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A review: Genesis and classification of tropical residual soils for engineers

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ABSTRACT: The paper describes simply the genesis of tropical residual soils and classification, based on a pedological subdivision by Duchaufour (1982), into three principal soil phases, fersiallitic, ferruginous and ferrallitic, which represent a continuous increase in tropical soil development from a Mediterranean to a hot, wet, tropical climate. His system has been broadly followed and developed for engineering classification by Anon (1990): the description of this classification forms the core of the paper.

"Standard" red tropical residual soils typically belong to the ferruginous and ferrallitic phases. Modification of significance to the engineering characteristics is made where there is a seasonal dry climate. The soils then develop a hardened (lateritic) zone or crust. Dark young soils (typically the fersiallitic stage) can be further subdivided to distinguish those with swell/shrink characteristics and other properties of significance to engineering, depending on the clay mineral species formed.

1. INTRODUCTION

Engineering in tropical residual soils is often straightforward, and may be based successfully on experience (Brand 1982, 1985). However, as the principles of the engineering science of soil mechanics have been largely developed for sedimentary soils, they are often inappropriate for tropical residual soils and can cause confusing results when they are applied to such materials. Tropical residual soils frequently exhibit special engineering properties and characteristics which differ from those found in sedimentary soils as a result of the predominant role of weathering in the genesis of the soil. These special characteristics are summarized here. Effective stress changes seasonally and when surface evaporation is impeded these changes can produce large strains in the superficial soil. In addition, the surface layers of soil may be more chemically active than is usual for sedimentary soils.

This paper is primarily a review of the genesis (i.e. the origins) and classification of tropical residual soils which has largely been based on the Geological Society of London Engineering Group Working Party Report, "Tropical Residual Soils" (Anon 1990), for which the author was the Chairman of the Working Party. Therefore, for fuller discussion on the following refer to Anon 1990. In Anon 1990, tropical residual soils are considered to be the saprolith and solum (see Fig. 1 and discussion following) of the earth's surface in tropical regions. These approximate to engineering weathering grades IV, V and VI (Fig. 2). However, for the purposes of this review, tropical residual soil is defined as weathering grades V and VI as the engineering and geological characteristics of weathering grade IV still show some influence of the original parent rock type because the true tropical residual soil properties are not yet fully developed. This occurs in weathering grade VI and is discussed further following, particularly in 2.1 and 3.0.

Appendix A is a glossary of some of the terms used in this paper.

2. TROPICAL RESIDUAL SOILS

The processes forming residual soils include incorporation of humus (decaying vegetation), physical and chemical weathering, leaching of

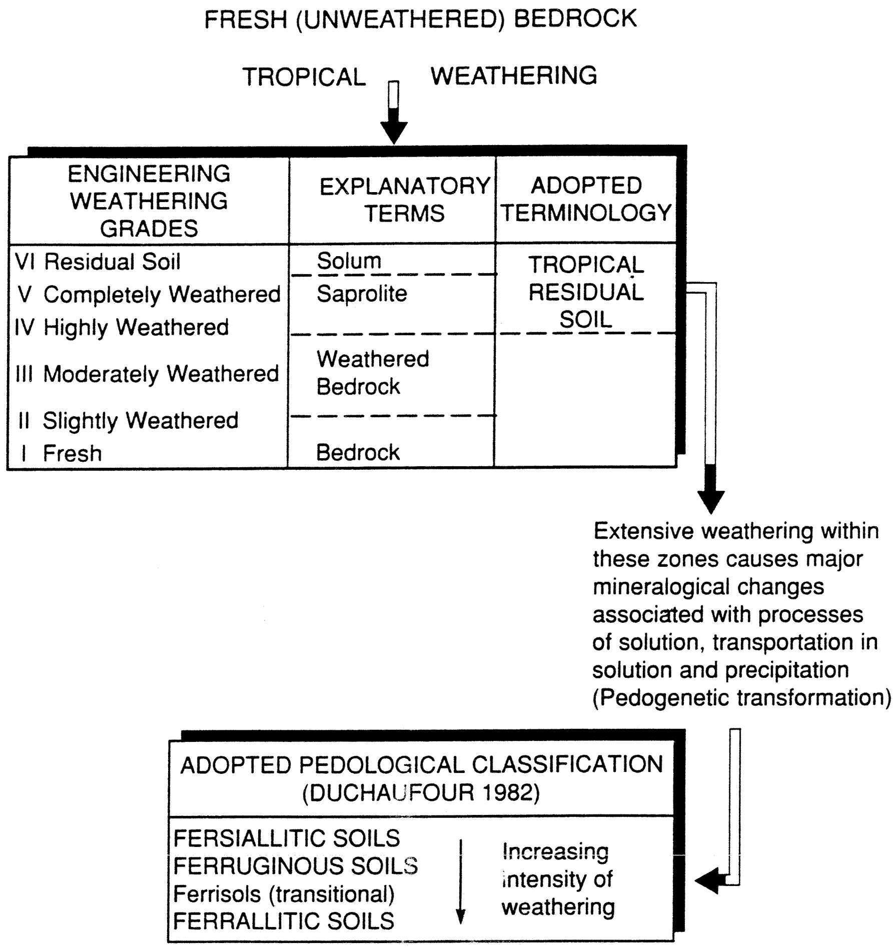

Fig. 1 Commonly used terms and adopted pedological classification (after Anon 1990 and Duchaufour 1982).

insoluble materials, accumulation of insoluble residues, downward movement of fine particles (lessivage) and disturbance by root penetration, animal burrowing, free fall and desiccation, Acting individually or together, they produce a succession of more or less distinct horizons approximately parallel to the land surface, which can be disconformable with the rock structure. The sequence of horizons at any one site constitutes the soil profile.

