained zonal soils having their dominant characteristics associated with low silica/sesquioxide ratios of the clay-fractions: low base-exchange capacities, low activities of the clay, low content of most primary materials, low content of soluble constituents, a high degree of aggregate stability, and (perhaps) some red colour. It may or may not contain "laterite". "Ground-water Laterite (soil)" should comprise all (imperfectly drained) soils having a gray or grayish-brown surface layer over leached yellowish gray A2 over thick reticulately mottled "cemented hardpan at a depth of one foot or more. Hardpan up to several feet thick. Laterite parent material. Concretions throughout". (N.B. The latter part of the definition was not in agreement with earlier descriptions of Kellogg and Davol 1949 and again a source of confusion).

Several objections were made (cf. Mohr and van Baren 1954) but the subdivisions and the terms gradually gained acceptance. Subsequently, a number of different Latosols were described (Kellogg and Davol 1949 for Congo, Bonnet 1950 for Puerto Rico, Cline et al 1955 for Hawaii, Lemos, Bennema et al 1960 for Brazil, Bramão and Lemos 1960, worldwide). French language soil scientists preferred the name "sols ferrallitiques" for these soils (e.g. Aubert 1958) and Sys (1961) introduced the term "Kaolisols" for the Congo Latosols. Extensive research on laterite formation ("cuirassement") was carried out by D'Hoore (1954) and Maignien (1958) in Africa, both agreeing largely with the Marbut concept by clearly contrasting "ferrallitization" versus "cuirassement". In the first case "accumulation relative" of sesquioxides would be concerned mainly, under conditions of free drainage (no formation of concretions, unless micro-ones: shot, perdigón); in the second case an "accumulation absolue" would be concerned under conditions of imperfect drainage in one way or another, with zones of accumulation of sesquioxides in larger concretions or continuous sheets). A lengthy though not very critical review on the process was given by Sivarajasingham et al in 1962. Also Alexander and Cady gave a review (1962). Sombroek (1966) confirmed with his field data on the Amazon valley the original findings of Marbut, supplying many profile descriptions.

Recently another effort was made to end the confusion: In the "7th Approximation" (Soil Survey Staff 1960, 1967) the terms "Oxisol" and "Plinthite" were introduced (soils rich in "oxides", and the material "plinthos" (Greek for brick) respectively. The Oxisol order would include not only the (well-drained) Latosols, but also most of the (imperfectly drained) Ground-Water Laterite soils, largely as an "Aquic" suborder! Plinthite would replace the word "laterite", but no systematic subdivision was foreseen for presentday's forming soft material and fossil, indurated material. For the latter therefore Sys (1968) has proposed the term "petroplinthite".

In conclusion: there have been and still are rather different opinions on the complicated soil forming processes (the pedogenesis), the nomenclature, systematics and classification of these important tropical soils. Many hypotheses have been presented by various scientists. The reasons for these differences can be summarized as follows:

a - the soil forming processes are complicated, and they are not yet completely understood;

b - many of the soils under consideration are old or extremely old (Tertiary), the soil formation generally is a very slow process and the influence of various factors of soil formation changed during such a long period; soils often are polygenetic.
The soil climate often has changed as did the natural vegetation cover (tropical rainforest, secondary forest, savannah);

c - soils are formed from various, quite different types of parent material;

d - many investigations had a local character and no comparison was made with other, similar soils in the same country or in other countries. In some cases complete theories were developed without any field-check;

e - soil scientists have applied different methods of soil sample analysis or they have analysed different soil characteristics, and consequently no comparison with similar soils is possible;

f - until a few years ago little is done on soil correlation in the various countries, and in the world;

g - poor writing and limited or retarded distribution of papers on the subject has been a common source for misunderstanding;

h - diagnosis of the weathering processes involved does not necessarily imply that the final stage of soil profile formation has already been reached at the particular site of study.

Nevertheless, it is by now generally accepted that two clearly distinguishable aspects of tropical soil formation are involved.

a - <u>the ferrallitization process</u> (lateri(ti)zation, lato(soli)zation: i.e. the formation, under conditions of free drainage, of soils poor in silica and rich in sesquioxides, leading ultimately to deep, friable, structurally stable, homogeneously red or yellow coloured profiles (Latosols, Ferrallitic soils, Oxisols).

b - <u>the plinthi(ti)zation process</u> (mottled clay formation, cuirass formation): i.e. the formation, under conditions of imperfect drainage, of a zone of prominently reddish mottled dense clayey material within the soil profile, as well as its hardening upon exposure and its fossilization, leading ultimately to respectively the imperfectly drained "Ground-Water Laterite soils" and the more-or-less well-drained "Soils-with-fossil-plinthite", only a part of the latter constituting (concretionary) Latosols.

Chapter 2. THE FERRALLITIZATION PROCESS.

In the past a number of hypotheses on the process of formation of ferrallitic (and plinthitic) soils have been put forward. In the beginning some scientists had the opinion that the materials involved were a product of sedimentation (aeolic, volcanic, or lacustrine). Others believed that a mere residual product of rock weathering was concerned. It has even been suggested that a tropical disease of rocks is concerned, the rock being destructed by pathogenic micro-organisms.

After mineralogical and chemical analysis of the materials concerned was taken up, a relatively simple theory of "laterization" by katamorphism of rocks came into being. The application of new techniques of study in recent years has however revealed that both a "ferrallitization" and a "plinthitization" process exist, both in fact forming a complex of various destructive and constructive subprocesses, influenced by many, often quite different factors of varying aggressivity that should be studied from mineralogical and chemical but also physical and biological point of view.

The ferrallitization process is discussed at length by Van Schuylenborgh in the new edition of Mohr and Van Baren's book "Tropical Soils", to which may be referred. The below gives only the main points:

An almost continuous, slow percolation of water through the soil causes the leaching of various ions and components to deeper soil layers or to a very deep-lying groundwater-table. In order to fulfill such condition a number of factors are of paramount importance viz.

a - the internal drainage of the rotten rock, of the parent material and of the soil. A high permeability permits excess rainwater to percolate through the soil,

b - the quantity of water percolating through the soil. This depends on the precipitation, that should be high, and on the natural vegetation, which should preferable be a tropical rainforest;

c - the mineral composition of the parent rock or parent material. As a result of the weathering process different components will be formed in the soil; some are leached, whereas others remain in the soil;

d - the organic matter produced by the vegetation, and the way in which its decomposition takes place.

Generally speaking, the ferrallitization process can be divided in some subprocesses, which will be discussed separately. However, it should be kept in mind that in nature these processes all act together or consecutive with varying degrees of intensity in material in different stages of development. These main subprocesses are:

a - the weathering of primary minerals, in most cases leading to a hydrolysis of silicates

b - the leaching of bases and silica

c - the formation of new minerals (neosynthesis)

2.1 The weathering of rocks and minerals

The formation of soils from primary rocks and minerals starts with weathering, an irreversible process influenced by water, air (oxigen), organic matter and temperature. It consists of desintegration (physical break-down of rock into smaller fragments) and decomposition (chemical break-down, normally followed by formation of new chemical compounds). In the hot and humid tropics the chemical weathering is by far the most important. For the most important primary minerals in rocks and sediments it can be expressed in a general way as follows:

amphiboles and pyroxenes (basic rocks) ⟶ bases (Ca + Mg) + silica + Fe-oxihydrates

felspars (acid rocks) ⟶ bases (K + Na + Ca) + silica + Al-oxyhydrates

Chemical weathering consists of

a) hydratation, being the formation of a thin layer of water molecules on the surface of minerals, becoming more and more important when the mineral particles become smaller.

b) oxidation, being the influence of air, in particular oxigen, or the loss of electrons.

c) solution of the easily soluble components, in particular of cations, giving the soil water a specific character.

d) hydrolysis: cations of the mineral surfaces are replaced by H^+ of dissociated water molecules. For potassium felspars the hydrolysis can be expressed as:

$$K(AlSi_3)O_8 + H^+ + (OH)^- \longrightarrow H(AlSi_3)O_8 + K^+ + (OH)^-$$

This alkalic reaction continues, since $H(AlSi_3)O_8$ is not stable. It transforms into single ions of Al and Si or into colloidal gels, which at the ferrallitization process are either leached or transform ultimately into clay minerals like gibbsite and kaolinite. Leaching more-over takes away the cations. In contrast to weathering at temperate climates no organic acids (which would further speed up the reaction by neutralizing the $(OH)^-$ ions) would be of influence at the ferrallitization process, because of the rapid and complete mineralization of the humic substances.

The weathering process depends on the type of parent rock, in particular its mineral composition. Some minerals are much easier weathered, e.g. olivine, than others e.g. quartz. "Weathering sequences" exist, and the stability of primary minerals can be expressed in terms of entropy (Van der Plas, lecture notes) and reaction potentials (Garrels and Christ 1965). The permeability of the rock is also of influence. Most sediments and basic crystalline rocks are more permeable than the acid crystalline rocks. Low permeability of the rock or of some rock- or sediment layers may lead to the plinthitization rather than to the ferrallitization process, because of percolation absence.

The intensity (aggressivity) of chemical weathering depends for a good deal on the temperature and moisture regime. In the humid and hot tropics it is 5-10 times stronger than elsewhere.

Also time plays a role. In the typical tropical soils the process of chemical weathering has been active for a very long period (relatively high stability of the landsurfaces due to protecting vegetative cover). This, and the high intensity of weathering has resulted in the situation that in fully developed soils in these areas practically no weatherable minerals are present anymore (which is used as a characteristic, see below).

2.2 The leaching of bases and silica.

The cations freed at hydrolysis of the primary minerals are very soluble. At the ferrallitization process, where a continuous excess of rainwater can freely percolate through the soil to deeper layers (in case of unconsolidated permeable sediments) or directly to the rivers (impermeable substratum of rock or stiff sediments in sloping terrain), these cations are easily and fully leached.

Also part of the silica is leached at the ferrallitization process, but not so, or to a lesser degree the sesquioxides (Fe and Al, some Mn, Ti). A relative increase in the sesquioxide content is the result. The ratios SiO_2/Al_2O_3 (=K_i value) resp. SiO_2/R_2O_3 (=K_r ratio) can therefore be used as indicators for the occurrence and the stage of the ferrallitization process. The differential leaching of Si versus sesquioxides is still not well understood. Various theories have been developed to explain this essential difference with temperate zone weathering (cf. Van Schuylenborgh in "Tropical Soils"):

a - the classical theory of different solubility of the simple ions conditioned by the pH. While in temperate regions any percolating water has an acid character under influence of presence of organic acids (humic materials being mineralized incompletely and at slow rate), in the tropics the percolating water would be alkalic since no such acids are formed (complete mineralization of the humus), leaving only the influence of cations. At such relatively high pH the silica would be more soluble than the sesquioxides, hence a relative increase in sesquioxides at the prevalent strong percolation rate is the result.

  A number of objections have been made to the above; the ferrallitization process continues also in (pre-)weathered soil material that is definitely acid; pure silica in laboratory trials has proven to be as soluble in basic as in acid conditions.

b - more recently it has been suggested that the different behaviour of components formed during the hydrolysis should be explained by different ion-potentials. The cations having an ion-potential of < 3.0 are always in solution; Al, Fe, Mn and Ti with ion-potentials 3.0-9.5 would precipitate (unless linked to humic acids), and Si, with ion-potential > 9.5, would become soluble in combination with oxigen.

  At any pH therefore, Si would be leached, the process only being only more intense with more regular and higher temperature percolation water.

c - desionization theory (Herbillon and Gastuche 1962).

2.3 The formation of new minerals.

It is well established that the ferrallitization process leads ultimately to predominance of sesquioxide clay minerals like gibbsite and goethite, and of silicate clay minerals of 1:1 lattice structure, notably kaolinite; the first being prominent in ferrallitic soils from basic rocks, the latter in ferrallitic soils from acid rock or sediments. The way in which the formation of these secondary clay minerals takes place is however subject to much controversy.

a) The formation of gibbsite (= hydrargillite, $\gamma Al_2O_3.3H_2O$, $\gamma Al(OH)_3$).
Several possibilities have been put forward:

- The crystallization of Al is determined solely by its amphoteric character, hence dependent purely on the pH (cf. Harrison 1934, following the classical theory of the iso electrical point (I.E.P.) of Mattson). In acid conditions (weathering of acid rock) Al would act as a base and attract anions, being those of Si gels (supposedly not or little leached at this pH; humic acids not formed; anorganic anions leached); Si and Al gels would combine to give directly kaolinite. In basic conditions however (initial weathering of basic rock), the Al-gel acts as an acid; its tendency to attract cations cannot be fulfilled since these cations are (being) leached.
  It therefore can combine only with itself, ultimately forming gibbsite ("primary laterite").
- Formation by desionization (cf. Herbillon and Gastuche 1962). In acid conditions the Al-gel would be surrounded by anions fixed at the (vague) structure in an irregular way; no crystallization as gibbsite is possible, kaolinite being formed instead, ultimately. In basic conditions the Al-gel can be surrounded only by cations. Since these are however (being) leached, the gel remains without impurities and the forming of hexagonic crystals of gibbsite at drying/ageing does not meet resistances.
- Formation by a titration effect (a.o. Bruggenwerth, in preparation). Whatever the original pH, the strongly active leaching water carries off H^+, which causes increased speed of concentration of $Al(OH)_3^-$ to an alkalic reaction, upon which crystallization to gibbsite can take place.

- Formation by gradual desilication of kaolinite. This would take place in old, already ferrallitic soils.

b) The formation of 1:1 lattice silicate clay minerals, notably kaolinite, $Al_2(Si_2O_5)(OH)_4$. (Sometimes halloysite - containing additionally 1.5 a 2 molecules H_2O - is formed, or meta-halloysite). Several possibilities have been put forward.
  - Direct formation from structural remains of some primary silicate minerals. The crystal-structure of felspar would not allow this; that of micas possibly.
  - Formation by simple combination of Al and Si gels in acid conditions (see a).
  - Resilication of gibbsite (Harrison 1934). Laboratory trials however have indicated that there is no affinity of SiO_2 towards crystallized sesquioxides.
  - Formation via short montmorillonite and halloysite phases of mineral formation. Quite likely to occur.
  - From gels of Al and Si in the pre-gibbsite stage of weathering (see a).

c) The formation of iron oxide clay minerals, notably the brownish goethite (↔ limonite), i.e. α-FeO(OH), and the reddish haematite, i.e. α-Fe_2O_3. (Sometimes additionally secondary minerals of Mn (doelterite) and of Ti (anatase)).
  - From Fe-gels being formed at the hydrolysis; a simple process, since there is no affinity - in contrast to the Al-gels - to combine with Si.
  - Directly from structural rests of Fe-rich primary minerals like magnetite, chromite and ilmenite.
  - By import of ferrous ions (soluble!) from elsewhere (=contamination). Especially in the latter case the iron oxides would occur as powder, micro-concretions, or coatings on other clay-minerals including clay-sized quartz, and one can speak of a transition to the plinthization process.

It is clear that much is still unsure or controversial as regards the details of the ferrallitization process. There are a number of reasons for this:

A. Spatial complexity of the (sub)process(es)

- The pH varies at very short distances in the zone of weathering, while only averages are measured.
- The intensity of leaching varies considerable at very short distance, due e.g. to variation in pore space.
- All phases can occur - at the same time - at very short distances, i.e. some mm's, especially nearest the weathering rock (=zone de départ).
- Often polygenetic materials, connected with climatic changes, are concerned for a particular "laterite" profile under study, while this can be established only with difficulty, if at all, because the processes of change are very rigorous.
- The processes should be essentially different at different sites of the soil/weathering profile. If the fresh rock is near or at the surface, weathering in its zone de départ takes place under conditions of relative richness of anions and cations. If the fresh rock is deep, then the continued weathering in the soil mantle above it takes place under conditions of poorness in bases, and some influence of humic acids c.q. carbonic acids of roots. The weathering at the zone of depart of this case would feel an influence of the processes taking place in top (e.g. import of percolating Si)
- The influence of biochemical processes is not fully acknowledged. Percolating water would not be acid, because nearly complete and rapid mineralization of fresh organic matter would take place, while CO_2 formed would escape. The few organic acids still formed would chelate with Fe and Al, forming complex components with an alkalic reaction.
- The influence of macro-biological soil processes is often disregarded. Termites, ants and rodents are however abundant and have an enormous physical influence (homogenization). Also biochemical influence is possible (termites form a basic environment, leaf-cutting ants incorporate organic matter deep down in the soil!).
- There is an influence of living vegetation.
Roots have both physically (porosity) and chemically (CO_2 liberation) a strong influence on the ferrallitization process.

B. Complexity of the analysis methods (cf. Schellman 1964a)

- Optical methods: microscopic study concerns only the sandfraction, electronmicroscopic study (electronmicrographs) concerns the clay-fraction, including amorphic parts, but is very expensive.
- Crystal analysis with X-rays studies the clayfraction but not its amorphic parts, is rather qualitative and expensive.
- Crystal analysis with DTA: do, rather quantitative, but elaborate.
- Chemical analysis methods are several, e.g. 1) total analysis with calculation of element balance, 2) analysis of soluble components; solvents of much varying aggressivity are used; the surphuric acid attack, for instance, concerns all secondary minerals and colloidal materials, 4) determination of the cation exchange capacity. Often the influence of organic matter is not properly acknowledged, and 5) determination of specific surface.

  At any of these methods, grainsize determinations may be incomplete (incomplete dispersion), the influence of organic matter may not be acknowledged, or analysis on total soil - including concretions - may not be clearly contrasted with analysis of the clay fractions.
- Analysis of the drainage water. An interesting new approach, but liable to much interpretation errors.
- Experimental weathering. Influence of biochemical processes and of soil fauna is very difficult to include in the experiments.
- Use of micromorphology. A very useful new tool for study of the ferrallitization process, but selection of samples should be based carefully on surveys findings (compare Kubiena 1962, general versus Stoops 1968 for Congo and Bennema, Jongerius and Lemos, 1970, for Brazil), to avoid similar confusion and controversy as has been the result of earlier chemical analysis (with Harrassowitz 1930 as glaring example).
- Surveys. This most essential basis for selection of materials for analysis and the interpretation of its results has been lacking to large extent, being remedied only recently (Brazil, Congo, W. Africa). The approach to survey is of influence as well: if mapping takes place on pre-fixed genetic concepts, the results may be biased. Mapping on profile morphometry together with physiography (landforms) seems more reliable as basis for subsequent analytical work and the formulation of hypotheses on genesis.

Chapter 3. FINAL RESULTS OF THE FERRALLITIZATION PROCESS.

First of all it should be stated that the occurrence of the process does not automatically imply the presence of ferrallitic soils. The latter are only the end (mature or rather: senile stage) of weathering sequences, where the whole process has been completed. Some weathering sequences in the tropics are given in the scheme no. 2 (cf. also Bennema, Jongerius and Lemos 1970). The general characteristics of ferrallitic soils are the following (cf. Bennema 1963, Sombroek 1966)

A. Morphometrical aspects.

1) deep profiles. The C horizon often extends to many metres depth.
2) well drained. If drainage was imperfect, the plinthitization process would have entered (chapter 4).
3) uniform colours, without mottles, below the A1 horizon usually red or yellow and of relatively high chroma. Due a.o. to the presence or predominance of sesquioxides in the clay fraction.
4) texture often clayey, because all weatherable minerals have been transformed into clay minerals. Only when "rego-genetic" materials (pre-weathered sediments) relatively rich in quartz grains are concerned, the texture may be rather sandy. A minimal clay percentage of 15% is however frequently used, in the understanding that in still sandier tropical upland soils the activity of the colloidal part becomes insignificant.
5) the silt content is low. This generally observed fact (Van Wambeke 1962) is apparently due to a relatively easy destruction of silt-size fragments to claysize, in part because a good deal of the silts consists of easily weatherable minerals like micas. The silt/clay ratio is therefore an useful indicator for ferrallitic soils. Limits vary somewhat, a.o. because of a difference in the definition of silt (U.S.A. "silt" 2-50μ, France a.o. "limon" 2-20μ), but in general the ratio should be below 0.25. Older data can often not be used for this purpose, because granulometric dispersion (difficult because of strong coatings in the microstructure) in early laboratory tests was often not complete.