Soil layers close to the ground surface are strongly influenced by humus, and seasonal and other cycles of wetting and drying. With increasing depth, there is an absence of organic matter and reduction of seasonal moisture content fluctuations. At depth, water movement is slower, and solutes and fine particles are less easily transported through the soil profile (see Fig.3). Consequently mineralogy and particle size distribution, and hence engineering properties, may change with depth even though the entire profile has developed from an originally uniform parent rock. Highly altered minerals in horizons near the surface (ferrallitic) often pass downwards to less altered (fersiallitic) horizons, in which the original minerals of the rock are preserved largely unaltered, or as partly altered but still intact pseudomorphs. Clay contents often decline downwards and 1:1 layer lattice minerals (e.g. kaolin) may change to 2:1 minerals (e.g. smectite), giving significantly different engineering characteristics (see Fig. 4). Material found at depth in a tropical soil profile may resemble 'grus' or eluvium found in higher latitudes over weathered

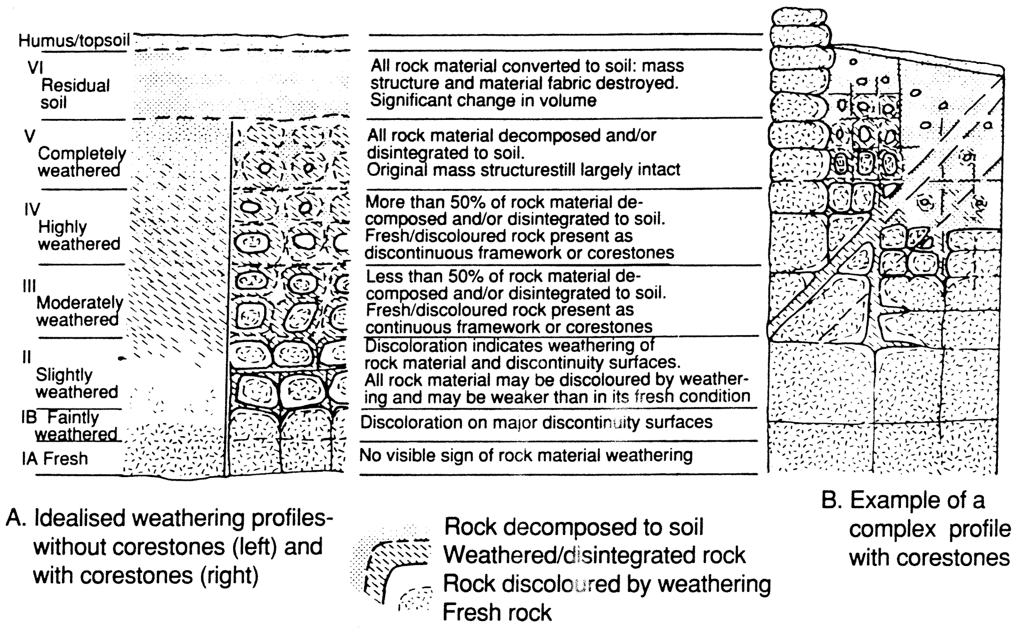

Fig.2 Rock Weathering Classifications and idealized weathering profiles (adapted from BS 5930: 1991)

rock. Iron segregations are typically found in the upper parts of the profile, although they may extend to depths of more than 10m.

2.1 Classification

Traditionally, the classification of residual soils has been on the basis of pedogenetic criteria, which is the logical basis for a scientific classification. Unfortunately, at least three major pedological classification systems exist for tropical soils. Each system is complex in terminology and relies on subtle changes in the soil profile; moreover, pedological classifications relate to profiles, any one of which may contain several material types. Thus this basis of classification is less helpful to the engineering geologist or geotechnical engineer attempting to classify such soils in terms of their geotechnical characteristics and hence engineering behaviour (Netterberg 1975; Nogami & Villibor 1981; Queiroz de Carvalho 1981; Netterberg & Weinert 1983). It is largely for this reason that many other attempts at classification have also been published, each having a particular end use in mind.

The majority of current classifications of tropical residual soils can be divided into four types:-

(1) Those that depend on environmental criteria and are therefore useful in a geographical distributive sense, especially for land systems mapping.
(2) Those that employ strict pedological criteria, such as the silica-sesquioxide ratio.
(3) Those that merely extend the standard geotechnical soil classifications, therefore not fully admitting tropical soils as a special category.
(4) Those that develop a special parameter of particular relevance to a specific end use of tropical soil as an engineering material.

However, none of these methods gives a satisfactory coverage of the variety of soils that may exist.

Traditional geotechnical classification schemes generally have been developed to assess the engineering behaviour of temperate soils. These soils are often little altered sedimentary or transported deposits and in the majority of cases their engineering behaviour can be predicted from schemes based on plasticity and grading characteristics measured in standard laboratory tests. For tropical residual soils, however, engineering behaviour cannot be so easily predicted because:

(a) The weathering products that result under certain tropical conditions may contain minerals with unusual properties.

(b) Weathering of a material in situ implies the presence of a relict structure which may persist as a form of weak bonding even in the most extremely weathered products. Such a bonding can influence metastable behaviour. Under certain engineering applications relict structures may also determine, for example, joint block failure patterns throughout the history of a slope.

These factors raise many doubts as to the reliability of conventional laboratory tests in predicting behaviour under field conditions. Early recognition is important so that appropriate tests may be properly employed. A different approach to geotechnical classification is therefore appropriate for tropical residual soils.

For these reasons it was decided that the formal French classification (Duchaufour 1982) would be adopted for the Working Party Report, Anon (1990). As already stated, weathering products depend on the mineralogy of the parent materials, on the nature of the tropical climate and on the drainage conditions. In addition, special soil groups may develop from certain young volcanic materials, particularly where they are found at altitudes where the higher elevation or the location has a modifying influence on temperatures. The importance of recognizing the interaction of these factors for engineering classification is that the groups of secondary minerals formed in the genesis of the tropical soil, which form the basis of the pedogenic classifications, are all characteristic of distinct geotechnical behaviour.

Within the weathering profile certain general divisions may be made (see Fig. 2). Above the fresh "bedrock" (Grade 1) the slightly weathered and moderately weathered zones (Grade II and III) behave in engineering terms as rock and are defined simply in this review as 'weathered bedrock'. In the highly weathered zone (Grade IV) and above the material tends to behave in engineering terms as a soil.

Grades III and IV represent an important transition zone in terms of engineering behaviour; the change from a rock, in which behaviour may be controlled by movement along discontinuities, to a grade V and VI soil where behaviour is generally controlled by mass deformation. The role of discontinuities is particularly influenced in the tropical regime by the presence of altered material as a lining. Becker (1985) defined 'saprolite' as that part of the weathered mantle (behaving as a

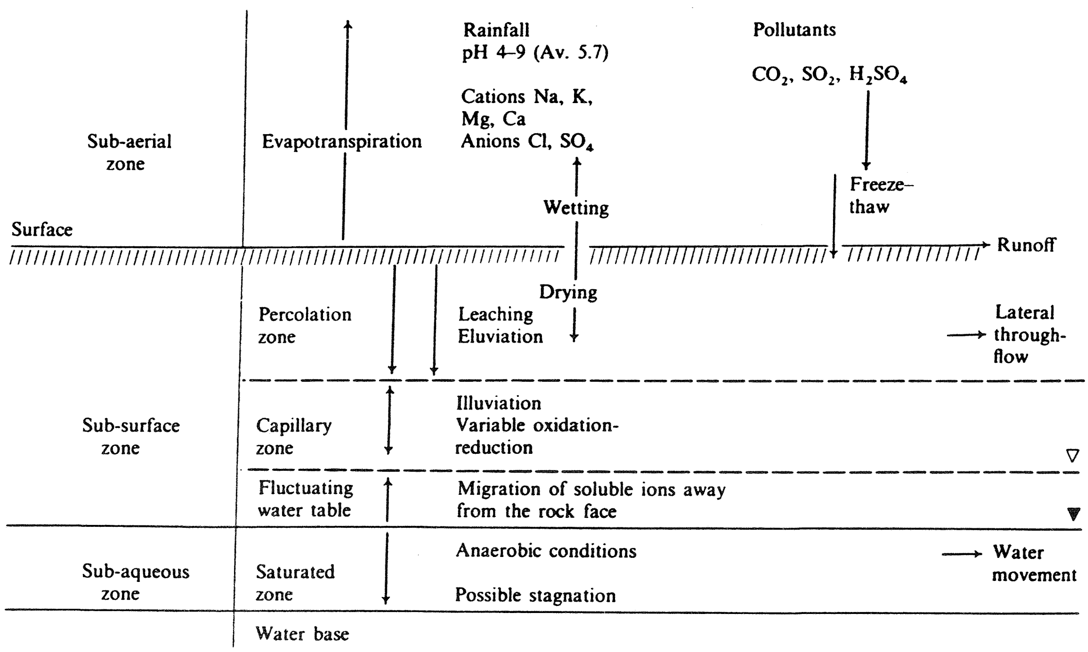

Fig. 3 Some characteristics of the principal hydrological zones (after Keller 1957).

soil in engineering terms) which exhibits textural and structural features of the parent rock to the extent that identification of the parent rock could still be made. This is defined here as applying to Grades IV and V and is discussed later in the paper. In Grade VI all semblance of original texture and structure has been lost. This grade includes the pedological soil horizons A and B and it is for this grade that the Tropical Soil Engineering Classification adopted in this review is specifically recommended.