Even with modern dispersion agents the ratio cannot be used reliably in case high percentages of sesquioxides are involved (cf. Bennema 1960 for the Terra Roxa Legitima).

6) the horizon differentiation is indistinct. Except for that of the A1 (or Ap) to the A3, all horizon limits are diffuse or gradual, due a.o. to little or no clay illuviation and the strong homogenization by soil animals. In relatively sandy profiles with limited percentage of sesquioxides in the clay fraction, the total difference in texture between A and B horizon can still be rather large. As limits are sometimes taken: a textural gradient (=difference in clay content over a certain distance) of less than 70% increase over 20 cm, or a textural ratio B/A (=arithmetic mean of clay content of the B subhorizons except the B3, divided by the arithmetic mean of the clay content of the A subhorizons) of maximally 1.8.

7) absence, or presence in only very low percentages of the total ped surface, of distinct clayskins on structure peds or distinct claylinings in the pore channels. Related with 5).

8) the structure is weakly coherent porous massive, composed of stable very fine granules, which on their turn may form weak subangular blocky elements.

9) the consistency is friable or very friable, when moist, relatively little sticky and plastic when wet, soft to slightly hard when dry. Due in large part to the low physical activity of the clay minerals.

10) the aggregate stability is high, due to the nature of the clay minerals. Horizons with little or no organic matter have little or no "natural clay" (i.e. clay-size elements obtained by shaking with destilled water only - no dispersion agent used), unless the sesquioxide clay mineral percentage is extremely high (excess of electro positive charges, instead of excess of electro negative charges as in the case of organic matter).

Consequently, the "structure index" (=difference between natural clay and total clay after dispersion, in percentage of total clay) is high to very high - normally 95-100% in the B horizon.

11) the porosity is high throughout, especially as regards the smaller pores.

12) a small tendency to sealing or crusting of the surface layer. Related with 10).

13) the water passage is rapid, both as regards infiltration rate, percolation rate and hydraulic conductivity.
14) the erosion susceptibility is small. Related with 9 - 13.
15) rooting is deep, as is the activity of soil animals etc., down to several metres.

B. Mineralogical aspects

16) Low amount of weatherable minerals in the sandfraction, a reflection of the intense and long-lasting chemical weathering. Primary minerals with small resistance to weathering (micas etc.) should form less than 1%, those with moderate resistence (turmaline, staurolite, etc.) maximally 4%. In fact therefore, practically all of the sand fraction consists of quartz-grains and micro concretions of sesquioxides.
17) the clay fraction consists of clay minerals of low activity, being sesquioxides (often a minimum iron oxide content is taken, viz. 12 %), kaolinite, minor percentages of clay sized quartz, and possibly inactive gels of Si and Al (more active, compound gels, e.g. the amorphous aluminium-silicate allophane, should not occur).

The strong predominance of kaolinite + sesquioxides implies that a K_i value ($=SiO_2/Al_2O_3$) of smaller than 2.0 (which is the theoretical ratio for pure kaolinite) is taken as a criterion. Many ferrallitic soils have in fact a $K_i < 1.5$.

C. Chemical aspects

18) Low cation exchange capacity (CEC) of the clay fraction, due to the nature of the clay minerals. This holds in particular for the soils low in kaolinite ($K_i < 1.0$), but also some ferrallitic soils rich in this material, but with it crystals coarse and coated, have extremely low CEC's. Limits depend on the method of analysis (influence of the pH chosen at the determination of the "potential" CEC!), being roughly below 10 m.e./100 g clay. Care should be taken that dispersion has been complete, and the - relatively very high - activity of the organic matter is duly subtracted (for the method cf. Bennema 1966).
19) Low amount of exchangeable metallic cations, in percentage of the potential CEC, i.e. a low base saturation (V). Values of < 35-40% are normal, but some A horizons and the whole of ferrallitic profiles in presently relatively dry regions may have higher values.

Associated with the low V values are low values for pH_{H_2O}, namely normally ≤ 5.0.

20) relatively high anion exchange capacity, and related high fixing power for phosphorus, especially in the ferrallitic soils rich in sesquioxides.

21) low active acidity, i.e. low percentage of $(H + Al)^+$ at the pH of the soil in the field. In fact however, in tropical soils, the relative amount of H in the percentage of non-metallic cations is insignificant in comparison to the $(Al)^+$. Therefore one often mentions low percentage of exchangeable aluminium instead. Values of less than 2 m.e./100 gr soil are common ($<$ 25% of the potential CEC, contrasting with $(Al)^+$ percentages of 75% for acid Hydromorphic soils in the tropics, cf. Sombroek 1966).

Associated with this are relatively small pH_{H_2O}-pH_{KCl} differences (0.5 unit or so). Sometimes pH_{KCl} is even higher than pH_{H_2O} (very old ferrallitic soils rich in sesquioxides).

Detailed limits for all these aspects, and subdivisions, depend on the different systems of classification, and are described in chapter 8.

Chapter 4. THE PLINTHIZATION PROCESS.

The material "plinthite" is a highly weathered mixture of clay, quartz and other diluents, containing many humus-poor segregations with a high percentage of sesquioxides; this mixture occurs either in soft form (i.e. non-indurated, cuttable with knife) and is then characterized by a light gray matrix with red mottles in varying size, density, shape and pattern, the mottles changing irreversible into slag-like material upon repeated wetting and drying ("Buchanan's laterite", "mottled clay", "Fleckenzone", "argile tacheté", "horizon bariolé"). The material may also occur in hard form (i.e. indurated, breakable only with hammer) and is then characterized by slag-like elements of varying size, shape, arrangement and texture, within varying percentages of earthy material ("laterite", "ironstone", "iron concretions", "cuirasse", "carapace", "Eisenkruste", "canga", "petro-plinthite"). Definition after Soil Survey Staff 1966, slightly modified.

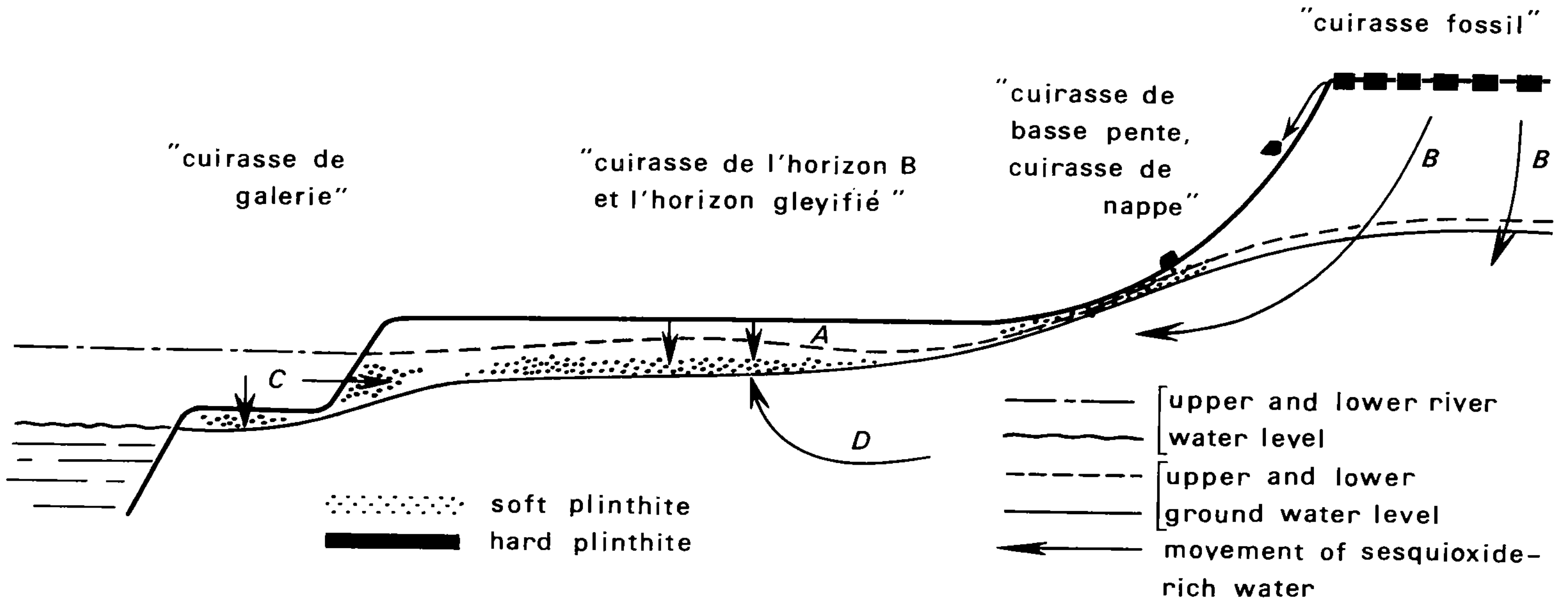
4.1 Formation of plinthite

- Conditions for absolute accumulations of sesquioxides, notably iron oxides, are according to the great majority of recent publications (Prescott and Pendleton, 1952; D'Hoore, 1954; Maignien, 1958; Sombroek, 1966):
   a) imperfect to poor drainage
   b) repeated temporary oxigen supply
   c) water entering the soil without enriching substances, i.e. little or no inorganic salts, no sedimentary particles in suspension.

In fact this implies that the process takes place on approximately flat landsurfaces and/or where a dense substratum occurs, with a yearly fluctuating watertable, of which the lower boundary is not too deep (about 3 m), and where no flooding (unless mainly from rainwater) occurs.

- Transport of sesquioxides may take place
  as Fe^{++} ions: important also at micro transport
  as Fe/Al oxihydrate gels: possibly important at lateral transport
  as Fe/Al: humus complexes: important at downward transport in the soil profile ("bleaching")

Fig. 1. ACCUMULATION ZONES OF SESQUIOXIDES.
(after D'Hoore, 1954, slightly modified)



as Fe/Al clay minerals: possibly important at downward transport in the soil profile ("lessivage")

- Zones of enrichment of sesquioxides are those where the carrying water undergoes a change in redox potential. This can concern

a) downward percolating rainwater, giving the "cuirasse de l'horizon B" (pseudo groundwater level above compact B) or the "cuirasse de l'horizon gleyifié" (groundwater level proper) - cf. D'Hoore 1954 and figure 1.

b) laterally moving groundwater, giving the "cuirasse de nappe (phreatique)" or "cuirasse de basse pente".

c) laterally penetrating or flooding (silt and salt poor!) river water, rich in Fe/Al, giving the "cuirasse de galerie".

d) upwards moving groundwater (seepage), and possibly also some upwards moving capillary water.
Precipitation at the soil surface by capillary rise of Fe-rich groundwater as a cause for cuirasse formation is nowadays not anymore considered. The fossil character of surface cuirasses is nearly always established.

The by far most widespread mode of enrichment is the one mentioned under a). The latter might be considered as a special case of relative accumulation (cf. Maignien 1966), which holds also for the microtransport at the concentration within the mottled zone (see below).

Form of concentration

a) in foliations: taking place usually at lateral import of sesquioxides (notably basse pente).

b) in massive sheets: complete impregnation of sandy layers at downward percolation, or at precipitation from riverwater (galerie).

c) in mottles: at horizon B/gleyifié. A micro-pedological process of solution, translocation and precipitation due to local oxidizing and reduction conditions (much comparable to the gley mottling!) at the zone of intermittent saturation, possibly with an influence of microbes and/or enzymes (Russian School). Sivarajasingham et al (1962) give several examples of the micromorphology of this microtransport. Form, size and pattern of mottling vary (cf. Sombroek 1966) from individual pedsize concretions to nearly massive complexes, depending on:

1) texture: tendency to accumulation in sandy parts, often nearly massive (little Fe required for coating of grains!)
2) structure of soil or parent rock (massive, blocky, prismatic, granular)
3) biological activity (tubular due to roots, reticular due to termites)

4.2 Hardening of plinthite

Conditions for hardening:

- basse pente: evaporation of Fe-rich water in dry season?
- galerie : evaporation of Fe-rich standing riverwater?
- horizon B etc.:
    1) during dry months in actual position of formation, as a final part of the process of soil formation; then namely a relatively easy access of oxigen through the leached sandy A on top of the mottled layer is possible;
    2) at a change in climate to drier conditions;
    3) at a lowering of the zone of groundwater oscillation (due e.g. to artificial or natural change in base level of the rivers);
    4) by far the most important: surfacing of the layer, at erosion of the leached part on top of the mottled layer ("truncation"), due to one or a combination of the following. a) Complete vegetation degeneration at the end of profile development, b) change in climate, c) tectonic movement, d) change of river base level and e) detrimental influence of man like burning, overgrazing etc.

Note: little or no hardening takes place when the mottled zone is in fact the "Zersatz"zone (rotten rock, zone de départ) where the silicate clay minerals are not yet kaolinitic. In this case the mottling is less red, the matrix less whitish and the boundaries between mottles and matrix are less prominent.

The hardening process is a process of irreversible dehydration of the precipitated and crystallized sesquioxides in a rigid frame, at prolonged exposure at or near the surface, allowing full access of oxigen to the zone (and helped by intermittent moistening by e.g. rainfall; hardening

in dry laboratory conditions is not complete or very slow). Sivaraja-singham et al (1962) give several examples of the chemistry, mineralogy and micromorphology of the hardening process.
Goethite changes to haematite (Fe O(OH) H_2O ---> α Fe O(OH) ---> α Fe_2O_3);
gibbsite to boehmite and ultimately to bauxite.
Only the reddish mottles harden. The light gray to white parts inbetween become gradually oxidized and slowly homogenized (soil fauna!) ultimately till friable brown or red earth!

The form of the hardened parts is much varied (compare form of mottles):

1) nodular/pisolithic ("pea-iron", "iron-concretions"): spherical, with smooth surfaces.
2) blocky: more or less spherical, but with irregular often sharp edges.
3) vesicular/vermicular: massive with tubular holes, often breaking to rough prisms.
4) reticular/cellular ("scoriaceous"): massive with cellular holes.
5) stones: solid massive blocks.
6) conglomeratic: recemented nodular (=oölithic) or (rests of) other forms.

"cuirasse" is a massive thick layer (partly comparable to "hardpan")
"carapace" is a more or less loose thick layer (partly comparable to "crust")
"nappe de gravats"/"nappe de concretions" is a thin layer, often transported (partly comparable to "stone line").

The arrangement of hardened parts varies:

1) according to a pattern if hardened in situ; the pattern is related to the pattern of the original mottling and is downwardly still grading into present mottling (soft plinthite).
2) irregular if transported after hardening, which can be active (horizontally) or passive (sinking; earth between and below the hardened parts removed by erosion (see 4.4)).

The chemical composition of hardened parts can be

1) ferruginous: predominance of Fe (and Mn)

2) manganous: predominance of Mn; especially in valleys with lateral transport.
3) aluminous: predominance of Al; very old hardened layers where Mn and very gradually also Fe has been removed.

The occurrence in the landscape. The hardening process of a mottled clay layer can take place anywhere, but is most prominent and deep at plateau edges. There are some indications that the lower part of the soft plinthite (cuirasse de l'horizon B etc.) very gradually "shifts" to the edges (cf. fig. 5), the cause of which is not clear.

4.3 Destruction of plinthite

Hard plinthite can be destructed, though very slowly, by the following processes:
1) mechanical: especially at plateau edges, by undercutting of the soft material below.
2) biological: by roots, termites etc.; a combination of micro pressures, gnawings and release of decomposing chemical compounds.
3) chemical: a mobilization and leaching of the sesquioxides, often under influence of humic acids.

The first process is stronger if massive sheets are concerned, the second and third process when there is a relatively high percentage of earth inbetween, especially if this contains some weatherable minerals. As a whole however, the destruction is an extremely slow process, with as consequence that there are many Cretaceous and Tertiary fossil cuirasses (and also soft plinthites).

4.4 Transport and/or Buryal

a) Transport can take place:
  - as sesquioxides brought in solution, precipitating elsewhere (see above). This mode of transport is relatively unimportant.
  - mechanically:
    1) absolute transport: hardened elements are carried off by erosion and are redeposited colluvially (short distance) or alluvially (long distance) elsewhere, e.g. at feet of slopes, in alluvial

fans, in river terraces. This leads to the formation of geologic/sedimentologic stonelines.

2) relative transport: carrying away of soft fine earth between and below the hardened elements over a very long period, causing a lowering of the level of hardened parts over up to several tens of metres.

b) Burying after change in climate burying of fossil plinthite, originated in situ or transported can take place. This can be by fluviatile sediments (river terraces: Amazon), lacustrine sediments (Chad basin), aeolic materials (loess, coversands of Congo), or volcanic materials (ash: Indonesia). If the coverage is in a thin layer, then it can be easily mistaken for the A-layer of present or fossil cuirasse de l'horizon B/Ground-Water Laterite profiles (see below).

4.5 Recycling

After relative or absolute transport and/or buryal, climatic and hydrologic conditions may change again to conditions favourable for renewed formation of plinthite (either at basse pente, or on flat terrains), which may or may not be at the zone where the fossil plinthite was accumulated. In the first case the hard elements of the fossil plinthite are recemented: conglomerates are formed upon hardening. In the second case a new zone of mottled clay above or below the fossil plinthite will be formed; after hardening two separate layers of fossil plinthite will be present. Etc. ....

Chapter 5. RESULTS OF THE PLINTHIZATION PROCESS

At formation of a soft plinthite zone below or at the lowest part of the solum.

Where relatively light textured, unconsolidated rego-genetic sediments form the cover of the land, a zone of fluctuation of the groundwater-level between approximately 2 and 4 m depth may cause formation of a zone of soft plinthite at that depth with little or no effect on the soil forming processes in the upper 2 metres, there still taking place under conditions of free drainage. The soil profile there may be, or develop towards, a ferrallitic soil (or an Acid Sand, cf. chapter 8). Examples of such a situation are reported by Sombroek (1966). In this case, the plinthization process is a geologic rather than a pedologic process. Note: More or less clayey weathered material of some metres thick on top of impermeable rotting rock would give below an (ultimately) ferrallitic solum a zone of mottled material ("Zersatz"), which however at progress of weathering would gradually become fully aerated, and disappear as such, unless the rock is both shallow and very poor chemically.

At formation of plinthite within the solum.

Where the zone of oscillating groundwater-level is nearer to the surface (arbitrarily less than 2 m), a restriction of the activity of roots and soil fauna in the solum takes place. No full homogenization - normally resulting in a ferrallitic soil profile - is possible. Clay-sized particles and sesquioxides are carried downward by the percolating rain-water, which in this case contains a substantial amount of humic acids since the imperfect drainage impedes full mineralization of the humus. These particles are accumulating in the lower part of the zone of groundwater oscillation and form essentially the B horizon of a pedological profile: the Ground-Water Laterite profile, as recognized by Marbut (1934) and successors, develops. The classification as "Ground-Water Laterite soil" is essentially a genetic one. The morphometry of the profile varies much (cf. Sombroek 1966 for examples) depending on:

a) the texture of the parent material
b) the richness or degree of pre-weathering of the parent material
c) the character of fluctuation of the groundwater-level
d) the length of time that soil forming factors, notably climate and hydrology, stay favourable for the process.

It is therefore understandable that in a morphometric system like that of the 7th Approximation it is difficult to combine the varying profile morphometric features into a separate Order. (On the other hand, the inclusion in the Oxisols is essentially wrong, because the latter should be confined to well-drained soils!). But within the genetic concept, there is nevertheless an idea of what is the "modal" Ground-Water Laterite profile: Per definition (Marbut 1934, Kellogg 1949) the clay minerals should be "lateritic", i.e. should consist of sesquioxides and 1:1 lattice silicate clay minerals ($K_i \leq 2.0$). The ultimate stage of Ground-Water Laterite soil formation can therefore be reached relatively quickly in rego-genetic parent material, especially if rather sandy, but takes both considerable leaching and weathering in case of relatively rich parent material. In the latter case only rarely the ultimate profile is allowed to develop, because during the long time required a gradual erosion may offset the natural slow growth of the leached toplayer. Examples of fully developed Ground-Water Laterite profiles are given by Sombroek (1966) for the more or less sandy terrace sediments of the Amazon valley: A thick, bleached and sandy to very sandy A horizon ($A_1 + A_2$), grading sharply into a thick, relatively heavy textured, dense and slowly permeable B horizon ($B_2 + B_3$) of soft plinthite. This horizon has a blocky to prismatic structure, though clay skins are little apparent. At the transition zone of the two horizons some plinthite material occurs that has already hardened (A_3 or B_1). Often, though not always, there is a grayish C horizon ("dissolution zone", "Bleichzone", "pallid zone") below the soft plinthitic B, before the original parent material is reached.

It will be clear from the foregoing that the majority of Ground-Water Laterite profiles would fall within the Plinthaquults, because of the clear argillic character of the B. Others may constitute Plintaquepts. Only the ultimate stage, where the clayskins tend to disappear and the chemical activity of the clay fraction has become very low, can be grouped with the Plinthaquox. This ultimate stage, on the other hand, can be easily confounded with the tropical Ground-Water Podzol (Tropaquods), which has also a bleached sandy A_2 horizon. In fact the Tropaquod soil profile can easily be formed within the A horizon of the ultimate Plinthaquox.

The above concerns essentially the "cuirasses de l'horizon-B et l'horizon gleyifié". It is not always clear from the descriptions of D'Hoore and Maignien which are the typical profile morphometric features in case of "cuirasse de basse pente", "cuirasse de nappe" and "cuirasse de galerie" respectively. Possibly with the exception of the first (strong pallid zone below the plinthite rather than an A_2 above it?), differences with the morphometry as outlined above seem small. But anyhow, these three site formations of soft plinthite are insignificant when compared with the cuirasse de l'horizon B etc.

At hardening upon truncation

A change in hydrologic conditions and/or change in climate, provoking complete erosion of the A horizon of a Ground-Water Laterite profile, results in hardening of the soft plinthite. In first instances, the hardened layer is impenetrable for roots, moisture etc. For all practical purposes, the material represents unweathered parent material for a new cyclus of soil formation. From genetic point of view one might speak of "Ground-Water Laterite soil, truncated phase" (Day 1961) but drainage conditions are not really imperfect anymore. It is more consistent to speak either of bare Rock-outcrop or Lithosol ("sol brut mineraux"), depending on the completeness of the truncation.

At destruction of hard plinthite

Depending on the pattern of sesquioxide accumulations within the originally soft plinthite layer, a gradual "catthering" of the partially hardened plinthite layer may or may not take place.

If massive sheets are concerned, the soil will remain a Lithosol or even Rock-outcrop for a very long time. If the light-gray matrix parts of the original soft plinthite were considerable, these gradually become friable, while its mineralogical composition is already "ferrallitic", at least to a degree. Roots, organic matter and soil fauna can develop. A gravelly/concretionary friable layer comes to overly in this case a

dense, soft or only partly hardened layer of plinthite, containing often (fossil) elements of an argillic B: Morphometrically classified, the profile is a normally well-drained (not aquic!):
Inceptisol or Ultisol, (petro)plinthic/concretionary; a Sol Ferrugineux Tropicaux, à concrétions/à cuirasse.

Only when earthening of a fossil (hard) plinthite layer in which the sesquioxide accumulation is not massive, can go on for a very long time, in climatic conditions favouring the "ferrallitization process", this earthening will proceed to great depth and result in a Concretionary Ferrallitic soil/Latosol.

On the other hand, the fossil plinthite layer, and/or the pallid zone below it, may be such impermeable that a renewed shallow groundwater oscillation occurs. This will result, provided climatic conditions are appropriate, in renewed formation of soft plinthite: Concretionary Ground-Water Laterite soil. In this case presentday forming soft plinthite is often difficult to distinguish from fossil soft plinthite.

At transport of fossil hard plinthite

At transport, during periods of relatively dry climate, the sesquioxide accumulations of plinthitic material necessary harden, while the non-sesquioxide matrix is brought into suspension. At absolute transport the whole is sedimentated elsewhere (in the process being normally enriched with material of freshly weathered rock). The hardened parts normally form sedimentologic stonelines (of rounded stony elements within earthy material). If climatic conditions become favourable again for the ferrallitization process, a Concretionary Ferrallitic soil develops ultimately on the new site (unless the stoneline is too deep: plain Ferrallitic soil). If drier climates prevail a Concretionary Ferruginous Tropical soil (Sol ferrugineux tropical, à concrétions/à cuirasse) will develop.
Soils developing at relative transport are comparable to those of 5.4.

At buryal of fossil plinthite

At deep buryal the fossil plinthite has no influence on soil formation.

Shallow burying results in either Concretionary Ferruginous Tropical soil, Concretionary Ferrallitic soil, Lithosol, or Concretionary Ground-

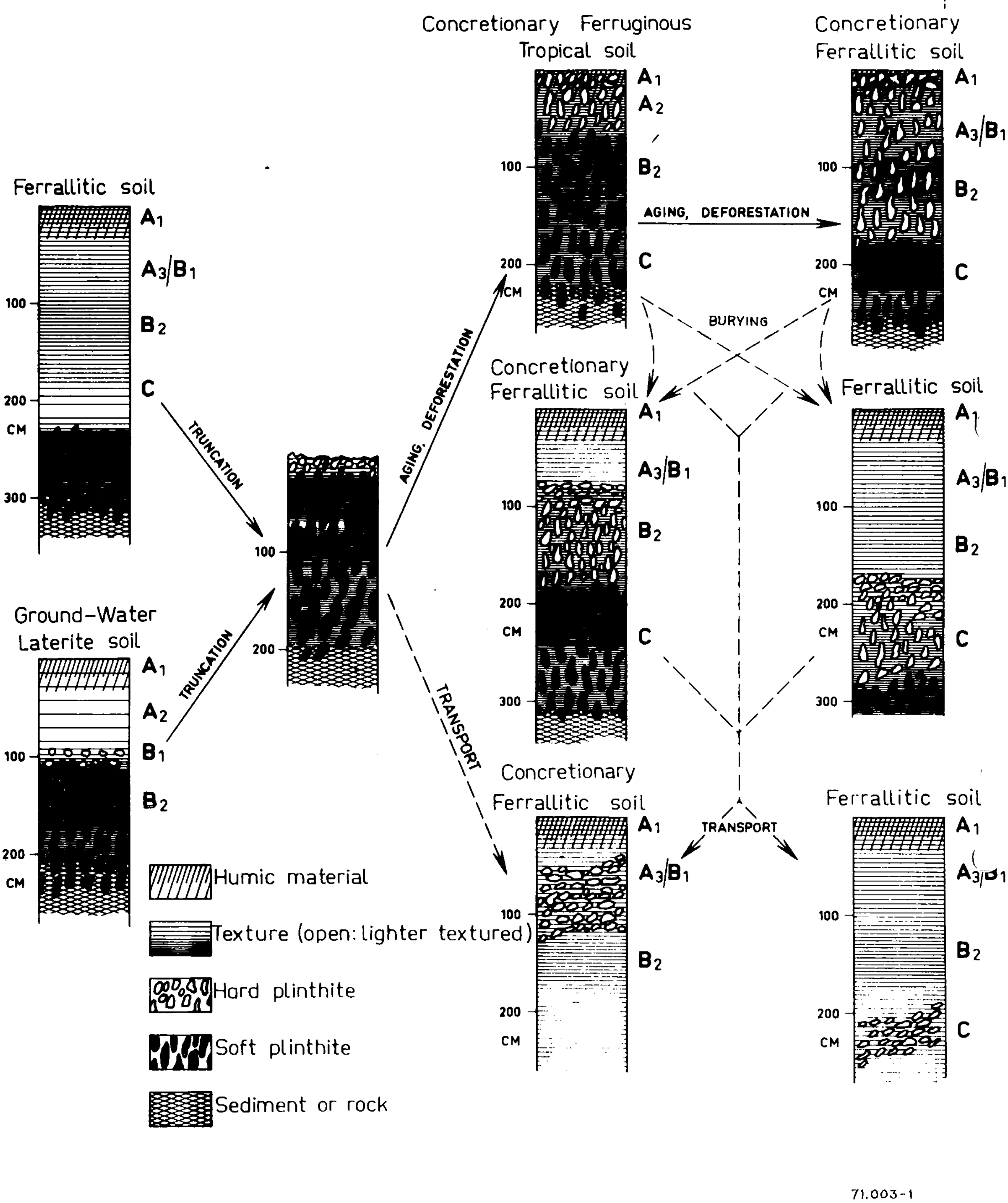


Fig. 2. SOIL PROFILE CLASSIFICATION AT PRESENCE OF PLINTHITE.
(after Sombroek, 1966)

Water Laterite soil, depending on climate, general hydrologic conditions and degree of imperviousness of the plinthite layer.

Figure 2 gives a general scheme of the various profiles that may develop in the presence of plinthite (originally with discrete mottling).

Chapter 6. SOIL FORMING FACTORS.

There are six classical factors of soil formation, discussed at length in handbooks on soil formation like Jenny (1941), Eden (1952), Russell (1961) and Rode (1961). They are: 1) climate, 2) parent material, 3) topography and landforms, 4) ground and surface water, 5) vegetation and soil organisms and 6) man and animal.

These factors do not act independently from each other, but in an interrelated way. Moreover, some of the factors, at certain stages of soil development, are rather a result than a cause of a particular soil formation.

6.1 Climate

There is an important difference between soil climate and atmospheric climate. Classification systems for the latter (Köppen, Lang, Meier, Thornthwarte) cannot well be applied to characterize tropical soil climates. Therefore new criteria are given in the 7th Approximation (Soil Survey Staff, 1960, 1967). Actual measurements on soil climate are however very restricted; a discussion therefore has to be centered on atmospheric climate, but keeping in mind the relative value. Conditions favouring the ferrallitization process are, in the following, always contrasted with those favouring the plinthization process.

Temperature etc.

a) for the ferrallitization process
- high; 24°- 29° mean annual temperature; in soil under forest the value is somewhat lower (by ± 3°C) and shows hardly any oscillation over day, month and year.
  Under savannah the microclimate and the soil climate are considerably different. Instead of 25°C, 40° à 45°C maxima occur, and lower minima (cf. Schulz 1960, Nye and Greenland 1960)
- little direct radiation (clouded half the day); under forest only 1-2% of the total light
- daylength always 12 hours
- with altitude decrease of 0.5-0.6°C annual temperature per 100 m.

- with latitude decrease irregular (deserts as an interruption); seasons becoming more important than annual means.
  There is supposedly no ferrallitization, especially not so if acid rock, where the average annual temperature $< 20^oC$.

b) for plinthization process:
   - at formation a lower average and larger variation of annual temperatures is possible than at the ferrallitization process, though not necessary.

Rainfall and humidity.

a) for ferrallitization process:
   - total annual rainfall often 3 000-6 000 mm (> 10 000 Cameroon, variations over the years may be large), but also ± 2 000 mm (Amazon, Congo)
   - effective rainfall under forest 70-80%, under savannah variable
   - (more important!) regular distribution over the year (< 60 mm is a "dry" month, 60-100 mm a "moist" month, > 100 mm a "wet" month) and high relative humidity (a.o. related to cloudiness), which under forest is 80-98%, much less under savannah (Schulz 1960)
   - high rainfall intensities, up to 5-6 mm/minute sometimes
   - under extensive anthropogenic savannah within the humid tropics there is a tendency for the rainfall to become lower and less regular (observations in Amazon, Surinam, Congo).
     Supposedly the ferrallitization process would occur with regular rainfall as low as 1300 mm (acid rock) and even 1100 mm (basic rock. There is no relation between the K_i value of the clay fraction of the ferrallitic soil and the total annual rainfall (though the theory of the process would lead to such an assumption).

b) for plinthization process:
   - the formation is possible under the same conditions as above, but a seasonal variation in the rainfall stimulates the process. Maignien (1966) indicates that for West Africa the zone of strongest present-day plinthite formation would be between the 750 and 1200 mm isohyets, while formation to a lesser degree would take place till isohyets 1500 mm and 500 m resp. Data from N.Nigeria however (Sombroek 1970) are not in support of this.

- exposure would take place in drier climates (or rather: at the change to a drier climate);
- hardening after exposure takes place at any climate, though strong dry seasons are favourable.

There exists also an evaluation of the climate with a "laterite number L" (Kerner-Marilaun 1927):

$$L = \frac{R^{3/4} \cdot (S-s) \cdot t_m}{R \cdot 100}$$

at which R = total rainfall
$R^{3/4}$ = effective rainfall
S = wet-season semi-annual rainfall
s = dry season semi-annual rainfall
t_m = minimum monthly mean temp. in $^{\circ}C$

If $L > 50$ then plinthite formation would take place.
The formula was however developed from occurrences of both recent and fossil, hard and soft plinthite, and is therefore essentially unreliable.

Paleo climate

The above considerations have very restricted value in view of the slowness of the processes (or rather: the great length of the processes), and the by now known important changes in climate during the Cretaceous, Tertiary and Pleistocene, as exemplified by the occurrences of river-terraces and aeolic sands in nowadays forest-covered parts (Amazon, Congo), plinthite crusts in presentday deserts (Australia, S.W. Sahara) and temperate regions (Germany, France).

Some literature on climatic changes: Aubreville 1949 (Africa), Heinzelin 1952 (Congo), Van der Hammen 1957 (Andes), Butzer 1957 (Mediterranean), Wilhelmy 1952 (S.America), Grove and Warren 1968, Pias 1968, Faure 1967, Michel 1970 (W. Africa and Sahara), Zeuner 1959 (general). Cf. also: Revue de Geogr.Phys. et de Geol.Dynam. 11; Bulletins ASEQUA.

6.2 Parent materials

a) for ferrallitization process:

- in principle on all types of material when favourable climate
- more widespread and more intensive on basic rock than on acid rocks
- influence of texture of the rock or sediment, because rapid percolation is essential. If material is very sandy: tropical upland humus podzols ("Giant Podzols") instead of ferrallitic soils develop examples: Borneo, Serawak, Congo, Amazon).
- influence of the degree of pre-weathering. "Rego-genetic" materials like those rich in kaolinite are easier/quicker reaching the end-point of ferrallitization.

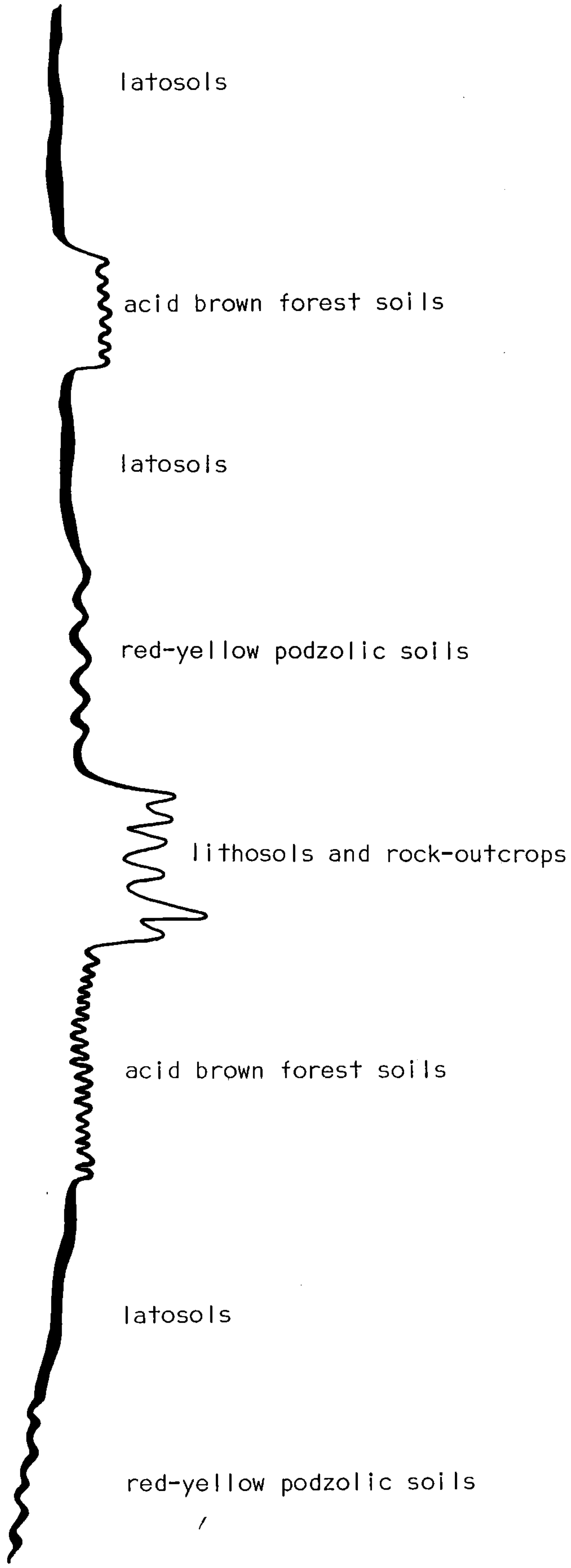
The great depth of weathering, the strong homogenization, the often long time involved (in the mean time e.g. rejuvenation by deposition of volcanic ash, aeolic dust etc.) and the apparent uniformity at the senile stage make it often difficult to establish for sure which was the original parent material.

b) for plinthization process:

- formation also occurring on all types of rock or sediment, but the segregation of Fe is more abundant when basic rock; on the other hand, sandstones need little Fe for formation of widespread "iron cemented quartzite". Very sandy materials give ground-water podzols instead, containing Fe/Al + humus.
- real hardening only occurs if the soft plinthite has reached its final stage of development, i.e. if the silicate clay minerals are largely kaolinitic.

It is less difficult than at the ferrallitization process to establish which is the original parent material of the plinthite (profiles not deep, no homogenization, final stage less uniform), unless lateral Fe-supply is concerned (foot-of-slope) or the material is transported. In situ formation can be established on unrounded form and a certain arrangement of the hardened elements, and on occurrence of related soft plinthite lower down, with a gradual transition. There may be however several cycles involved, occurring at the same level or very near to each other ("level-crossing", cf. 6.3).

Fig. 3. LANDFORMS AND SOIL DEVELOPMENT
(after Bennema, Camargo and Wright, 1962, schematised)



6.3 Topography and landforms

Geomorphologic processes are of paramount importance, both for understanding the soil genesis and for mapping purposes, especially when aerial photo-interpretation is applied. Landforms are also an important element for land classification/evaluation.