The use of these terms is illustrated in Fig. 1 and for comparison the general terminology of the adopted scientific classification of residual soils given in this paper is also shown.

The weathering profile referred to above is necessarily idealized and this point cannot be too strongly emphasized. In tropical climes extremes of temperature and rainfall abound and soil movement by landslip and water transport is widespread. A tropical residual soil profile can develop on any parent material, including fully formed in situ weathering profiles developed in a transported 'parent' material, such as a river terrace deposit. It may not be unusual, therefore, to encounter one weathered profile grading into a transported soil, which in turn rests on a horizon representing an old erosion surface within a second weathered profile.

Concretionary products can be a significant component of tropical residual soils and may be encountered as relatively immature material behaving as a 'soil' in the engineering sense, or in their maturity as duricrusts which behave in the engineering sense as a 'rock'. Duricrusts also appear and are often more dominant in non-tropical environments although they are the product of a pedogenetic process often initiated under tropical conditions. For completeness, therefore, duricrusts must also be included in any classification.

2.2 Genetical Background and Duchaufour

There are a number of scientific systems of classification in use for tropical soils, many of which are considered by Anon 1990 and discussed therein. The Working Party considered that a successful, established scheme should be chosen as the basis for their engineering classification firmly rooted in a scientific base. The scheme that appeared most suitable was that by Duchaufour (1982) as it was based firmly on weathering and other processes of pedogenesis established by detailed analytical and experimental work and was relatively straightforward for use by geologists and

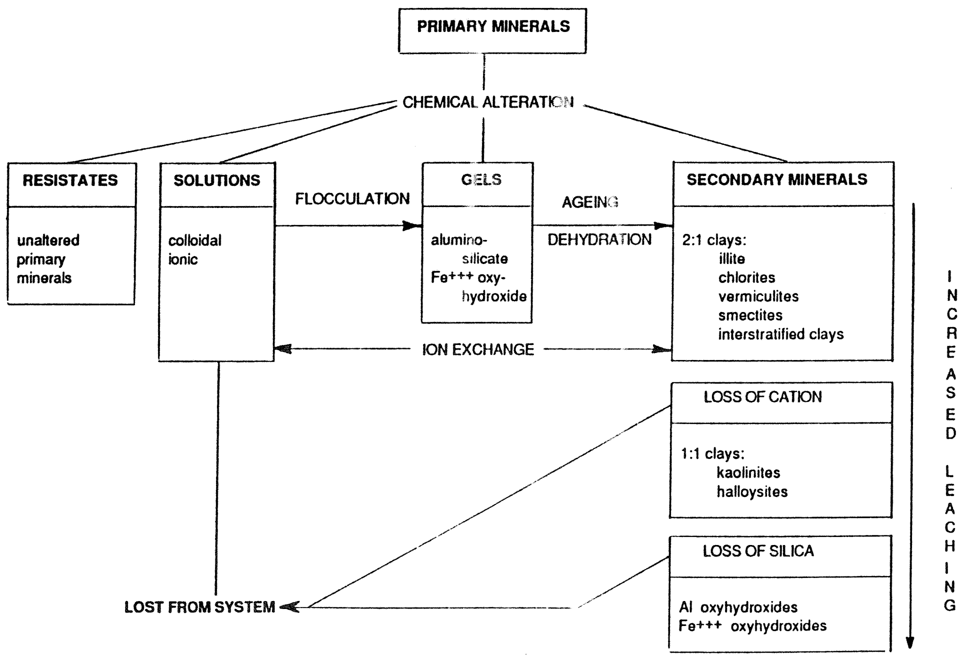

Fig. 4 Processes and products of chemical alteration of minerals in rock weathering (after many sources)