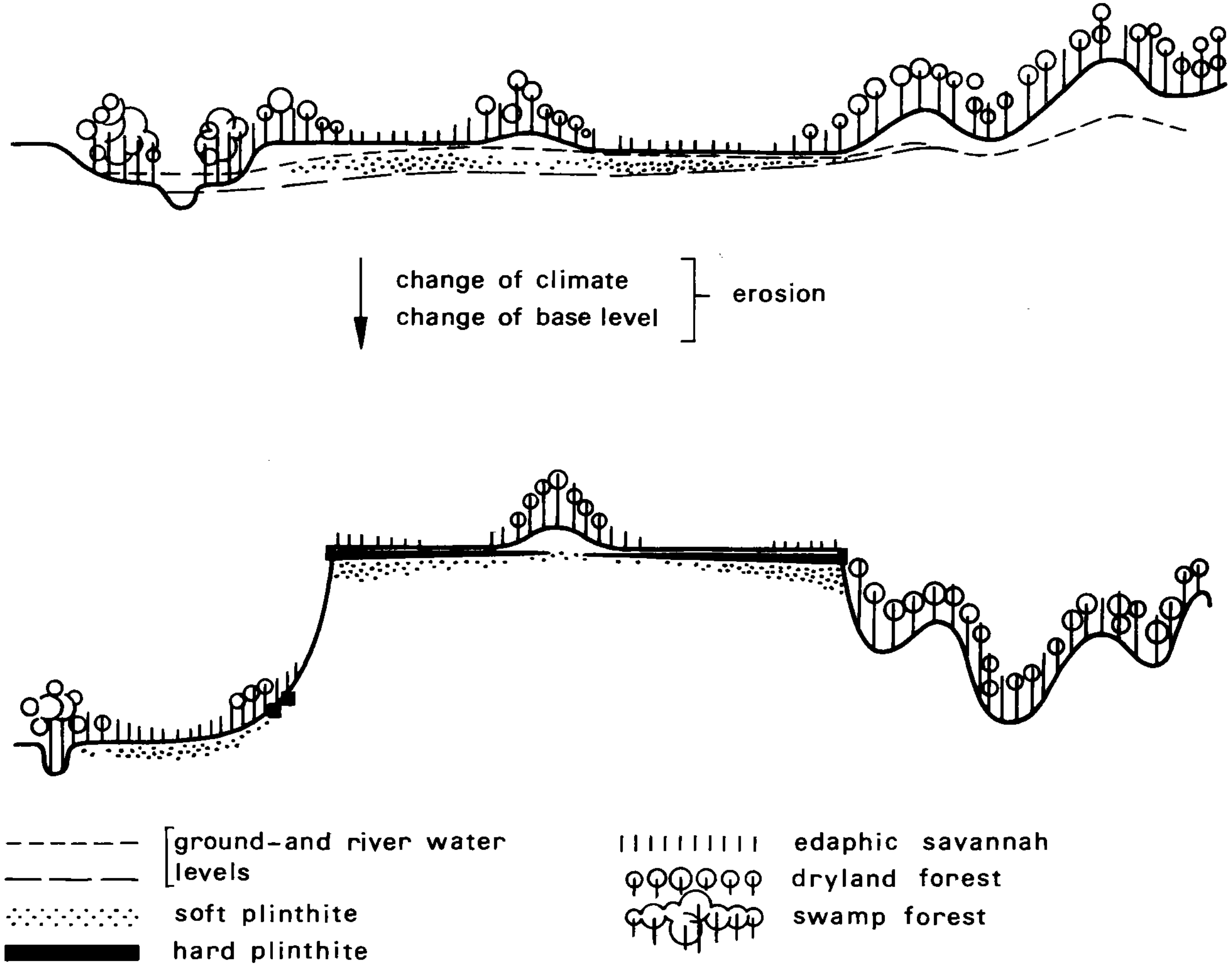
a) for ferrallitization process:
- influence altitude cf. 6.1
- slope %, the process is most effective on gentle undulating, stable terrains; if the slope percentage is too high, erosion and landslides (falling trees!) take place; if slope percentage is too low, imperfect drainage is likely to occur.
- slope form: preferably convex, because this results in easier drainage than concave.

In fact ferrallitic soils happen to occur mainly on planation surfaces if not too flat, and on terraces.
As regards the planation surfaces there are several main ones all over the tropics (cf. Davis, King, Ruhe): a Gondwanic surface (Jurrassic), a post-Gondwanic surface (late Cretaceous), an African/Sul America surface (Miocene) and a Niger/..... surface (Pliocene). There may be peneplains (i.e. the stable end of an erosion cycle with a certain base level) or pediplains (i.e. headwater retreat of scarps and forming and coalescing of scarp-foot pediments).

Dissected terrains in-between planation-surfaces often show less strongly developed soils (Ultisols, Inceptisols or even Lithosols), because the weathering materials have been and/or are being carried off to large extent: the ferrallitization process never comes to its logical end (cf. Bennema, Camargo and Wright 1962, for South America; Michel 1968, 1969 and Kaloga 1969 for West Africa, Chatelin 1967 for Central Africa, D'Hoore 1959 for Africa in general; CSIRO publications for Australia). As regards terraces it is important to know their age (Pliocene - Pleistocene - Holocene), but also whether they are fluviatile (braiding versus meandering), estuarine or marine, erosional or depositional, thalassostatic (i.e. formed mainly under influence of sealevel change: relative levels of 180 m - 100 m - 60 m - 45 m - 18 m - 7.5 m - 3.5 m and 2.0) or climatic (i.e. mainly under influence of changes in climate). Levels of different age and character can moreover cross at certain sites.

vegetation and inversion of relief at plinthite occurrences

Fig. 4.



71.003-4

Older terraces, especially if depositional (permeable substratum), well above the river level (no shallow ground-water level oscillation) and consisting of rego-genetic not too sandy materials, are most liable to have ferrallitic soils (cf. INEAC publications on Congo, Sombroek 1966 on Amazon).

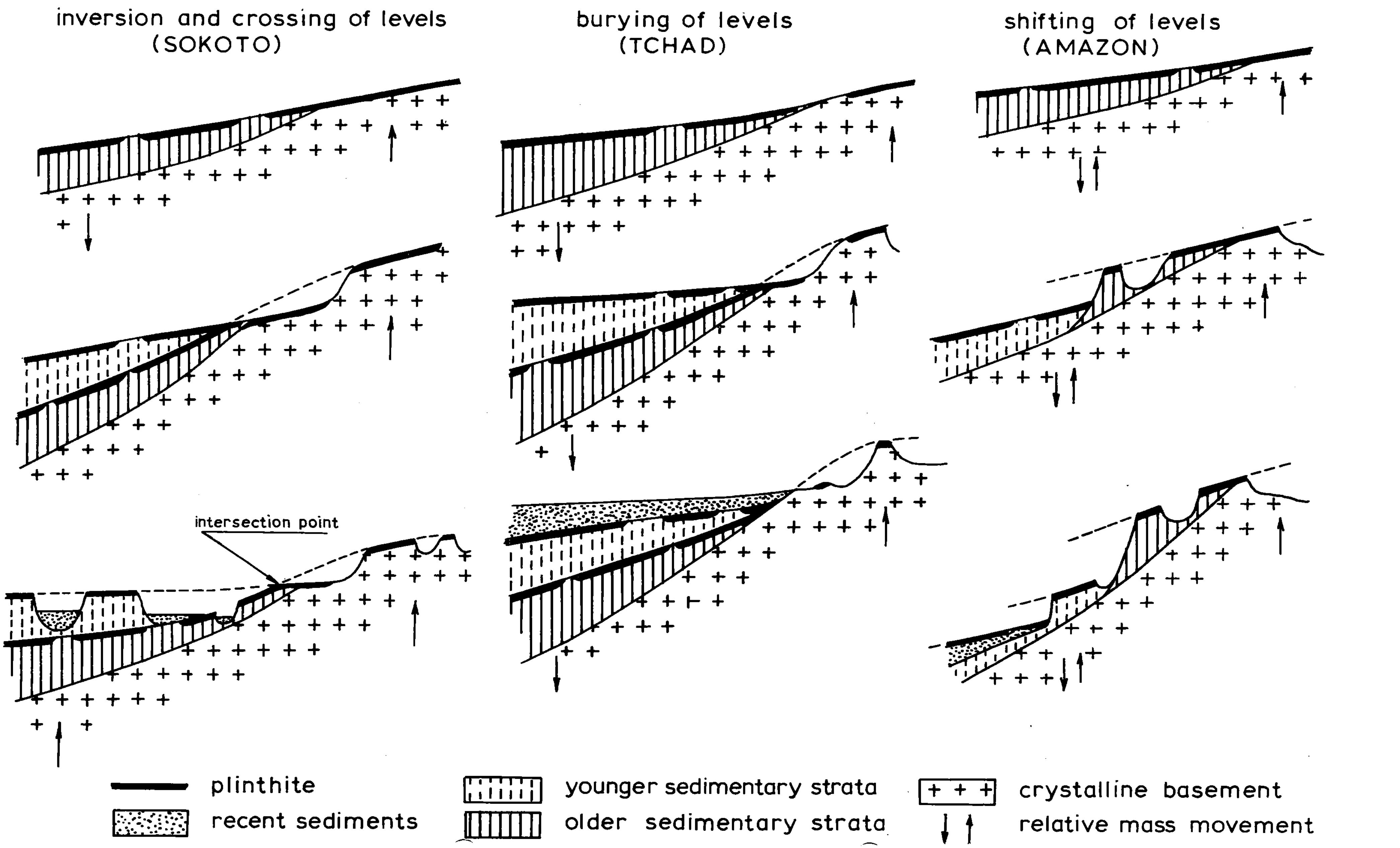
Note: Different concepts on landforming processes have influenced the various systems of genetic soil classification (Russian, French etc.; cf. Chatelin 1967).

b) for plinthization process:

- formation takes place mainly on flat land-surfaces that have impermeable substratum or layers (of any type and origon!), are relatively low-lying in respect to base level, have strong seasonal variation in the water level of nearby rivers, and/or have a seasonally very high rainfall without a proper discharge, while no enrichment takes place by volcanic ash, silt-rich flooding, desert dust etc. Also formation at foot-of-slope can take place, notably where at higher level decomposing fossil plinthite occurs. Exceptionally over whole lengths of slopes formation can take place, namely if the slope % is constant and the substratum very dense (e.g. due to prior formation of a strong argillic B).
  There are areas where Ground-Water Laterite profiles predominate on flat water-devide areas (while next to the rivers Ground-Water Podzols develop, cf. Sombroek 1966), and other areas where Ground-Water Laterite profiles predominate near to the rivers ("cuirasse de galerie", Maignien, D'Hoore 1954). The reasons for these different topo-sites are not clear.
- exposure and hardening of soft plinthite is promoted by any change in the geomorphologic processes, linked normally with changes in climate. The result may be an inversion of the landscape (Fig. 4: landform as a result of soil development!): "tafelberg-", "ouklip-" or "high-level" laterites (Van der Merwe 1950 for S. Africa), "boval" laterites (ORSTOM publications for W. Africa) and "table-land" laterites (CSIRO publication for Australia, Prescott and Pendleton 1952, general).

RELATIVE POSITION OF PLINTHIZATION LEVELS

Fig. 5.



71. 003-3

Several cycles of plinthization may have taken place in the same area, representing a geomorphologic succession. The highest situated table lands/scarps are not always the oldest. Depending on the geomorphologic history one may discern respectively burying of plinthite levels, shifting of levels, inversion of levels and crossing of levels (cf. fig. 5).

The above applies to plinthite levels formed in situ; similar schemes can be developed for layers of transported plinthite (geologic stone lines).

Note: a protecting sheet of fossil plinthite may enable ferrallitization in deeper layers below it (constant percolation with sesquioxide containing but otherwise sterile water), in areas normally too dry for the process (Sudan).

6.4 Ground- and surface water.

a) for ferrallitization process:
- free percolation necessary
- no flooding, unless incidental and then with poor water (rain-water)

b) for plinthization process:
- either: ground-water level oscillation necessary, not too deep (intermittent oxigen supply for effective concentration of Fe necessary)
- or (less common): ground-water seepage necessary, Fe rich, at foot-of-slope. This latter is a cause for the process possibly only if some dry season is present (in a pér-humid climate precipitation of Fe would not take place); if the dry season is too strong then the effective seepage would be too small (10° N. for W. Africa as upper limit?)
- inundation (by flooding water, horizontally moving) or submergence (by standing rain-water) may or may not prevent the process, depending on the quality of the water. One can distinguish (with Brazilian names between parentheses):

- though there is less organic matter, the higher degree humification may start a plinthization process in cases where the balance ferrallitization-plinthization was already precareous (e.g. the case of chapter 5.1).

6.7 Time.

Time is not a factor of soil formation sensu strictu, but it determines the net effect of the factors already discussed. It may be repeated that many soils subject to the ferrallitization or plinthization process have not yet reached their final "senile" stage (i.e. Ferrallitic soil resp. Ground-Water Laterite soil/Cuirass soil).

a) for the complete ferrallitization process much time is necessary. The process should have started in the Early Pleistocene, or Tertiary, unless strong rego-genetic materials are concerned (terraces). Calculations by Lenouf and Aubert 1960 for Ivory-coast conditions (2000 mm rainfall, 26°C average) are that a period of 22 000-27 000 years would be needed for only 1 m granitic material to become completely ferrallitic. Under less humid conditions the period would increase to 200 000 years and more.

   As mentioned before, establishing the age of Ferrallitic soils is very difficult in view of past climatic changes.

b) for the complete plinthization process a relatively short time can be sufficient.
   - formation can be in rather short time, especially if rego-genetic materials are involved. In natural conditions a period as from the Early Holocene is known to be sufficient to give the Ground-Water Laterite profile; at artificial change in conditions the profile may develop in some centuries or even decennia.
   - truncation and (partial) hardening can take place in a few years.
   - on the other hand, the destruction is an extremely slow process.

   Even plinthites dating from the Cretaceous are known to exist. This explains the frequency of plinthite occurrences (of any kind of type: soft or hard, in situ or transported, exposed or buried) throughout the tropics and beyond.

a) river water containing sediments (agua branca): prevention
b) river water containing nothing (agua limpa/azul): no prevention
c) river water containing humic acids (agua preta): no prevention
d) river water containing sesquioxides (agua marrom): stimulation
e) rain water (containing nothing): no prevention
f) river or sea-water containing salts: prevention.

Therefore annotation over the year of the quality of the surface waters is of importance, when carrying out surveys.

Notes:

1) The upper level of submergence or flooding does, of course, not coincide with the upper limit of the zone of plinthite formation; also however when ground-water level oscillations are till near or at the surface, the zone is at some depth, depending mainly only the type of parent material and the degree of development of the Ground-Water Laterite profile.
2) The above always concerns intermittent waterlogging (seasonally, exceptionally daily). Where permanent waterlogging occurs no Ground-Water Laterite soil develops but a peat(y) soil, covered with swamp forest.

6.5 Vegetation and soil organisms.

a) for ferrallitization process:
- most favourable is a dense evergreen forest, mixed in species, in rooting depth and in storey composition. Though there is much fresh organic residue formation (Congo: 12 ton/ha/year dry matter, i.e. 80 kg Ca, 50 kg Mg, 50 kg K, much N) no humification takes place but rapid and complete mineralization, followed by recycling in the vegetation, largely by a dense net of tiny roots on the forest floor.
- the process is less and/or slower under savannah, due to less favourable macroclimate in case of climatic savannah, in case of anthropogenic savannah (due to long shifting cultivation) the ferrallitization continues, but less intense because
  i) organic matter is different (grass-litter produces much Si, known to form opal phytolithes (bar-shaped, 10 µ-0.1 mm) in topsoils.

ii) macroclimate is somewhat changing.

iii) microclimate and soil climate become rather irregular instead of practically constant over the day, month and year.

iv) burning causes extra drying-out of the soil (and baking around taproots).

v) some surface sealing occurs, which may cause run-off, instead of rapid percolation.

vi) run-off may cause (sheet and rill) erosion, hence the natural growth of the ferrallitization profile is partly offset.

vii) less deep and less intense rooting and lower organic matter production causes lower and/or shallower activity of soil organisms: less homogenization.

Because of these less favourable changes, there is often some gradual subsoil compactation, some clay-illuviation or even podzolization (humic acids carrying Fe downward).

- termites (<u>Sys</u> 1955), ants (notably leaf-cutting ants: Atta spp.) forest crabs, and microbes (possibly also through enzymes - Russian school), are very active at the ferrallitization process: homogenization. Worms are absent.

b) for plinthization process:

- at formation the natural vegetation is often less luxuriant than elsewhere (some dry season often more liable to the plinthization) but also less than in the immediate surroundings. The latter is due to the imperfect drainage: rooting depth is limited. This poorer vegetation causes larger oscillation of the ground-water level, and more formation of organic acids (because the surroundings for microbes is less favourable), which on its turn stimulates the Ground-Water Laterite formation, which causes further deterioration of the vegetation, etc.: mutual reinforcement.

  Finally an open <u>edaphic savannah</u> develops (fig. 5), which through accidental or purposely started fires becomes xerophytic just like the climatic and long-lasting anthropogenic savannahs. Size and shape of these edaphic savannahs vary according to the shape of the landforms and the hydrological conditions.

- at truncation and hardening (due to climatic change to drier) a still poorer vegetation develops because of the dry and extremely shallow soil. Sometimes no vegetation at all occurs ("boval" areas in the Sudan-zone of W. Africa).
- at gradual destruction of fossil hard plinthite (due e.g. to a change of climate to more humid) a gradual return to savannah and ultimately to forest is possible (mutual reinforcement in opposite direction), unless the cuirass is completely impenetrable. In some cases even (pér-humid, loose concretionary instead of cuirasse) the forest vegetation is more luxuriant than in the surroundings, because at slaking of the concretions some locked-up primary minerals may come available.
- the soil fauna is of different composition and less abundant than at the ferrallitization process. Termite activity may be more apparent (constructions on top, rather than in the soil).

It will be clear that thorough study of the origin of tropical savannahs (climatic, anthropogenic, edaphic) as well as their influence on the ferrallitization process c.q. plinthization process is of paramount importance, a.o. as a base for sound schemes for their recuperation to some form of productivity, to effective control of erosion, and/or to re-establishment of the macro-biological balance in the tropics.

6.6 <u>Man and animal</u>.

Some actions of man in the tropics having a bearing on soil formation are:

- cutting and burning of forest for shifting or permanent cultivation.
- cutting of wood for fuel supply, and some construction purposes.
- burning of grassy terrains for fresh palatable growth, pest control, weed- en shrub control.
- cattle herding, causing trampling (surface sealing), sapling eating or bruising (degeneration of woody species), and sometimes overgrazing (baring of the soil, causing erosion).
- change in local ground-water level/flooding level, purposely or accidentally.
- change in downstream flooding regime and flooding quality (Rio de la Plata).

a) for ferrallitization process.

The influence of man and animal is largely negative (i.e. slowing down the process or stopping it alltogether. This because:

- less organic matter and less mineralization of organic matter, less abundant soil life: ferrallitic weathering less deep, less active or even replaced by lessivage and/or podzolization and/or (exceptionally) plinthization.
- erosion (a.o. due to sealing) may start: less deep profiles.

  Note: the influence of man on the fertility of the soils can be both negative and positive (cf. chapter 9):
- erosion may take away fertility as stored in the humus, but may lay bare deep subsoils with some primary minerals.
- man may burn away fertility of the natural vegetation, but improve fertility by tree-crop farming + leguminoses, and reforestation.
- continuous dwelling may cause local stable humus-accumulation (Terra Preta).

b) for plinthization process.

The influence of man and animal is either nihil or positive (i.e. stimulating):

- the formation may be accelerated due to less regular micro-climate, still less rooting, still larger ground-water level oscillation.
- the truncation and hardening may start due to erosion of the top-layer of the Ground-Water Laterite profile, due to increase of periods of dryness in the zone of soft plinthite, etc.