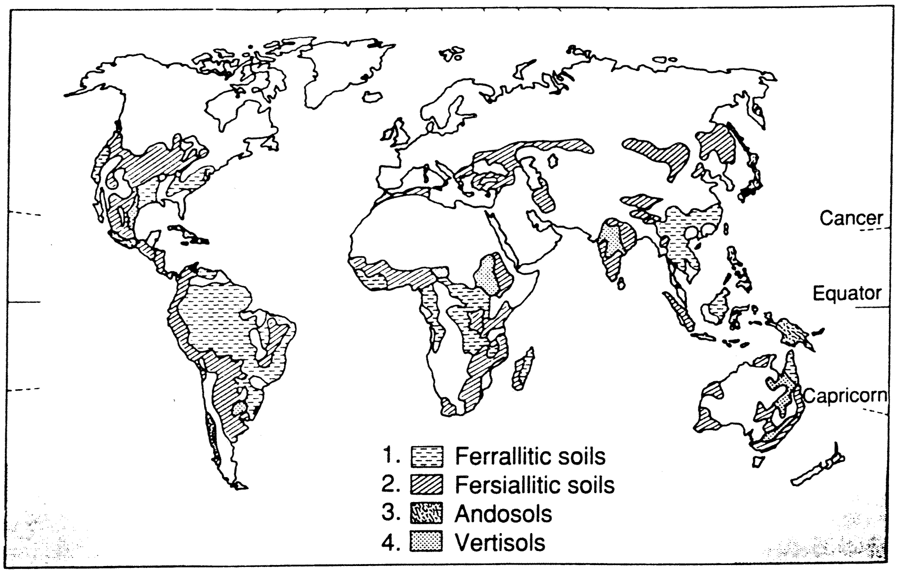

Fig.5 Simplified world distribution of the principal types of tropical residual soils (based on F.A.O. World Soil Map). These broad classes of soils extend beyond the tropics in favourable circumstances, which include high rainfall sub-tropical, continental east coasts (ferrallitic soils), and the west coast/Mediterranean and continental interiors in mid latitudes (fersiallitic soils) (after Anon 1990).

engineers who were not necessarily conversant with pedological terminology and techniques. It highlights the compositional soil characteristics which influence engineering behaviour, e.g. mineralogical composition. It is therefore more relevant to engineering and geology than those based on other often ephemeral criteria usually of more value in agriculture.

Duchaufour (1982) distinguished three phases forming a continuum of residual soil development in tropical areas (Table 1 summarizes these). They are characterized by increasing weathering of primary minerals, increasing loss of silica and increasing dominance of new clay minerals formed from dissolved materials (cf Fig. 4). Their generalized distribution is shown in Fig. 5. The phase represented by the soil profile at any particular site is determined by numerous factors including: the age of the land surface (how long the soil has been forming), the climate during this period of soil development (temperature, humidity and seasonal desiccation), the composition of the soil parent material (amounts of iron and base-rich primary minerals, of total silica and alumina), and the topography (controlling lateral transportation of bases, silica and iron in solution, and rejuvenation of profiles by erosion of steeper slopes, e.g. Fig. 6 which shows different phases of development on the same slope). Many features, however, are related to weathering in earlier periods and to different climatic conditions (Fookes 1991). Fig. 7 summarizes this.

Phase 1 : fersiallitic soils

Such soils probably form mainly in subtropical or Mediterranean climates, with mean temperatures of 13 to 20° C, rainfall 500 to 1000 mm., and a hot dry season; tropical sub-types are also known (Duchaufour 1982, p. 378). Under subtropical and Mediterranean conditions, the upper soil horizons undergo decalcification and weathering of primary minerals during the wet season. The elements freed by these processes are largely retained in the profile as a result of capillary rise during the dry season and effective bioturbation of the soil (e.g. by termites). With limestones much of the dissolved calcium carbonate is re-precipitated in this way to form a thin discontinuous calcrete horizon in the subsoil. In regions with a dry season too long to allow a dense forest to develop, the calcareous crust becomes thick and continuous, especially of footslopes which periodically receive bicarbonate-rich water from upslope (Netterberg 1980).

Although the weathering of primary minerals is more intense in tropical than temperate (siallitic) soils, it does not affect quartz, alkali felspars or muscovite. Because of the more intense weathering, fersiallitic soils contain more iron oxide than the brunified (siallitic) soils of Duchaufour (1982) and the free iron is usually greater than 60% of the total iron content. The main new clay mineral formed is smectite, especially where drainage is impeded so that much of the silica and bases released by weathering are retained in the profile. However, kaolinite may appear on older well drained land surfaces and silica-poor parent materials, such as basalt. Where the parent material is clay-rich, the composition of the soil clays may be determined mainly by minerals derived with little alteration from the sediment. The 2:1 clays often undergo lessivage (downward movement of solid particles) to form clay-enriched subsurface horizons, and some iron oxide may be carried down with the clay to form a red or red-mottled, clay-enriched B horizon. The clay fraction (<2 μm) usually has an exchange capacity of about 50 mEq/100 g, but it may be as small as 25 mEq/100 g. Extremely quartzose rocks without iron or weatherable minerals do not produce fersiallitic soils in any topographic or climatic situation.

Silica and bases lost in solution may also move laterally and accumulate where drainage is impeded, for example on footslopes, valley floors and enclosed hollows (Figs. 6 and 7). In such situations recombination with other weathering products to form swelling 2:1 clays often results in patches of clay-rich deposits. These crack in dry seasons and humic, weathered topsoil is incorporated into subsoil horizons by self-mulching to form vertisols (black cotton soils).