  Note: There is no automatic plinthite formation and/or hardening at clearing of the tropical forest (as feared by some doomsday ecologists like McNeil 1964). On the contrary: the need for clearing. i.e. the existence of forest proper, implies that drainage is good. That nevertheless there are some cases of plinthite appearance at clearing is rather because of some side-effects:
- erosion may start, lying bare already existing fossil hard plinthite or soft plinthite (which of course hardens at that moment) of deeper layers.
- the ground-water regime may change (a.o. because of more run-off) to the worse, inducing plinthite formation.

- though there is less organic matter, the higher degree humification may start a plinthization process in cases where the balance ferrallitization-plinthization was already precareous (e.g. the case of chapter 5.1).

6.7 Time.

Time is not a factor of soil formation sensu strictu, but it determines the net effect of the factors already discussed. It may be repeated that many soils subject to the ferrallitization or plinthization process have not yet reached their final "senile" stage (i.e. Ferrallitic soil resp. Ground-Water Laterite soil/Cuirass soil).

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   As mentioned before, establishing the age of Ferrallitic soils is very difficult in view of past climatic changes.

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   - truncation and (partial) hardening can take place in a few years.
   - on the other hand, the destruction is an extremely slow process.

   Even plinthites dating from the Cretaceous are known to exist. This explains the frequency of plinthite occurrences (of any kind of type: soft or hard, in situ or transported, exposed or buried) throughout the tropics and by ond.

Establishing of the age of plinthite materials is often relatively easy, once it is known that they are in situ, by consulting geologic columns (sedimentary areas) or by correlation of planation levels (crystalline areas).
Cf. CSIRO publications on Australia, Bulletins ASEQUA and Sombroek 1970 on parts of W. Africa).

Chapter 7. REVIEW OF THE OLDER NAMING OF FERRALLITIC AND/OR PLINTHITIC SOILS.

A soil man often has to rely, when starting studies in a tropical area, on older soil or geographic information, in which obsolate names for tropical soils are used. Since moreover early concepts on tropical soils and soil formation still linger on till at present, it is useful to have a review of early classifications and concepts at hand.

- Lacroix (1913), a Frenchman working in Madagascar and West Africa, distinguished, only on chemical grounds:

Laterites	: 90-100% sesquioxides
siliceous laterites	: 50- 90% sesquioxides
lateritic soils	: 25- 50% sesquioxides

It can be seen that the first two refer to stony material (hard plinthite) rather than to soils.

- Eichinger (1920), a German working in East Africa, distinguished:

Ältere Roterde	(∾ ferrallitic soil)
Jüngere Roterde	(∾ ferruginous tropical soil and Andosol pp.)
Lateriterde	(∾ cuirassed surfaces)
Lateritroterde	(∾ concretionary ferrallitic soil and ferruginous tropical soil)

- Vageler (1938), a German working in Indonesia mainly, but also in Brazil and Africa, discerned:

Rotlehm Braunlehm	} rather compact and rather plastic soils (∾ argillic horizon: ferruginous tropical soil)
vererdeter Rotlehm vererdeter Braunlehm	} transitional
Roterde	: friable and porous (∾ oxic horizon: ferrallitic soils)

Often however, especially in later publications, the term "Erde" or "earth" is applied to soils with a blocky structure and "Lehm" or "loam" is used for ferrallitic soils, especially the ones relatively poor in sesquioxides, e.g. "Braunlehme" for the Amazon ferrallitic soils. See also below.

- Milne (1935), an Englishman working in East Africa, introduced the term: laterized Red Earth for soils more or less comparable to the presentday ferrallitic soils. He devised subdivisions on the type of parent rock - a hazardous basis because of many uncertainties.

- Ivanova and Rosow (1960), Russians working a.o. in China, distinguished:

  Krasnozems (ferrallitic and ferruginous tropical soils)

  Krasnozemic Gley soils (∿ ground-water laterite soils)

- Stephens (1962), for Australia, used:

  Krasnozems (Red Loams, Latosols), which are haemorphic and ferrimorphic and consist of deep, friable, red or brown-yellow clay (∿ ferrallitic soils)

  Lateritic Krasnozems, which are polymorphic and contain laterite and a pallid zone (∿ lithosols from plinthite, some concretionary ferrallitic and ferruginous tropical soils).

  Lateritic Red Earths, which are polymorphic, deep and reddish and contain laterite lower down; the A is sandy to loamy, the B slightly heavier and compact (∿ ferruginous tropical soils).

  Lateritic podzolic soils, which are polymorphic, have a bleached horizon with laterite concretions lower down and an illuvial clay horizon (∿ Ground-Water Laterite soil).

It can be seen that "laterite" here is indeed used systematically for plinthite materials.

- Aubert a.o. (e.g. 1954) has described the older French classification for African countries:

  sols ferralitiques actuels: containing some illite

  sols ferralitiques anciens: the proper ferrallitic soils, not containing illite.

  sols ferralitiques à horizon sombré/foncé: with a dark subhorizon in the lower part of the B, occurring at higher altitudes.

  sols gris lateritiques (∿ Pale Yellow Latosol?, or Ground-Water Laterite soil?)

  sols lateritiques foncé/humifère: with high organic matter content in A, developed on basic rock.

  sols de cuirasse: with plinthite, of any kind (?)

  sols lateritiques très evolué: has an argillic horizon!

- Charter (1954), Brammer (1956), Englishmen working in West Africa, distinguished Latosols from Basisols:

  Their Latosols were subdivided as

  forest oxysols : excessively leached, pH 4.0-4.5 in top, C/N > 15, orange-brown (∼ ferrallitic soils)

  savannah oxysols : shallower, lower % C, for the rest comparable.

  forest ochrosols : less leached, pH 6.0-7.0 in top, C/N 10-12, reddish brown (∼ ferruginous tropical soils pp?)

  savannah ochrosols : as above, but shallower and lower % C.

  Note: Basisols, which are either the dark red Rubrisols or the dark brown Brunosols, are plastic, blocky to prismatic and with a higher CEC (Comparable with the Red-Yellow Mediterranean soils/Alfisols?).

- Marbut (1934 a.o.) distinguished:

  Tropical Red Loams : well-drained, having a high percentage of friable clays, apparently with few sesquioxides (Amazon).

  Ferruginous Laterite soils: well-drained, having much sesquioxides, partly as micro-concretions called shot or perdigón (Nipe clay of Cuba).

  Lateritic soils : well-drained, having larger concretions (?)

  Ground-Water Laterite soils: imperfectly drained, with mottled clay.

- Baldwin, Kellogg and Thorp 1938, at their official account of the older USA classification in "Soils and Man", discerned:

  Lateritic soils:

  Yellow Podzolic soils: with clear clay illuviation, grouped with Lateritic soils only because of occurrence of sesquioxides in the clay fraction.

  Red Podzolic soils : idem

  Yellowish Brown Lateritic soils: brown, friable clays and clay loams over yellowish brown heavy but friable clays. Acid to neutral. External and internal drainage good to excessive (∼ Tropical Red Loam of Marbut).

  Reddish Brown Lateritic soils: reddish brown to dark reddish brown friable clayey soil over deep-red friable and granular clay. Deep substratum may be reticulately mottled. External and internal drainage good.

(Red) Laterite Soil : red-brown surface soil, red deep B horizon. Red or reticulately mottled parent material. Very deeply weathered. External and internal drainage good. (∾ Ferruginous Laterite soil/ Nipe clay of Marbut).

Ground-Water Laterite soils: gray or gray-brown surface layer over leached yellowish gray A2 over thick reticulately mottled cemented hardpan at a depth of 1 foot or more. Hardpan up to several feet thick. Laterite parent material. Concretions throughout. Imperfectly to poorly drained.

Note: apparently "lateritic" and "laterite" are applied to denote sesquioxide-richness of the clay-fraction, after the Lacroix concept and K_i ratios.

In 1959 Thorp and Smith repeated this subdivision, except that the Podzolic soils were not any more included in the Lateritic soils. At the same time the term "Latosol" was suggested for both Lateritic soils and Laterite soils.
Note: elsewhere, Reddish/Yellowish-Brown Lateritic soil was maintained for some of the ferruginous tropical soil groups, while accepting Latosol for the ferrallitic soils).

- Middelburg (1950) at the ISSS Amsterdam Congress suggested a main subdivision, in accordance with Marbut, as follows:

  Laterized Red Soils with $SiO_2/Al_2O_3 < 2$: Nipe clay (Cuba); Red Loam (Sudan); Tana mera, Lixivium, Lateriet-grond (Indonesia), Lateritic soil (Puerto Rico), Lateritic yellow earth (S. Africa), Lateritic red earth (East and South Africa), Latosol.

  Ground-Water Lateritic Soils: Buchanan's laterite; low-level laterite; Mottled clay; Ouklip soils (South Africa); Paddy soil (China); Sawah gronden (Indonesia).

- Kellogg (1949, 1950), an American requested by INEAC to classify the Congo soils, discerned, mainly on colour:

  Red Latosol: reddish brown A, red permeable B, seldom hardpans or crusts, mottled zone deep if present at all, medium fertility.

Black-Red (or Dark Red) Latosol: very dark red to black A, finely mottled reddish yellow B, black micro-concretions, medium fertility.

Earthy Red Latosol : like the Red Latosol but very porous.

Reddish-Yellow Latosol: reddish yellow (5 YR6/6) rather sticky A, mellow (=loose) B, from acid rock, low fertility.

Reddish-Brown Latosol: dark reddish brown A, reddish brown B (5 YR4/3), friable only under pressure (nut structure!) from basic rock, high fertility.

Yellow Latosol : yellow to reddish yellow (7.5 YR6/8) A and B over mottled zone, laterite concretions usually present, low fertility.

(Yellowish Brown Latosol): brownish A, yellowish brown B.

(Brown Latosol) : brown to dark brown A, reddish brown to brown B, often rel. high % C, from volcanic materials.

Apart from the above well-drained soils, the imperfectly drained Ground-Water Laterite is mentioned. The subdivision is partly very arbitrary, and some of the mentioned ones would presentday not, or not completely, belong to the ferrallitic soils.

- Cline (1955), an American working in Hawaii, made a subdivision as follows:

Humic Latosol : 10% organic matter in A, red or brown or reddish brown B, very strongly acid, friable, no textural differentiation (∾ Humic Latosol).

Ferruginous Humic Latosol: A massive to crumbly and purplish, B reddish, containing magnetite and anatase (TiO_2), less acid (∾ Terra Roxa legitima of Brazil, Nipe clay of Cuba).

Low-Humic Latosol : red to reddish brown, structured B, with much MnO_2 (∾ Terra Roxa Estructurada of Brazil).

Hydrol Humic Latosol : humic A, red or yellowish red smeary B, irreversible dehydration of clay (∾ Andosol).

The latter two are nowadys excluded from the ferrallitic soils.

- Bramão and Dudal (1958), of FAO, distinguished on world-wide basis less groups than Kellogg and Cline, namely:

Red-Yellow Latosols: red to yellow, on acid rock.

Dark Red and Dark Reddish Brown Latosol: dark red to dark reddish brown, on basic rock (in fact partly having an argillic B!)

Brown Latosols : dark brown B, at higher altitudes, often from volcanic materials (in fact partly Andosolic).

Low-Humic Latosols/Terra Roxa: coarse granular surface, on basic parent materials (in fact largely no ferrallitic soil).

Also was introduced:

Reddish-Brown Lateritic soil, as being distinguishable from the Latosols by having textural differentiation and relatively high fertility. Ground-Water Laterite soil was also set apart.

- Bramão and Lemos (1960), of FAO, distinguished for the first draft of their "Soil map of South-America" still some other groups (in addition to the ones mentioned above) drawing for a good deal on Brazilian data:

Rego-Latosols : yellowish, relatively low in sesquioxides (∾ Kaolinitic Yellow Latosols of Amazon).

Pale-Yellow Latosols: pale yellow colours (∾ Hydro Kaolisols of Sys et al 1961).

Concretionary Latosols: considerable amount of loose concretionary plinthite elements.

Areno-Latosols : very sandy (∾ Latosolic Sands, Acid Red and Yellow Sands pp.).

- Aubert and Duchaufour 1956 and Aubert 1963 describe the classification units employed by ORSTOM for African countries until rather recently:

Sols ferrallitiques (i.e. having a ferrallitic B horizon, rather well defined at the time):

Sols faiblement ferralitiques (ou recents): K_i 1.7-2.0 subdivided into modal, ferrisolique, hydromorphe and induré (the latter three would fall outside the modern concept of ferrallitic soils).

Sols fortement ferralitiques (ou typiques): $K_i < 1.7$. Subdivided mainly on colour.

Sols ferralitiques humiques (ou humifères): > 5 à 7 % organic matter in upper 20 cm. Subdivided mainly on colour.

Sols ferralitiques lessivés: with a leached A horizon; subdivided mainly on the type of leaching.

- Botelho da Costa et al 1958 describe a rather similar classification, as employed by the Portuguese in Angola:

  Solo fraca mente ferralitico (or levi-ferralitico): K_i 1.7-2.0.

  Solo mediamente ferralitico: K_i 1.7-1.33.

  Solo fortemente ferralitico: $K_i < 1.33$.

  Solo psamo-ferralitico: sandy, K_i variable.

  Solo para-sialitico on para ferralitico: with some weatherable minerals (∾ Ferrisols of Congo).

Table 1.

General diagnostic characteristics of ferrallitic soils

Classification systems / Characteristics	U.S.A. older (a.o. Kellogg '50) "lateritic soil"	Africa-ORSTOM * Aubert+Du Chaufour '56 Aubert+Segalen '66 "sol ferralitique"	Congo-INEAC (Sys '61, Tavernier + Sys '65 *) B deconsistence/compos. ferralsolique (B ferralitique	Brazil (Bennema '63 *, Bennema '66) latosol-B	USA recent (Supplement '67 of 7th Approx.) oxic horizon	FAO (Dudal 1968) oxic horizon
Thickness	-	often thick	* > 50 cm	thick	>30 cm, above 2 m depth	> 30 cm
Transitions of hor.	-	-	-	diffuse to gradual	diffuse to gradual	diffuse to gradual
Drainage conditions	well-drained	-	-	well-drained	-	-
Colour	red or reddish	-	reddish, yellowish	dark red (Fe), dusky red (Fe + Mn), brown or yellow (humid)	gray, brown, red or mottled	-
Clay %	-	-	* > 20 %	> 15 %	> 15 %	> 15 %
Clay illuviation	-	-	< 25 % clay skins	no silicate clayskins, -linings, - bridges	clayskins < 1 % of volume	-
Textural change	no accum. horizon	-	-	absent, or gradual, textural ratio B/A < 1.8	absent, or gradual	-
Structure	-	-	granular, or weak to moderate subangular blocky	fine granules, composing sub- angular blocky or porous massive	very fine granular, composing massive, weak blocky or weak prism	-
Aggregate stability	high	-	"pseudo-concretions" of clay	high; "natural" clay ⩽ 2% unless C%/clay% > 0.015 (upper part) or $pH_{KCl} > pH_{H_2O}$ (lower part)	natural clay < 3%, excluding subhorizons with > 1% C or electro-positive	no, or only traces of water-dispersable clay in some subhor.
Consistence	friable	very friable	relat. firm	(very) friable	(very) friable	-
Porosity	-	-	-	very porous	very porous	-
Permeability	-	-	-	very permeable	-	-
Erodibility	low	-	-	low, unless sandy	-	-
Minerals of clay fraction (scm= silicate clay minerals)	high % of sesquioxides	scm 1:1, hydroxides of Fe + Al, highly resistant pr.minerals (quartz)	kaolinite, iron oxides, often gibbsite, non-appreciable 2:1 scm	sesquioxides, kaolinite, quartz, no allophanes of high CEC, no 2:1 scm or poorly crystallized 1:1 scm	hydrated sesquioxides, often amorphous; 1:1 scm, quartz a.o. no 2:1 scm, no allophanes	-
SiO_2/Al_2O_3 (Ki)	< 2.0	* ⩽ 2.0, often < 1.7	< 2	< 1.8 (sometimes 1.8-2.2)	-	-
Rock structures	-	-	-	absent	visible in < 5% of soil mass	visible in < 5% of s.m.
Weatherable primary minerals in sand fraction	low	absent or rare	50-250µ: < 10%	20-2000µ: < 4%	20-200µ: < 6% mica, < 3% feldspars+ glass+Fe-Mg minerals	only traces of primary alumino- silicates
Silt/clay ratio (s=2-50µ, l=2-20µ)	relat. low	* l/c < 0.25 in B and C	l/c < 0.2 sedim. < 0.15 igneous/metam.	relatively low, * l/c < 0.25	low	-
Plinthite	absent	absent or present		absent, or concretions (massive or (soft only below)	absent, soft or hard	
Cation exchange capacity	medium to low	low * < 20 meq/100 g soil	* < 16 meq.	active potential (pH) typical ⩽ 6.5, trans < 13 potential (pH 8.1) < 22	active ($1N NH_4Cl$): < 10 me/100 g clay potent. (NH_4OAc : < 16 " (no correction for org. matter!)	< 10 m.e. < 16 m.e. (no correction)
Base saturation	low	often low * < 40% in A and B	< 40-50%	-	-	-
$pH_{H_2O}-pH_{KCl}$ difference	-	-	-	large, small or negative	small or negative	-
Anion Exchange Cap. and P-fixation	relat. high	-	-	high	-	-

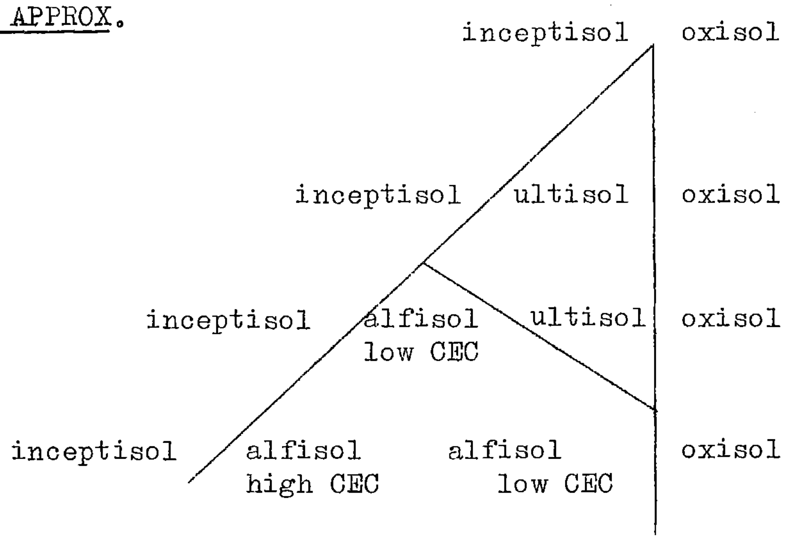
71.009-2

s.c.m.= silicate clay minerals

Table 2

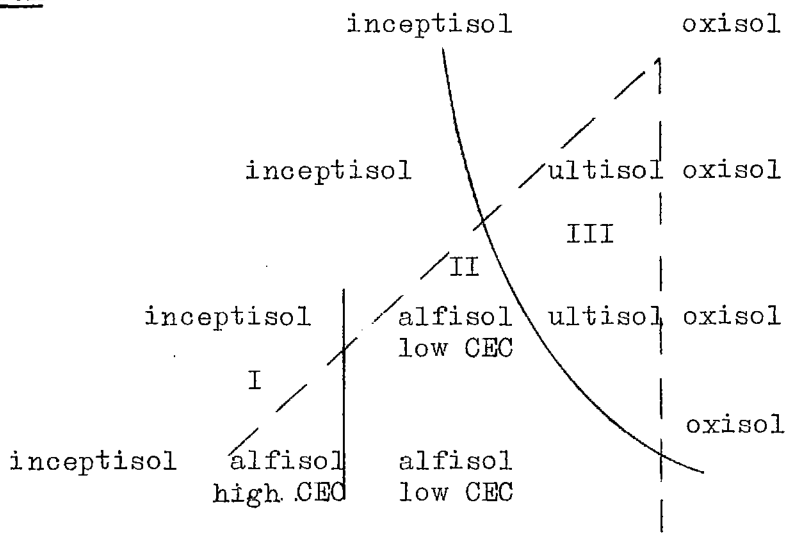
Comparison of classification systems for red and yellow soils of tropical and subtropical uplands.
(after Bennema 1969, lecture notes of the international soil science course L.H./I.A.C.)