Of engineering importance on recent volcanic ashes, fersiallitic soils on slopes are often associated with uniformly dark-coloured, very porous soils of low bulk density, known as andosols. These immature thixotropic soils owe their characteristics

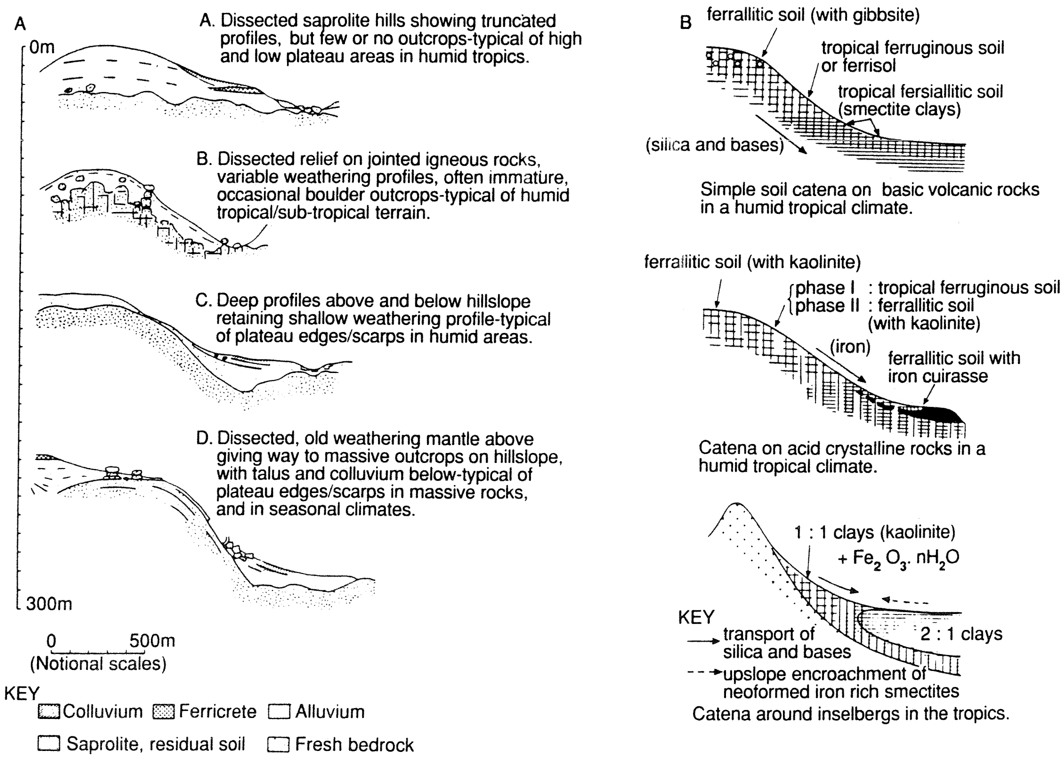

Fig. 6 A. Example of hillslope profiles illustrating common sequences of weathering and landforms (after Anon 1990).

to the formation of complexes between humus and imperfectly crystallized aluminosilicates (allophanes) produced by rapid weathering of volcanic glass. As silica is lost during development of andosols, allophanes are replaced by disordered fibrous clay minerals (imogolites) and eventually by the globular or tubular 1:1 clay mineral halloysite (Dudas & Harward 1975).

Phase 2 : ferruginous soils

These soils form in climatic zones which are either more humid (without a dry season) or slightly hotter than the Mediterranean areas where most fersiallitic soils originate. They tend to be somewhat more strongly weathered than the fersiallitic soils, but orthoclase and muscovite typically remain unaltered. Kaolinite is the dominant clay mineral; 2:1 minerals are subordinate and gibbsite is usually absent. The exchange capacity of the clay fraction is 16 to 25 mEq/100 g and is greatest in the clay enriched horizons because of preferential lessivage of 2:1 minerals.

Phase 3: ferrallitic soils

Ferrallitic soils form in the hot, humid tropics (annual rainfall greater than 1500 mm, mean temperature $> 25°$ C, with little or no dry season), and typically have profiles several metres thick. All primary minerals except quartz are weathered by hydrolysis in the neutral conditions, and much of the silica and bases are removed in solution. Any remaining silica combines with alumina to form kaolinite, but usually there is an excess of alumina, which forms gibbsite. The exchange capacity of the clay fraction is less than 16 mEq/200 g, and usually there is no clay lessivage. Upper horizons of the profile are weakly acidified by organic decomposition products which cause dissolution, chelation and mobilization of iron and aluminium oxides, and decompose any kaolinite present to produce more gibbsite. Depending on the balance between iron and aluminium oxides, ferrallitic soils may be divided into ferrites, in which iron oxides dominate and which occur mainly over rocks low in aluminium, and allites in which aluminium oxides (usually gibbsite) predominate.

2.3 Engineering Classification

The engineering classification is summarized in Fig. 8 as a simple field and laboratory guide to quick establishment of the tropical soil phase. Fig. 9 is a more elaborate guide, giving more detail on the geological and environmental background to the soil phases which may be developed.

2.3.1 Recognition of geotechnical characteristics

The flow chart, Fig.8, suggests that geotechnical characteristics may be broadly predicted by accessing existing sources of information. It is intended to provide general preliminary guidance to predicting the soil groups most likely to be found under any particular combination of parent materials and environmental conditions. This system of prediction may begin at the feasibility stage of an engineering project using the figure. Figure 9 elaborates on this, viz:-

(i) *Parent materials*. Acid igneous and metamorphic rocks, together with sedimentary sandstones, are composed dominantly of quartz and feldspars. As quartz is very resistant to weathering, it has an important role in influencing the texture of the secondary products by remaining as quartz particles while silica in solution can lead to the formation of silcrete duricrusts. Feldspars either slowly weather to clay minerals of the kaolinite group or release hydrated oxides of aluminium and small amounts of iron.

Basic igneous and metamorphic rocks are composed dominantly of minerals such as biotite mica, amphiboles, pyroxenes and olivines, which weather initially to clay minerals of the smectite group. This general statement may be misleading, however, as the exact processes depend on climatic and other local characteristics.

Extrusive volcanic rocks, when associated with cooler tropical climates experienced at altitude, can produce allophanes, halloysites or metahalloysites.

Sedimentary mudrocks generally contain original illites, chlorites or smectites.

Limestones and other carbonate-rich rocks dissolve to produce carbonate-rich groundwater, which in certain conditions can lead to the development of calcrete or dolocrete duricrusts (Netterberg 1969, 1971, 1983).

Evaporites dissolve readily to release the soluble sulphates which can lead to the development of gypcrete.

(ii) *Environmental conditions*. The information from geological maps should be supplemented by an assessment of the environmental influences on the weathering process. Topographic maps, aerial

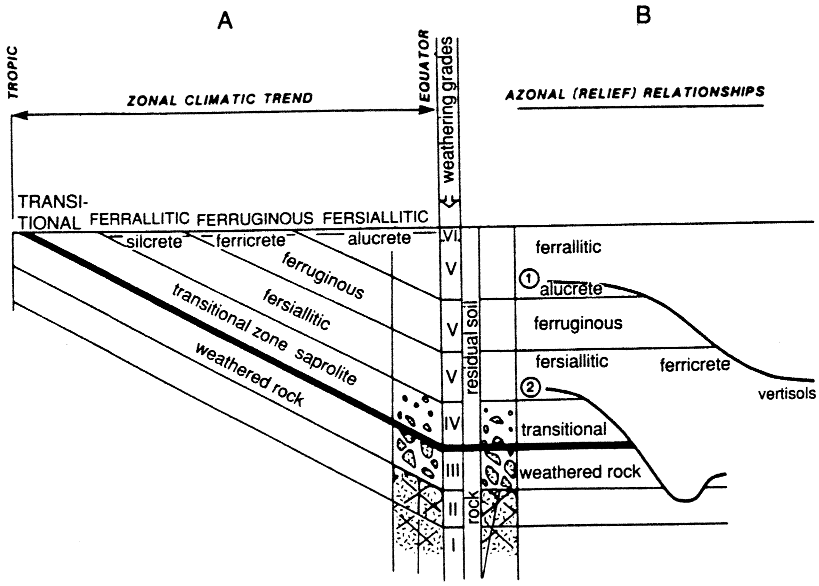

Fig.7 Schematic diagram to relate weathering depth and grade with adopted residual soil classification in zonal and azonal contexts using the Strakhov model. In A the intention is to demonstrate the general correspondences between residual soil class and weathering type as indicated by Strakhov (1967) and between weathering grade and residual soil type in a vertical profile. Such correspondences may be conceptually helpful but must be used with caution. (after Anon 1990).

photographs and remote sensing imagery provide information on present slope angles, site elevation, drainage conditions and morphological history. A site reconnaissance is particularly recommended for example to assess whether the specific site is affected by erosion indicating that weathering profiles may be of limited thickness. Conversely, a more stable site may comprise deep weathered profiles.

Climatological data, such as annual rainfall, mean annual temperature and length of the dry season are also important. Every effort should be made to describe the area in terms of three fundamental climatic groupings; wet tropical, seasonal (dry) tropical or cool tropical at altitude. For duricrust development, it is important to note that seasonally dry conditions are an essential criteria for full development.

In locations where profile drainage is impeded, reducing conditions dominate and initial weathering products such as smectites and chlorites remain dominant within vertisol profiles. Where oxidizing conditions prevail, generally on slopes between 10 and 30° and where adequate throughflow of water occurs, the smectites which originate from basic rocks change to kaolinite group minerals and the hydrated oxides of iron and aluminium are released. These minerals dominate the ferruginous soil profiles, which develop under stronger weathering to ferrisols and ultimately to ferrallitic soils. Progressively stronger weathering results in increasing amounts of the hydrated oxides of iron and aluminium. The process is encouraged in areas of high rainfall by strong leaching. When periods of high rainfall are separated by a dry season, concentrations of the hydrated oxides may develop as layers within the ferrallitic soil profiles.

(iii) *Pedogenic information*. Where pedological survey data is available this should also be referenced. Application of the Duchaufour system tends to be limited in geographical coverage to those areas of the world that have developed historically under French influence. At least two other classifications are used widely, those of the US Soil Conservation Service and the FAO/UNESCO system. To enable use of data based on these systems, Fig. 9 contains a summary of their general terminology which is related to the classification adopted in this paper (see Anon 1990 for more details).