7th APPROX.



⟶ increasing degree of weathering, ↓ increasing length of dry season

ORSTOM

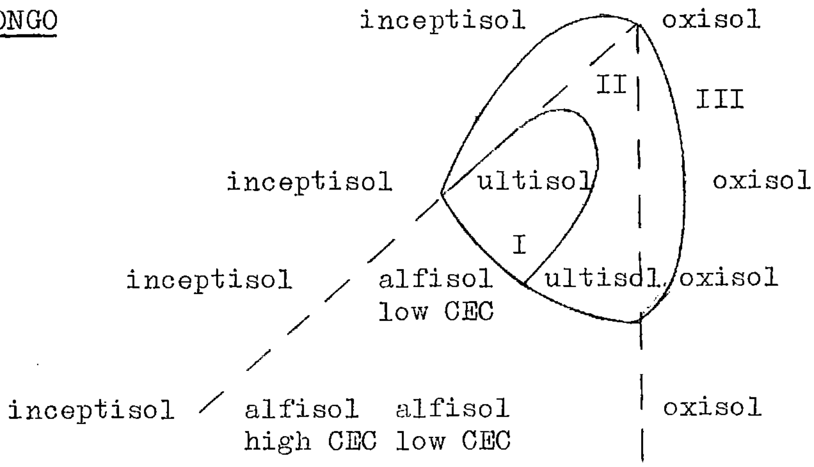


I. sols méditerranéens

II. sols ferrugineux tropicaux

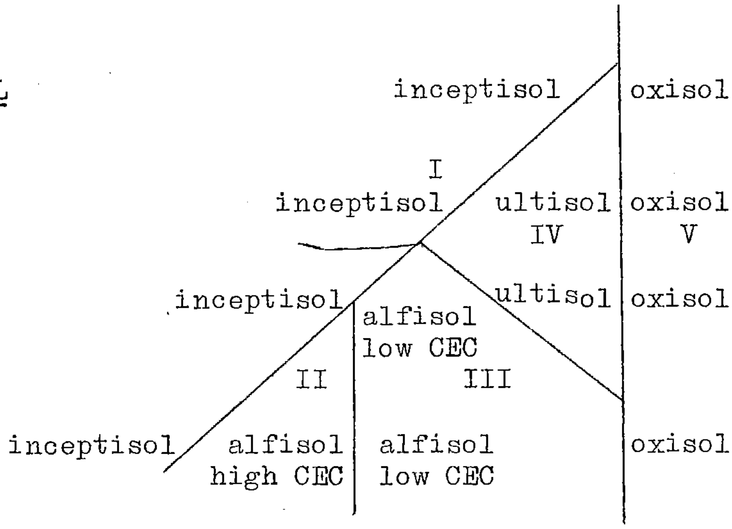
III. sols ferrallitiques

CONGO



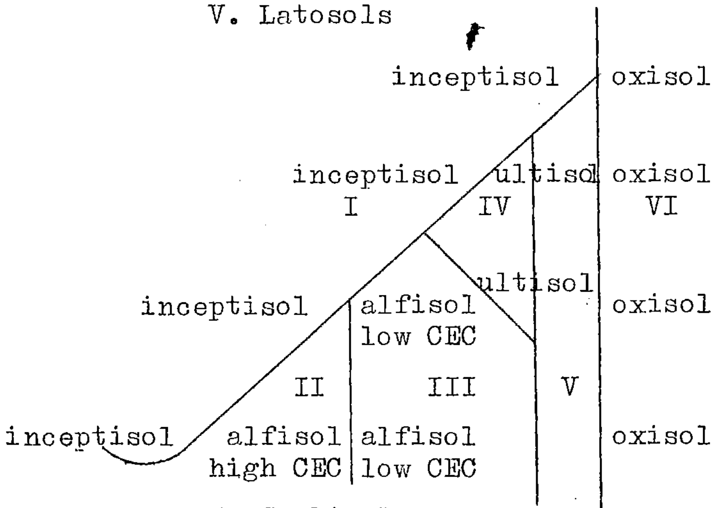
I. Kaolisols lessivés
II. Ferrisols
III. Ferralsols

BRAZIL



I. Mainly Acid Brown Forest soils
II. Red-Brown Mediterranean soils
III. Red-Yellow Podzolic soils, with high base status
IV. Red-Yellow Podzolic soils, with low base status
V. Latosols

FAO



I. Cambisols
II. Orthic and Chromic Luvisols
III. Ferric and Plinthic (?) Luvisols
IV. Acrisols
V. Nitosols
VI. Ferralsols

Chapter 8. COMMONLY USED RECENT CLASSIFICATION SYSTEMS FOR FERRALLITIC AND/OR PLINTHITIC SOILS.

Only short descriptions are given. Therefore, if one wants to use one or another system in a particular country, one has to consult the detailed description of criteria of the original publications. The slight differences in the concepts on ferrallitic soils in general in the different systems are given, in summarily comparison, in table 1. The comparison is also shown, graphically, in table 2 while table 3 compares the systems as a whole, the genetic approach put central.

8.1 The newest French system.

In use in French-speaking African countries, where soil studies are carried out by ORSTOM. Described by Aubert and Segalen (1966).

a) Subdivision of the ferrallitic soils.

classe 9. Sols ferralitiques:

"ferrallitic" composition defined relatively vaguely and broader than in other systems

sousclasses:

9.1 Sols ferralitiques fortement désaturés

in the B horizon: S < 1 m.eq., V < 20%, pH < 5.5
(∾ Udox, no or short dry season, > 1800 mm rainfall)

9.2 Sols ferralitiques moyennement désaturés

S 1-3 m.eq., V 20-40%, pH 4.5-6.0
(∾ Orthox, dry 2-3 months, > 1300 mm rainfall)

9.3 Sols ferralitiques faiblement désaturés

S 2-8 m.eq., V 40-70(80)%, pH 5.5-6.5
(∾ Ustox, 3-6 dry months, 1200-1600 mm rainfall)

Subdivision of the "sous-classes" into "groupes":

.... 1. typiques: normal ones

.... 2. humifère:

> 1% organic matter over 100 cm, or > 7% over 20 cm depth
(not occurring for 9.1)

.... 3. appauvri:

disappearance of clay or iron from A, which however not accumulates in B (e.g. decomposition or oblique migration taking place); textural ratio B/A ≥ 1.4 (∾ B-structural of Congo).

.... 4. remanié:

new soil material has been brought into the upper part of the profile, which is however as much weathered as the original, in situ, lower part of the solum; separation of "old" and "new" layers is indicated by e.g. a (geologic) stoneline.

.... 5. rajeuni on pénévolué:

either a) new soil material (maximally 50 cm thick) has been brought into the upper part of the profile, which is less weathered than the in-situ material of the lower part (= rejuvenation); b) erosion to the less weathered substratum (C) has taken place, usually followed by covering of, or reworking with, the strongly weathered in-situ material of the solum (= érosion); c) weathering in the solum has not yet reached completion due to relatively short time of soil formation (= pénévoluation).
(∾ "Ferrisols" of Congo; "Thapto" of Soil Survey Staff 1967).

.... 6. lessivé (en argile, en fer): migration of clay and/or iron from A to the upper part of the (thick) B horizon; textural ratio B/A $\geq$1.4, clay-skins in canals and pores, but rarely around structure elements; organic matter not much decomposed (∾ part of B-textural of Congo), occurring only in sous-classe 9.3.

Subdivision of the "groupes" into "sous-groupes"

modal: the normal type

jauno: ?

induré:

in the B a cuirasse or carapace (∾ hard? plinthite); (if at surface: sol brut, see below)

hydromorphe:

with (pseudo)gley at base of A or upper part of B (∾ soft plinthite?)

faiblement rajeuni on pénévolué:

relatively rich in weatherable minerals but not enough for groupe-level

faiblement remanié:

weak re-covering, showing only in such minor differences between A and B as other distribution curves of the sand-fractions.

humique: > 3% organic matter in A.

éluvié:

at the transition of A to B a subhorizon of many course elements occurs (implying very old soils developed from soils with an argillic-B, in which only the rests of a "biologic" stoneline are visible).

podzolisé (only in case of lessivé):
clear A2 with somewhat ashy appearance (∾ Tropical Upland Podzol-like).

avec apport aeoliën (only in case of remanié)

avec erosion et remaniëment (only in case of remanié)

avec horizon humifère très contrasté (only in case of humifère):
humic topsoil has an abrupt lower boundary (∾ Terra Preta of Amazon)

avec horizon humifère très profond (only in case of humifère):
(∾ Dark Horizon Latosol?)

b) Non-ferrallitic associated soils, in part plinthitic.

sols ferrugineux tropicaux (ou fersiallitiques):
appreciable amounts of weatherable minerals; less deep; argillic B.

- non ou peu lessivé
- lessivé: subdivision as:

  sans concrétions
  à concrétions
  à cuirasse
  à pseudogley de profondeur
  (∾ Various soils with plinthite, but not massively at surface).

sols mineraux bruts

- d'érosion squelettique: in-situ
- d'apport: colluvial

(both contain a subdivision on "cuirasse ferrugineux": massive plinthite at or near the surface).

c) Evaluation.

- the use of S as one of the criteria for main subdivision is interesting, since it varies in accordance with the CEC of the clay, but it cannot be used at the same level as V (which is useful), because S (or CEC) and V do not vary concordantly
- the approach is too genetic in the sense that it gives too few boundary criteria at the various levels of classification to be practical in the field
- geomorphologic aspects are brought into the soil profile classification system, while in fact it should be a part of the mapping unit classification, i.e. the legend of the soil map.

8.2 The newest Belgian system.

In use in Congo (Kinshasa) and surrounding countries, where soil studies have been carried out by INEAC. Described in first instance by Sys et al in 1961 and completed, still more along the lines of the 7th Approximation, by Tavernier and Sys in 1965.

As regards diagnostic horizons one distinguishes:

- B-textural : clay-illuviation; clay-skins present; more than one-fifth heavier in texture.
- B-structural : no clay-illuviation, but nevertheless (some) clay-skins; firmer consistence than A; blocky-prismatic structure.
- B-de consistence : no clay-illuviation; no clay-skins; firmer consistence; granular to subangular blocky.
- B-ferralitique (only after 1965, before that time most real ferrallitic soils were described as A-C profiles): no clay illuviation; no clay-skins; no firmer consistence; granular ("poudreux"), cf. table 1.

As regards mineralogic composition one distinguishes:

- fersiallitique : also 2:1 lattice silicate clay-minerals
- ferrisolique : a) > 25% clay-skins (= B structural), or b) fine silt/clay > 0.2 (when from sediments) resp. > 0.15 (when from igneous or metamorphic rock), or c) > 10% weatherable minerals.
- ferralsolique : unlike the above, see table 1.

a) Subdivision of the ferrallitic soils.

Ordre Kaolisols

Sous-ordres:

1. Hygro Kaolisols : well-drained, permanently moist (i.e. less than 2 dry months), forest coverage, V in the B < 25%, C/N ± 10, ferri- or ferralsolique (∾ Udox).
2. Hygro-Xero Kaolisols : well-drained, > 2 dry months, savannah, V < 40-50%, C/N 11-12, ferri- or ferralsolique (∾ Ustox).
3. Xero Kaolisols : well-drained, many dry months, xero-phytic savannah, V > 40-50%, relatively thick A1. Originally (1961) defined as fersiallitic and with B-structural; in 1965 redefined and put within the ferri- or ferralsolique (∾ Ldox).

4. Hydro Kaolisols : imperfactly to poorly drained, gray or with mottles (∿ Aquox pp; ∿ Ground-Water Laterite soils pp)

5. Humic Kaolisols (or Kaolisols Humifères, originally part of 1 and 2): well-drained, V in A $\lessdot$ 50%, > 20 kg organic C/m^2 in the upper 100 cm (∿ Humox).

Subdivisions in grandes groupes for each of the sous-ordres:

ferrisols (hydro-ferrisols, hygro-ferrisols etc.): ferrisolique; > 20% clay.

ferralsols : ferralsolique; > 20% clay

areno ferralsols : ferralsolique; < 20% clay (not occurring for sous-ordres 4 and 5)

dark-horizon kaolisols (only for 5): Humic Kaolisols with a dark sub-horizon in the B.

Subdivision on subgroupes for all grandes groupes:

typic : the normal ones

humic : A not weak (= umbric)

eutrophic : V in A > 50%

humic eutrophic : V in A > 50% and not weak (= mollic)

plinthic : soft plinthite within 100 cm depth

chromic (only in case of Hydro-): with (yellowish) chroma instead of gray

gleyic : with some gley mottling

weakly ferralsolic (for ferrisols only): intergrading to ferralsols

weakly ferrisolique (for ferralsols only): intergrading to ferrisols

.... : intergrading to Recent Tropical Soils

.... : intergrading to Brown Tropical Soils

podzolic : with a bleached A2.

b) Non-ferrallitic associated soils, in part plinthitic.

Ordre:

Kaolisols lessivés/Leached Kaolisols: with an A_2 and a B textural B_{2t} (∿ Ultisols).
Some subdivisions with soft or hard plinthite, if not massive at surface.

Ordre:

Sols Mineraux Bruts/Raw Mineral Soils: some subdivisions with massive hard plinthite crusts at or near the surface.

c) Evaluation

- rather practical in the field, because of detail and rather much attention to boundary criteria.
- the inclusion of hydromorphic soils is liable to create some confusion.
- not sufficient attention is given to the detailed chemical composition of the clay-fraction within the properly ferrallitic soils. This composition indicates a.o. distinct differences in inherent fertility and is relatively easy to apply for subdivision by using CEC-clay values (and S values).

8.3 The newest Brazilian system.

In use in Brazil (i.e. half of South America) and some surrounding countries, still in development. First approximation described by Bennema (1963) and Sombroek (1966, written 1963), second approximation by Lemos (1968, written 1966) and third approximation - summarized below - by Bennema (1966).

The system contains elements of both the ORSTOM, the INEAC and the American approach. It is not identical to the 7th Approximation Supplement (Soil Survey Staff 1967), but there is mutual influence and it is expected that it will be largely included in the final (?) U.S. Soil classification system. This is one of the reasons why no new names are given as yet (comparative old names are given below in brackets). Also, the detailed subdivision is not always systematically or fully defined. Widespread occurrence in the field and differences in agricultural qualities are considered to be more important than categorical perfection of the system.

It may be noted that the concept of latosolic-B of the Brazilian system (cf. table 1) is slightly narrower than that of the oxic horizon (which latter conceivably can contain an argillic horizon). Characteristic for the system is the use of the CEC-clay at a high level, and of the ratios $SiO_2:Al_2O_3:Fe_2O_3$ of the clay fraction (often expressed in % Fe_2O_3). This is possible because the determination of these oxides is included in the standard analysis of soil samples (sulphuric acid attack, for description cf. Lemos et al 1960, Sombroek 1966).

The description below is rather extensive, in view of the often difficult access to the original publications (and incorrect printing).

a) Subdivision of the ferrallitic soils.

1. Latosols with CEC-clay (corrected for the organic matter) < 6.5, V in B $< 50\%$.
"normal" latosols, developed often on old landscapes, within the subhumid or humid tropics; CEC and V related to landscape evolution and parent material, not intimately with the (minor!) differences in climate; variable amounts of gibbsite and iron oxides, which determines the subdivision next to the degree of development of the A.

1.1 with very strongly developed A:
C $> 1\%$ at 100 cm if clayey.

1.1.1 orthic:
not anthropogenic; possibly to be subdivided on:
- gradual decrease of organic matter with depth
- abnormal distribution of organic matter with depth (∾ Dark Horizon Latosol)

Further subdivision on iron-content and colour:
a) $Fe_2O_3 > 10\%$, reddish in B; on schistose rock (∾ Humic Dark Red Latosol)
b) $Fe_2O_3 < 10\%$, yellowish; on acid igneous rock (∾ Black-Yellow Latosols, Humic Red-Yellow Latosols)
c) $Fe_2O_3 \ll 10\%$, yellowish; on sediments of terraces

1.1.2 with anthropogenic A
subdivision possibly as above; in that case a typical example of c) would be (∾ Terra Preta do Indio of the Amazon)

1.2 with moderately or weakly developed A:

1.2.1 ortho subgroup
colours related to the amount of iron, therefore subdivision on the latter possible; further subdivision on occurrence of loose concretions and on texture; ultimate subdivision, in phases, on vegetation types (cf. Bennema 1966)

a) high iron-content:

$> 18\%$ if clayey, dusky red; mainly from basic rock

- non concretionary clayey (∾ most of the Latosol Roxo ≡ Terra Roxa Legitima)
- concretionary clayey

b) medium iron-content:

8-18% Fe_2O_3 if clayey, % Al_2O_3/% $Fe_2O_3 > 2$ (= $Al_2O_3/Fe_2O_3 < 3.14$) if relative sandy*, dark red; from clay-stones or iron-rich sandstones.

- non concretionary clayey (∾ most Dark Red Latosols)
- concretionary clayey
- non-concretionary sandy (∾ Dark Red Latosol, sandy phase)

c) low iron-content: $< 9\%$ Fe_2O_3 and $K_i < 1.8$ if clayey, $Al_2O_3/Fe_2O_3 > 3.14$ and $K_i < 1.5$ if sandy*, bright reddish or reddish yellow; from acid rocks, sandstones, and some relatively rich sediments.

- (non-concretionary) clayey (∾ Red-Yellow Latosols)
- (non-concretionary) sandy (∾ Red-Yellow Latosols, sandy phase)

d) very low iron-content: < ?% Fe_2O_3, $K_i > 1.5$, yellow; from iron-poor sediments (∾ Kaolinitic Yellow Latosols, Rego-Latosols). Subdivision on texture and concretion content possible.

1.2.2 (hygro-)subgroup

colours of B not related to iron content, being in general yellow due to intense humidity without any dry season (pér-humid) (∾ Pale Yellow Latosol) Subdivision?

1.2.3 (ferri-)subgroup

higher silt content or higher % weatherable minerals, often relatively shallow (∾ Ferrisols)

* in fact: medium textured (15% clay as textural limit for ferrallitic soils!)

2. Latosols with CEC-clay < 6.5, V $> 50\%$ * and weak A.
typical for semi-arid regions (north-eastern Brazil); possibly $K_i >$ 1.85 (∾ Idox)

3. Latosols with CEC-clay > 6.5, V $< 50\%$

probably zonal for areas less hot than the real tropical climate, and applying also to relatively young profiles within that climate. Relatively high exchangeable Al ($>$S, or $>$ 4 m.eq/100 g of clay), relatively hard in upper part of B when dry, rather compact consistence of B when clayey, pressure faces (= glazes) in B if clayey
Subdivision? (∾ Latosol profiles of the extreme South of Brazil; compare "b-de-consistence", "ferrallitique récent")

4. Latosols with CEC-clay > 6.5, V $> 50\%$.
probably zonal for the transition area subhumid - semi-arid, with deciduous tropical forest or poorer.
Subdivision on iron content and colour, since these are apparently closely related in the above climatic area.
a) High iron-content, dusky red; from basic igneous rock (∾ part of Latosol Roxo, transitional to Terra Roxa Estructurada)
b) Medium iron-content, dark red (∾ part of Dark Red Latosols)
c) Low iron-content, yellow-red.

5. Brown Latosols of high altitude
probably zonal for the pér-humid and at the same time relatively cold climates
Yellowish even when high in iron (compare 1.2), cracking of the soil upon drying (roadcuts), strongly to very strongly developed A, relatively high values for moisture aequivalent if not dried before analysis (compare characteristics of Hydrol-Humic Latosols and other transitions to Andosols).
Subdivision on K_i?, on exhangeable Al %; or on degree of development of the A? (∾ Solos Campos de Jordão, Lemos et al 1960)

(In the earlier approximations also an "Acrox" group was discerned, occurring e.g. around Brasilia: very low K_i (< 1.0), very low CEC-clay, raw feeling, natural clay present, $pH_{H_2O} < pH_{KCl}$).

* or at least increasing to $> 50\%$ in the lowest part of the profile

b) <u>Non-ferrallitic associated soils, in part plinthitic.</u>

<u>Non-hydromorphic soils with a textural-B (= argillic horizon), CEC-clay < 24 m.eq.</u>

with V in B < 35% (or Al^+ > S, or Al^+ > 50% (∿ Red Yellow Podzolic soils with low base status)

<u>very strongly developed A:</u> (∿ Rubrozem, <u>Bramao</u> 19..)

<u>weakly to strongly developed A:</u>

- ortho: A and B well differentiated, no plinthite (∿ part of Red-Yellow Podzolic soils)
- ......: A and B less differentiated (∿ intergrading to Latosols)
- ......: continuous soft plinthite at less than 125 cm (∿ intergrading to Ground-Water Laterite soil)

<u>with V in B > 35%</u> (∿ Red-Yellow Podzolic soils with high base status)

<u>very strongly developed A</u>

<u>weakly to strongly developed A</u>

- ortho: A and B well differentiated (∿ part of Red Yellow Podzolic soils, some of the Red-Yellow Mediterranean soils)
- ......: A and B less differentiated (∿ Terra Roxa Estructurada)
- ......: soft plinthite at less than 125 cm (intergrading to Ground-Water Laterite soil)

<u>weakly developed A and V > 90% in C</u>

semi-arid regions, ortho group and intergrades

<u>Non-hydromorphic soils with textural B, CEC > 24 m.eq., V in B > 35%, no soft plinthite.</u>

(∿ Red-Brown Mediterranean soils)

- with prominent A, V in A > 50%
  (dark red to dusky red, or yellowish)
- with prominent A, V < 50%
- with moderately developed A
- with weakly developed A

Non-hydromorphic soils with an incipient B (=cambic horizon)

(∾ main part of Acid Brown Forest soils, many Alluvial soils and Andosols).

Hydromorphic soils

a.o. Ground-Water Laterite soils.

Lithosols

a.o. soils with massive hard plinthite shallow or at surface.

c) Evaluation.

- because the system is still in development, lacks names and uses some criteria not commonly determined in other countries (SiO_2-Al_2O_3-Fe_2O_3 ratios), it cannot well be taken over by other countries as yet
- the clear separation of the well-drained ferrallitic soils from the imperfectly drained Ground-Water Laterite soils is sensible
- the clear definition of boundary criteria (though not yet fully elaborated) chosen in accordance with the mappable occurrence of the various soils in the field is a great advantage above systems where, for the benefit of existing genetic concepts, artificial and vague criteria are handled
- the use of CEC-clay in combination with V, organic matter content and where possible sesquioxide content (in practice: iron content), with additionally phases for the occurring vegetation type, is very useful. This because specifically these factors determine the agricultural value and behaviour of the soils: inherent fertility (CEC, V, organic matter, vegetation) aggregate stability (CEC-clay, sesquioxide content), effect of fertilizing (CEC, P-fixation by iron-oxides) etc.

8.4 The newest U.S.A.System.

In use in the U.S.A. since 1960, and in many other countries. Described most recently for the ferrallitic soils in the 7th Approximation-Supplement (Soil Survey Staff 1967) and commented upon e.g. by Sys (1969). In fact for the ferrallitic soils only about a fifth approximation is concerned, a.o. because they occur only occasionally and in a-typical forms inside U.S.A. territories. The subdivisions for this group is therefore liable to change considerably, in consultation with South-American (Brazilian) and African (INEAC, ORSTOM) approaches.

The description below is very short, assuming that every soil student has a copy of the 7th Approximation at hand.

a) <u>Subdivision of the ferrallitic soils</u>.

Order :	<u>Oxisols</u>	: characterized by an oxic horizon (cf. table 1), <u>or</u> by plinthite forming a continuous phase within 30 cm of the surface.
Suborders:	<u>Aquox</u>	: hydromorphic and/or plinthitic. plinthite as above, or saturated with water at some time of the year (if not artificially drained) and an oxic horizon with histic epipedon or gley phenomena.
	Groups:	
	<u>gibbsiaquox</u>	: cemented sheet with $\geq$ 30% gibbsite or nodules, within 100 cm depth.
	<u>ochraquox</u>	: ochric epipedon
	<u>umbraquox</u>	: umbric or histic
	<u>plinthaquox</u>	: continuous plinthite within 125 cm (special subgroup when within 30 cm: lithic?)
		Note: this includes both the Ground-Water Laterite soils (with plinthite-in-formation), and many of the soils with fossil plinthite (even those that have a massive crust!).
	<u>Humox</u>	: humid areas, higher altitudes Less than 60 days dry, $\geq$ 20 kg C per m^2 within 100 cm, mean annual temperature $\nless$ 22° C, V > 35% in B, not hydromorphic or plinthitic.
	<u>acrohumox</u>	: CEC of one subhorizon < 1 m.eq./100 g of clay
	<u>gibbsihumox</u>	: sheet of gibbsite
	<u>haplohumox</u>	: CEC > 1 meq.
	<u>sombrihumox</u>	: with dark horizon in B
	<u>Orthox</u>	: humid areas, low altitudes Less than 60 days dry, mean annual temperature > 22% <u>or</u> < 20 kg C etc., not hydromorphic or plinthitic
	<u>acrorthox</u>	: CEC < 1 meq/100 g of clay
	<u>eutrorthox</u>	: V > 35% till at least 125 cm depth
	<u>gibbsiorthox</u>	: gibbsite sheet
	<u>haplorthox</u>	: ochric epipedon with < 1% C in some part above 75 cm.
	<u>umbriorthox</u>	: umbric epipedon, or ochric with > 1% C everywhere above 75 cm.

Ustox	:	subhumid areas, low altitudes More than 60 days dry, mean annual temp. $\geq$ 15°C, epipedon with values $<$ 4.
acrustox	:	CEC $<$ 1 meq.
eutrustox	:	mollic or umbric, V $>$ 50% in B when clayey, 35% in B when "loamy"
haplustox	:	unlike the above
Torrox	:	dry areas (formerly Idox) Usually dry, ochric epipedon

Subgroups for several of the groups, especially the haplic ones, are:

typic	:	the normal ones
aquic	:	mottles with chroma $\leq$ 2, accompanied by (dark) red ones, within 125 cm.
plinthic	:	non-indurated plinthite within 125 cm
psammentic	:	lighter than sandy clay loam in the oxic horizon
ruptic-lithic	:	shallow, i.e. oxic horizon extending till less than 125 cm, and lithic contact in maximally half the pedon
tropeptic	:	shallow and/or with "structure" in the oxic horizon, i.e. with some aspects pointing to argillic horizon ($\sim$ Ferrisols)

b) Non-ferrallitic associated soils, in part plinthitic.

Ultisols	:	argillic horizon, V $<$ 35%, mean annual temp. $>$ 8°C, no spodic or oxic (unless underlying the argillic) horizon, no continuous plinthite within 30 cm. The Aquults, Udults and Ustults have plinthic groups and/or subgroups.
Alfisols	:	argillic horizon, V $>$ 35% or mean annual temp. $<$ 8°C, usually moist, no spodic or oxic (unless underlying the argillic) horizon, no continuous plinthite within 30 cm. The Aqualfs, Udalfs, Ustalfs and Xeralfs have plinthic subgroups, the Ustalfs also a plinthic group.
Inceptisols	:	cambic horizon, etc. The Aquepts have a plinthic group; the Tropepts and Andepts have oxic subgroups ($\sim$ Latosol-like Acid Brown Forest soils and Andosols).
Entisols	:	no diagnostic horizons. A subgroup occurs, Oxic Quartzipsamments, having: below the A_p, or 25 cm, loamy sand or coarser till at least 100 cm, not hydromorphic, sand fraction $<$ 5% weatherable minerals ($\sim$ Red and Yellow Acid Sands, Latosolic Sands).

c) Evaluation.

- very clear as regards boundary criteria, but these are as yet not adequate for the main Oxisol areas
- subdivision on CEC-clay and detailed composition of the clay fraction is rudimentary
- instead of base-saturation - an easily measurable soil characteristic - (soil) climatic data are used, implying much guess work. Climatic conditions should form a separate factor, next to the soil, at land classification
- hydromorphic soils are included with the oxisols, which is genetically incorrect; plinthite moreover is not well defined nor subdivided. The Aquox suborder therefore is very messy
- unsympathetic nomenclature, for both soil men and non-soil men alike.

8.5 The FAO/UNESCO approach.

For the Soil Map of the World Project, FAO and UNESCO have procured to develop a legend that combines the advantages of the genetic approach to soil classification (Russian, French) with those of the morphometric approach (U.S.A., 7th approximation) and the many field data as collected a.o. in Congo and Brazil - cf. Dudal 1968, 1969 and table 3.

a) Subdivision of the ferrallitic soils.

Ferralsols	: characterized by an oxic B-horizon (= oxic horizon); for details, also as regards Munsell criteria of colours mentioned below, cf. original publications and table 1.
Orthic ferralsols	: yellow to yellowish red B, SiO_2/Fe_2O_3 ratio < 13, $V < 35\%$ in some subhorizon of B, no plinthite within 125 cm (∾ Red-Yellow Latosols)
Xanthic ferralsols	: yellow to pale yellow B, $SiO_2/Fe_2O_3 \geqslant 13$ (i.e. high kaolinite content, $< 9\%$ iron oxides), $V < 35\%$, no plinthite (∾ Kaolinite Latosols)
Rhodic ferralsols	: red to dusky red, V variable but often $> 35\%$, no plinthite (∾ Latosols Roxo=Terra Roxa Legitima)
Humic ferralsols	: a weighted average of $> 0.78\%$ C till at least 100 cm depth (∾ Humic Latosols)
Acric ferralsols	: with very low CEC of clay fraction (∾ Acrox)

Plinthic ferralsols : oxic B and/or plinthic horizon (i.e. continuous soft plinthite) within 125 cm depth; can be gleyic as well (∽ Plintaquox, many Ground-Water Laterite soils)

Gleyic ferralsols : with gley phenomena or periodically water-saturated, no plinthite.

b) Non-ferrallitic associated soils, in part plinthitic.

Nitosols : pallid (= ochric) or sombric (= umbric) A, diffuse boundary to argilluvic B (= argillic horizon), CEC-clay of B (not-corrected for organic matter) < 24 m.eq., often red to dusky red. A new order between the old Latosols and Red-Yellow Podzolic soils, very useful! Encompassing Ferrisols, Sols ferrallitiques appauvri/rajeuni/pénévolué, Terra Roxa Estructurada, Reddish Brown Lateritic soils etc.

- eutric : V in lower B > 35%
- dystric : V in lower B < 35%
- humic : 0.78% C till 100 cm, V < 35%
- plinthic :

Acrisols : pallid or sombric A, clear boundary to argilluvic B with V < 35% in lower part, CEC of B variable (?)

- orthic : yellow or yellowish red B (∽ Red Yellow Podzolic soil of low base status)
- humic : sombric A, V < 35% in all of B, > 0.78% C average till 100 cm (∽ Rubrozems)
- ferric : yellowish brown to reddish brown B
- plinthic : (A may be shallowly histic), plinthic horizon with 125 cm, can be gleyic as well (∽ Ground-Water Laterite soil pp.)
- gleyic : (A may be shallowly histic), gleyic but not plinthic or planic (i.e. with a clay pan-B)

Luvisols : pallid or sombric A, argilluvic B and V > 35% in lower part of B.

- orthic : CEC in B > 24 m.eq., A not hard when dry, brown B (∽ Gray-Brown Podzolic soils)
- chromic : CEC in B > 24 m.eq., A hard when dry, strong brown to red B (∽ Terra Rossa, Red-Yellow Mediterranean soils)
- ferric : CEC in B < 24 m.eq., yellowish brown to reddish brown B (∽ Red-Yellow Podzolic soil of high base status, Sols Ferrugineux Tropicaux lessivés)

<u>plinthic</u> : (A may be shallowly histic), CEC in B variable (?), plinthic horizon within 125 cm, can be gleyic as well (∽ some Ground-Water Laterite soils)

<u>gleyic</u> : (A may be shallowly histic), CEC variable (?), gleyic horizon, which is not planic or plinthic.

<u>Arenosols</u> : ⩽ 15% clay, oxic character of B if it were heavier (∽ Acid Red and Yellow Sands, Latosolic Sands)

<u>Lithosols</u>

<u>eutric</u> :

<u>dystric</u> : includes soils with massive hard plinthite shallow or at surface

<u>carbonatic</u> :

c) <u>Evaluation</u>.

- still too general to be applied at most surveys, unless broad reconnaissance
- inclusion of plinthic and gleyic in the ferralsols is not consistent with the ferrallitization process, however slightly less messy than in the 7th Approximation
- the introduction of Nitosols satifies a practical demand
- the approach in general combines the advantages of most "schools" of classification and has taken account of extensive field data from South America, Africa, Asia and Australia (many correlation trips and regional comparative conferences), it is orientated to practical significance of soil profile differences and it provides a correlation (<u>Dudal</u> 1968) with the existing names.

A graphic comparison of the place of the ferrallitic soils and associated ones in the various main classification systems, on the basis of the U.S.A. subdivision, is given in table 2 (after lecture notes <u>Bennema</u>).

Chapter 9. USES OF THE FERRALLITIC AND/OR PLINTHITIC SOILS.

9.1 Aspects of Land classification.

General information on the agricultural possibilities and limitations of ferrallitic and/or plinthitic soils can be found with Bernd Andreae (1965), general, Laudelout (1962) and Nye and Greenland (1960) as regards shifting cultivation and savannah management; Jacob and Uexhüll 1963 as regards fertilizing; and several regional monographs like Sombroek (1966, last chapter).

In very general terms ferrallitic soils can be compared, as regards their agricultural use, with the poor sandy soils of temperate regions, the soils with presentday soft plinthite with its Ground-Water Podzols and the soils with fossil massive hard plinthite with its Lithosols from very acid rocks.

The below discussion follows the concept of existence of qualities, which act more or less independently and are each of them the result of properties of varying degree of complexity. Qualities should always be seen in relation to the land utilization system(s) envisaged, which also determines the feasibility of the improvement possibilities for each of the relevant qualities (c.q. limitations); cf. Beek, Bennema and Camargo (1964), various publications of Vink, etc.

1. Physical soil fertility: net moisture storage capacity in the rootable zone.
   a) in non-concretionary ferrallitic soils: the field capacity/moisture aequivalent is rather high (porous and often clayey soils), but there are indications that the net moisture storage capacity per volume unit is still rather low, especially in those soils relatively poor in sesquixodes (cf. Sombroek 1966, Wessel 1971). Still, the total storage is large because of the extreme thickness of the rootable zone (several metres). Only exceptionally there is a supply from ground-water. Few data on moisture storage have been collected, a.o. because atmosferic moisture is often more than sufficient. However, when some dry months prevail a deep apparent drying-out of profiles has been observed, also under forest.

b) in soils with presentday plinthite: the storage capacity is very low, both because of the sandiness of the A, and the denseness and hydromorphy of the B where root penetration is very restricted.

c) in soils with fossil plinthite: capacity varies from fair to poor, depending on the % of stony material (> 25% is considered to be a hamper, especially if there are dry months) and the degree of massiviness of the plinthite, which restricts rooting (when fully massive the occurrence above 150 cm is already considered a hamper).

2. Physical soil toxicity: presence or risk of waterlogging in the rootable zone, i.e. absence of oxigen or excess of CO_2.

a) in non-concretionary ferrallitic soils: not a problem

b) in soils with presentday plinthite: waterlogging is a major limitation because of i) interference by dense layers with deficient percolation rate, ii) seasonally high ground-water table, iii) usually low hydraulic conductivity of the substratum. Improvement hardly possible or feasible.

c) in soils with fossil plinthite: degree of limitation depends on depth and massiveness of the plinthite.

3. Chemical soil fertility: availability of plant nutrients.

a) in non-concretionary ferrallitic soils: medium to low total CEC, both potential and actual, and often low or very low base saturation. Nutrients are in fact largely stored in the toplayer (subdivision on the pronouncedness of the A!) and in the vegetative cover (subdivision on vegetation phases!). But because of the deep rooting also the few nutrients stored in subsoil and substratum are important (subdivision on CEC-clay and on base saturation of B!)

- N deficiency is normal, except directly after clearing (due to rapid mineralization of fresh organic matter and humus); a limit is difficult to give, a.o. because the element occurs often in volatile or unstable forms.
- P deficiency is general, a.o. because of fixation by crystalline (at the edges) -, subcrystalline -, and gel-forms of Fe and especially Al (the latter also at exchangeable form at very low pH). Fixation normally larger and stronger when higher sesquioxide content (subdivision on sesquioxide content of clay fraction!), smaller when

high organic matter content (subdivision on pronouncedness of A!).
Very approximate limit: 1 mg P_2O_5 - Truog/100 g soil.

- K deficiency not so frequent and critically as P and N. Very approximate limit: 0.2 meq per 100 gr. soil.
- Meso nutrients: sulphur deficiency may occur.
- Micro nutrients: little studied; possibly common, especially for cattle; cobalt and manganese (the latter when relatively low % sesquioxides); for crops: zinc and boron.

b) in soils with presentday plinthite: fertility extremely low because of poor vegetative cover, thin A, and especially because of the shallow rooting.

c) in soils with fossil plinthite: variable, depending on percentage massiviness, and depth. Often highor P fixation (?); sometimes slightly higher CEC or content of micro-nutrients, because of some enclosed weatherable minerals in the decomposing hard plinthite.

4. Chemical soil toxicity: salinity, salinization hazard etc.

a) in non-concretionary ferrallitic soils: no problem of salinization, alkalinization, sulphatation. Manganese may however be toxic in some iron-rich ferrallitic soils from basic rock. Exchangeable Al is somewhat toxic due to very low pH. Absolute amounts are however small (Amazon: 20% of CEC, 1-2 meq/100 g), and toxicity is easily suppressed at pH-highering by liming; small amounts are sufficient because of low pH-dependent acidity.

b) in soils with presentday plinthite: Exchangeable Al % may be much higher, especially if K_i is still relatively high, due to hydromorphism (Amazon: 75% of CEC, 5 meq/100 g).
Salinity etc.: no problem.

c) in soils with fossil plinthite: see a.

5. Biological soil fertility: N-fixation etc.

a) in non-concretionary ferrallitic soils: N-fixation by free-living bacteria (Clostridium, Beyerinckia; no Azotobacter), but relative importance unknown. Fixation by symbiotic bacteria seems large under natural vegetation (many Leguminosae trees: Amazon 15-30%), but the root nodulation is often small or absent (due to P deficiency?).

Worms are absent, homogenization and porosity promotion is taken over by termites, ants, rodents etc. Termites can increase fertility (Sys 1955).

Data on mycorrhiza, fungi (for mineralization) etc. are very few.

b) in soils with presentday plinthite: very small activity of soil flora and fauna.

c) in soils with fossil plinthite: variable, depending on %, degree of massiviness, and depth of the plinthite.

6. Biological soil toxicity: presence or risk of soil-borne pests.

a) in non-concretionary ferrallitic soils: abundance of leaf-cutting ants (Atta spp.) is often very detrimental, especially for annual crops. Few data on occurrence of Nematodes.

b) in soils with presentday plinthite: few Atta spp.

c) in soils with fossil plinthite: variable.

7. Surface receptivity as seedbed: "tilth".

a) in non-concretionary ferrallitic soils: normally good seedbed because of good structure and high structure stability. On old savannah soils with low content of organic matter and splashy rainfall, some sealing and crushing is however possible, as well as the formation of hard nodules (Si?). Mulching however easy.

b) in soils with presentday plinthite: tilth poorer.

c) in soils with fossil plinthite: tilth good, except when massive plinthite at or near surface.

8. Surface treadability (for cattle etc.)

a) in non-concretionary ferrallitic soils: no problem.

b) in soils with presentday plinthite: trampling at seasonal high water is common

c) in soils with fossil plinthite: normally no problem.

9. Surface limitations for the use of implements: "arability"

a) in non-concretionary ferrallitic soils: no problems because not stony, good structure, high structure stability, relatively low stickiness and plasticity, slopes moreover gradual if any.

b) in soils with presentday plinthite: little or no problem

c) in soils with fossil plinthite: if plinthite at or near surface there is a moderate to absolute limitation, depending on the massiviness. Often also rather short and irregular slopes. Fine and loose concretionary constitutes little or no limitation at shifting cultivation.

10. Spatial regularity of soil and terrain pattern (determining the size and shape of fields with uniform management).

a) in non-concretionary ferrallitic soils: no problem, because profile characteristics are uniform over large distances, as is the macro-relief. There is no meso-relief, but micro-relief can be some limitation at mechanized farming because of abundance of termite mounds. Levelling however easy.

b) in soils with presentday plinthite: some limitation because soil profile characteristics are rather variable (e.g. depth and sandiness of A_2); macro and meso-relief are no limitation, micro-relief sometimes, characteristics of the substratum may vary considerable but since drainage is not worthwhile - even very dangerous - this is not of practical importance.

c) in soils with fossil plinthite: often considerable limitation because rather quick lateral differences in depth, thickness and massiviness of the plinthite layer(s) are common, often associated with irregular macro-relief (e.g. rests of table-lands).

11. Liability to erosion

a) in non-concretionary ferrallitic soils: both for water- and for wind erosion very low because of the structure stability (except for sandy profiles and when very poor in iron), high infiltration rate, gentle slopes if any, quick recoverage of vegetation. Fertility erosion on burned fields can however be considerable.

b) in soils with presentday plinthite: under actual conditions low because of flatness of the terrains and the high ground-water table. Potentially very high after artificial change in ground-water table, in view of very low stability of the A and the poor vegetative cover.

c) in soils with fossil plinthite: very low, like under a), or even less (larger, protecting elements).

12. Accessability

An accidental problem only.

13. Water storage capacity on terrain

In general poor (gentle slopes and/or high infiltration rate and hydraulic conductivity), but usually not of importance in view of the climate.

14. Fertility renewal by overflow or overblow

Not occurring, except for some areas with fossil plinthite (dust overblow from deserts).

15. Crop damaging by overflow and overblow

Not occurring, except for some areas with fossil plinthite (where moving coversands).

16. Crop-value of vegetation

a) in non-concretionary ferrallitic soils under forest: for timber supply usually too mixed; possibly useful for pulp and paper industry. Locally logging of some very valuable species, though scattered.

b) in non-concretionary ferrallitic soils under (anthropogenic) savannah and soils with presentday plinthite under (edaphic) savannah: very small value of woody vegetation (some fuel supply), moderate value of grassy vegetation (natural grasses are of low palatability).

c) in soils with fossil plinthite: variable, sometimes even better quality of a forest coverage than at a).

17. Crop- and cattle protection by vegetation

a) in non-concretionary ferrallitic soils under forest: very effective protection against sunburn and dehydration; can be utilized by selective clearing. Suppression of weeds (one of the reasons of fallow at shifting cultivation!)

under savannah: usually enough woody vegetation for cattle protection

b) in soils with presentday plinthite: woody vegetation may be too sparse for cattle protection.

c) in soils with fossil plinthite: variable.

18. Crop-hindrance by vegetation: "land development costs"
   a) in non-concretionary ferrallitic soils under forest: very strong light capture, very strong competition for water and nutrients: Clearing necessary but very cumbersome (a major obstack at land development).
   b) in soils with presentday plinthite: limitation small
   c) in soils with fossil plinthite: variable

19. Liability to atmospheric calamities: Locally hazard of tornados etc.

20. Atmospheric moisture supply:
Favourable to very favourable. High and often regular supply over the year, except in some areas with fossil plinthite.

21. Atmospheric energy of photo synthesis:
High because of year-round photo synthesis, no frost etc., but day-length and sunshine somewhat restricting. The possibility of tropical areas with ferrallitic and/or plinthitic soils to produce various annual crops per year, or to ensure rapid growth of perennial crops c.q. timber in fact offsets, at global scale of land evaluation, many of the disadvantages of the soils themselves.

9.2 General management practices for the ferrallitic soils.

Management practices have to be based on the prevailing natural conditions: Favourable climatic conditions but nearly closed nutrient cycle on and at the surface; recycling after degeneration by deep rooting plants (pumping mechanism).

Maintenance or increase of the organic matter content is paramount.

The organic matter is the main bearer of plant nutrients (S), determines the nutrient storage capacity (CEC) to large extent, is the main source of nitrogen, makes the phosphorus more easily available, increases the net moisture storage, maintains the homogeneity and porosity by activation of soil biology.

This can be done by green manuring, largely "biologic-dynamic", but often some additional chemical fertilizing is necessary to reactivate the pumping mechanism.

Farm-yard manures and compost are however also very useful, a.o. because they usually contain macro and micro nutrients in proper combinations.

Pure application of chemical fertilizers easily upsets the delicate nutrient balance (one of the reasons why liming to above pH 5.5 often has no or a negative result), the more so because only little fertility research per type of ferrallitic soil has been carried out. As a rule fertilizers should be of little soluble types, to prevent their leaching.

Among the adapted crop production systems the following may be mentioned.
- Shifting cultivation. In the absence of chemical fertilizers compounds for weed- and pest control, and capital-intensive farm implements, this system is in fact a rather logical use of the land. Care should however be taken that the fallow period is long enough, or the fallow growth is stimulated (e.g. by the "corridor-system" of Congo).
- Perennial tree crops (rubber, oil palm, cocoa), in combination with spade loving shrub-crops and/or annual crops, are largely comparable to the natural vegetative cover as regards maintenance of the quality of the soils - provided that fertilizers are applied to recompense nutrient-loss by crop-removal.
- High-value crops (specials), like black pepper can also be an adapted use of the land. The high cash-value namely allows to give intensive care to maintenance or improvement of soil conditions by green manuring, mulching etc.
- Mixed farming is feasible too. Parts with selected new types of grasses or palatable legumes can provide farm-yard manure for relatively small parts with annual crops, much the same as has been the practice for sandy soils in Western Europe.
- Adapted silviculture may be most feasible proposition, in the long run, for an efficient use of the ferrallitic soils. The quick growth of some selected tree species and varieties, including of Eucalyptus, would allow a large and constant supply of timber and pulp for the industrial countries, while it certainly prevents any degeneration of the land.

9.3 Non-agricultural uses of ferrallitic and plinthitic soil materials.

Ferrallitic soil material, because of its structure stability and very low swelling and shrinking, is useful for road bodies.

Soft plinthite can be used for bricks (India, Cambodja etc.) but also for road-base.

Hard plinthite is often used for road-coverage if not too coarse. Its use however leads to "wash-board" patterns at non-tarred road-surfaces, which is very inconvenient at driving. The material can also be used as gravel in cement, and if the elements are of the proper size also for bricks (houses, walls, field boundaries etc.). Only sometimes the hard plinthite is used for mining of iron-ore or manganese-ore. The aluminous plinthites are however very valuable as a source of bauxite. Much useful information on the properties of hard plinthites for civil engineering purposes is given by Persons (1970) - though his account of the genesis of the materials is largely wrong.

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COMPARISON OF SOIL CLASSIFICATION SYSTEMS (tentative)

Order	Group	AMERICAN USA till 1960 (+ = Canada, ++ = South America)	AMERICAN 7th approximation USA after 1960	FAO Soil Ma of the World	FRENCH (+ = Congolese)	RUSSIAN
MATURE, ZONAL SOILS Pedocal weathering	Soils of the cold zone	Tundra soils	Cry-aquents/udents, Cry-aquepts/udepts	tundric Cambisols tundric Rhegosols tundric Gleysols		Tundra soils
	Light coloured soils of the arid regions	Desert soils Reddish Desert soils	(Typic Camb/Dur-orthids (Typic Camb/Dur-argids (Typic Calciorthids	orthic Yermosols luvic Yermosols calcic Yermosols gypsic Yermosols	Sols bruts xeriques inorganisés Sols peu évolués xériques Sols gypseux pp	Desert soils
		Sierozems, Brown soils, Reddish Brown soils	(Mollic Camb/Dur-orthids (Mollic Hapl/Dur-argids (Mollic Calciorthids	orthic Xerosols luvic Xerosols calcic Xerosols gypsic Xerosols	Sols bruns isohumiques, Sols bruns subarides, Sierozems Sols gypseux pp	Semi-desert soils, Sierozems
	Dark coloured soils of semi-arid, sub-humid and humid grasslands of temperate regions	Chestnut soils, (Rego orthic(Dark) Brown soils + pp Reddish Chestnut soils (Eluviated(Dark) Brown soils + (Calcareous(Dark)Brown soils + pp	Haplustolls Argiustolls Calciustolls	orthic Kastanozems luvic Kastanozems calcic Kastanozems	Sols châtains modeaux Sols châtains à B-textural Sols châtains encroûtés	Chestnut soils of the dry steppes
		Chernozems (Rego Orthic Black soils + pp (Eluviated Black soils + (Calcareous Black soils + pp	Haploborolls Argiborolls Calciborolls	orthic Chernozems luvic Chernozems calcic Chernozems	Chernozems modeaux Chernozems à B-textural	typic Chernozems podzolised Chernozems PP
		Degraded Chernozems, (Rego Dark Grey soils + pp Brunizems/Prairie soils (Orthic Dark Grey soils + pp Reddish Prairie soils (	Hapludolls Argiudolls	orthic Phaeozems luvic Phaeozems calcaric Phaeozems	Brunizems modeaux Brunizems à B-textural	degraded Chernozems pp? Gray Forest soils pp, podzol. Chernozems pp
	Light coloured podzolised soils of forested temperate regions	Podzols, Brown Podzolic soils	(Orthods pp. (Ferrods (Humods pp. (Plac-orthods/humods	orthic Podzols ferric Podzols humic Podzols placic Podzols	Podzols humo-ferrugineux Podzols ferrugineux Podzols humiques pp.	humic-ferrous illuvial Podzols iron-illuvial Podzols humus-illuvial Podzols
		Gray Wooded + / Podzolic soils	(Eutroboralfs ? (Glossudalfs (Glossoboralfs	eutric Glossisols dystric Glossisols humic Glossisols	Sols lessivés glossiques, Sols podzoliques pp	derno Podzolic soils, ortho Podzolic soils ?
		Gray-Brown Podzolic soils Non-calcic(Shantung) Brown soils (Red-Yellow Mediterranean soils (Red-Yellow Podzolic soils, high b.s. ++	Rhodo/Haplo-xeralfs pp. Plinth-ust/oxer-alfs	orthic Luvisols chromic Luvisols ferric Luvisols albic Luvisols plinthic Luvisols pp.	Sols lessivés modeaux Sols fersiallitiques lessives, Sols rouges mediterr. lessivés Sols ferrugineux tropicaux lessivés, Xero-ferrisols +	podzolised Brown Forest soils Cinnamonic soils pp
Pedalfer weathering	Red and Yellow soils of the forest or savannah-covered tropical and sub-tropical regions	Red-Yellow Podzolic soils (Red-Yellow Podzolic soils, low b.s. ++ (Rubrozems ++	Hapl-ud/us/oxer-ults Humults Plint-ud/ust-ults	orthic Acrisols humic Acrisols ferric Acrisols albic Acrisols plinthic Acrisols	Sols fersiallitiques Sols ferrugineux tropicaux) Hygro(-xero)ferrisols + pp	Krasnozems pp ?
		Reddish Brown Lateritic soils pp (Terra Roxa estruct, high b.s. ++ (Terra Roxa estruct, low b.s.	Paleud/Rhodust-alfs pp. Rhod-ud/ust-ults, Palexerults pp.	eutric Nitosols dystric Nitosols humic Nitosols	Hygro(-xero) ferrisols + pp	Krasnozems pp.
		Red-Yellow Latosols pp. Pale-Yellow Latosols Dark-Red Latosols pp, Terra Roxa ++, Latosol Roxo ++ Brown Latosols pp, Humic Latosols Concretionary Latosols	Orth/ Torr/ Ust-ox pp. Orthox pp. Acrox Orth/Torr/Ust-ox pp Humox pp Plint-orr/ust-ox	orthic Ferralsols xanthic Ferralsols acric Ferralsols rhodic Ferralsols humic Ferralsols plinthic Ferralsols pp.	Sols ferralitiques moy. à fort. desat. pp.) Hygro(-xero) Sols ferralitiques jaunes fort. desat. pp.)) ferral/ferri sols + pp. Sols ferralitiques faibl. à moy. desat. pp) Sols ferralitiques fort. desat. humiques, Ferrisols humifières +	Ferralitic soils PP.
		Dry Sands pp, Red and Yellow(Acid) Sands ++ (White Sand) Regosols, Giant Podzol ++	(Oxic Quarzipsamments	ferralic Arenosols laminic Arenosols cambic Arenosols albic Arenosols	Areno ferrals +	
	Dark clay soils of trop & sub tropical regions	Black Cotton soils, Grumosols, Margalitic soils	(Pell-ud/ust/oxer-erts (Chrom-ud/ust/oxer-erts, Torrerts	pellic Vertisols chromic Vertisols	Vertisols a drenage externe nul) Argiles noires Vertisols a drenage externe possible) tropicales	Black and Grey Tropical soils, Regurs, Smolnitzas
MATURE, INTRAZONAL SOILS	Halomorphic soils	Solonchaks	(Salorthids (salorthidic Calci-Hapl-ustolls (Halaqu-ents/epts	orthic Solonchak mollic Solonchak takyric Solonchak gleyic Solonchak	Sols salins pp. Sols bruts xériques organisés d'apport Sols à gley salés pp	Solonchaks Takyrs saline Meadow - Coastal Marsh soils pp
		Solonetz, Solodized Solonetz	(Natr-ust/ixer-alfs, Natrargids (Natr-alb/ibor/ust/ixer-olls (Natraqualfs	orthic Solonetz mollic Solonetz gleyic Solonetz	Sols sodiques à horizon B, Solonetz solodizés	Solonetz meadow Solonetz
	Hydromorphic soils	Gleyed Dark Grey soils + pp Ground Water Podzols (Gray Hydromorphic soils)	Argiaquolls pp Aquods Aqualfs pp Aquults pp Aquox pp	(gleyic Chernozems (gleyic Phaeozems gleyic Podzols (gleyic Glossisols (gleyic Luvisols (gleyic Acrisols (gleyic Nitosols gleyic Ferralsols	Podzols à gley, Podzol de nappe Sols à gley lessives pp, Sols lessives hydromorphiques pp	Podzolic swampy humus-illuvial soils Podzolic Gley soils pp
		Ground Water Laterite soils pp	(Plinthaqualfs (Plinthaquults (Plinthaquox	plinthic Luvisols pp plinthic Acrisols plinthic Ferralsols pp	Hygro(-xero)ferralsols lessives à plinthite + pp	
		(Claypan) Planosols, (Brunizem) Planosols Solods	(abruptic Aqu/Ud//Ust-alfs pp (abruptic Aqu/Ud//Ust -ults pp. (abruptic Argi-alb/aqu-olls (abruptic Aqu/Ud//Ust-ults pp. Argialbolls pp.	eutric Planosols dystric Planosols mollic Planosols humic Planosols solodic Planosols	Solods	
		Low-Humic Gley soils, Alpine Meadow soils pp, Rego Gleysols + pp Humic Gley soils, Half-Bog soil, Wiesenboden,, Rego Humic Gley soils + , Carbonatic (humic) Gleysols + pp. Acid sulphate soils, Catclays	Aquents pp. Aquepts pp. (Haplaquolls (Humaquepts Calciaquolls pp.	(eutric Gleysols (dystric Gleysols mollic Gleysols humic Gleysols calcic Gleysols thionic Gleysols	Sols à gley profonds peu humifères pp. Sols humiques à gley pp, à an/hydromoor pp. Sols hydromorphiques à redistr. du calcaire/gypse Terres àlunées	Meadow soils, Swampy soils pp. Mangrove soils pp
		Bog soils, Organic soils ++	Histosols	(eutric Histosols (dystric Histosols	Sols hydromorphiques organiques	Bog soils
IMMATURE, AZONAL SOILS	Young soils	(Orthic) + Brown Forest soils Acid Brown Forest/Wooded + soils pp.	Eutr/Ust/Xer-ochrepts pp. Haplumbrepts Dystrochrepts Eutr/Ust/Xer-ochrepts Tropepts pp.	calcaric Cambisols eutric Cambisols dystric Cambisols humic Cambisols vertic Cambisols	Sols bruns calciques/calcaires pp. Sols bruns modeaux Sols bruns acides Sols bruns eutrophes tropicaux pp	
		Andosols ++, Trumao soils ++, Latosolic Brown Forest soils +, Hydrol Humic Latosols, Acid Brown Forest/Wooded + soils pp.	(Eutr/Dystr-andepts pp. (Andolls ? (Dystr-andepts pp (Vitrandepts (Hydrandepts pp.	ochric Andosols mollic Andosols humic Andosols vitric Andosols gleyic Andosols	Andosols, Sols bruns tropicaux sur materiel volcanique + pp	Andosols
		Rendzinas, Calcareous Rego Black soils + pp.	Rendolls	Rendzines	Rendzines pp.	Derno Carbonate soils
			lithic Haplumbrepts	Rankers	Rankers	
		Lithosols	(lithic subgroups	(eutric Lithosols (dystric Lithosols (calcaric Lithosols	Lithosols	Shallow Mountain soils
		Regosols, Dry Sands pp, Orthic Regosols + pp	(Orth/Psamm-ents pp	(eutric Rhegosols (dystric Rhegosols (calcaric Rhegosols	Sols mineraux bruts/ peu evolués, regosoliques ou d'apport éolien/volcanique, friable	Regosols
		Alluvial soils pp, Regosols pp, Unripe soils (potential Acid Sulphate soils)	(Fluvents	(eutric Fluvisols (dystric Fluvisols (calcaric Fluvisols (gleyic Fluvisols thionic Fluvisols	Sols mineraux bruts ou peu évolués, d'apport alluvial/colluvial Sols tropicaux récents + pp.	Alluvial soils pp. Mangrove soils pp.

pp = pro parte

b.s.= base saturation

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42x56