(iv) *Engineering terminology*. The engineering literature often describes tropical residual soils

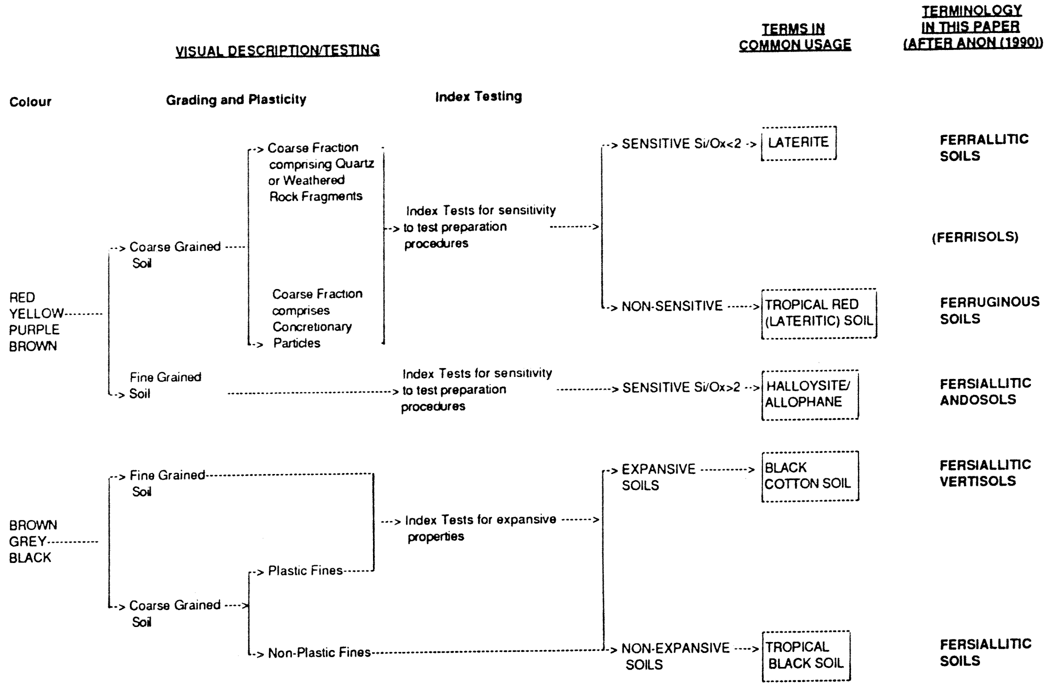

Fig. 8 Preliminary Geotechnical/Genetic Classification of Tropical Residual soils (after Anon 1990)

under two general categories; the tropical black soils and the tropical red soils. Whilst this may be a useful first approximation, there can be confusing overlap in detail and the engineer should refer to the indicators given in the flow chart (Fig. 8).

The black tropical soils found in vertisol profiles are generally described in the engineering literature as black cotton soils, black swelling clays or tropical black clays. Local terms such as negur, bmuga, adobe or vlei soils may also be used.

There is considerable confusion in the engineering literature over the use of terms for the so called 'red' tropical soils i.e. those soils contained within the ferruginous, ferrisol and ferrallitic soil profiles. Only a small proportion of sesquioxides will impart a red coloration and any red soil has tended to be termed a laterite. Such generalized usage should be avoided. In engineering terms it is particularly important to recognize different amounts of iron and aluminium oxides which possess unusual properties and thus have important effects on the geotechnical properties of the soils in which they are a major component.

Nogami (1985) described the group 'tropical red soils' (undifferentiated) as lateritic soils rather than laterite and suggested that strictly this term should only be applied to those soils that behave predictably in standard laboratory tests. However, as the hydrated oxides become more concentrated they have an increasing effect on engineering properties. Where these minerals become concentrated into discrete horizons such layers have been called plinthite and probably coincide with the original laterite defined by Buchanan (1807) as a red tropical soil which hardens on exposure to air. Under conditions caused by long term changes in climate, drainage or landform, such horizons can harden irreversibly to an indurated ferricrete or alucrete duricrust. These concretionary indurated strong layers have also been termed laterite in the literature.

(v) *Hard duricrust cappings*. These features mainly include ferricrete, silcrete, possibly the softer alucrete or 'bauxite', and also calcrete or 'caliche' (see 2.3.2 for definitions). Ferricrete duricrusts are widespread but have complex formative histories. Duricrusts on summits, often 2 to 10 m thick, may have resulted from long histories of landscape development (Gaskin 1975; Butt 1981) involving sequences of humid tropical weathering, progressive desiccation due to climatic shifts, and a fall in the water table due to incision of drainage. Lower slope laterites and ferricretes forming pediments and benches are generally younger and more detrital and often conglomeratic in origin. Groundwater laterite beneath lower valley slopes and valley floors is related to present and recent past groundwater regimes, and is generally thinner and less continuous. Calcrete forms at depths between 0.5 and 2.0 m in semi-arid fersiallitic soils; discontinuous and weakly indurated crusts often occur beneath calcereous surface horizons; massive indurated layers occur beneath non-calcereous horizons (Duchaufour 1982). Flaggy, lamellar calcretes form by recrystallization (Netterberg 1971) and possibly by replacement of silcretes. Thick calcretes often form in dry

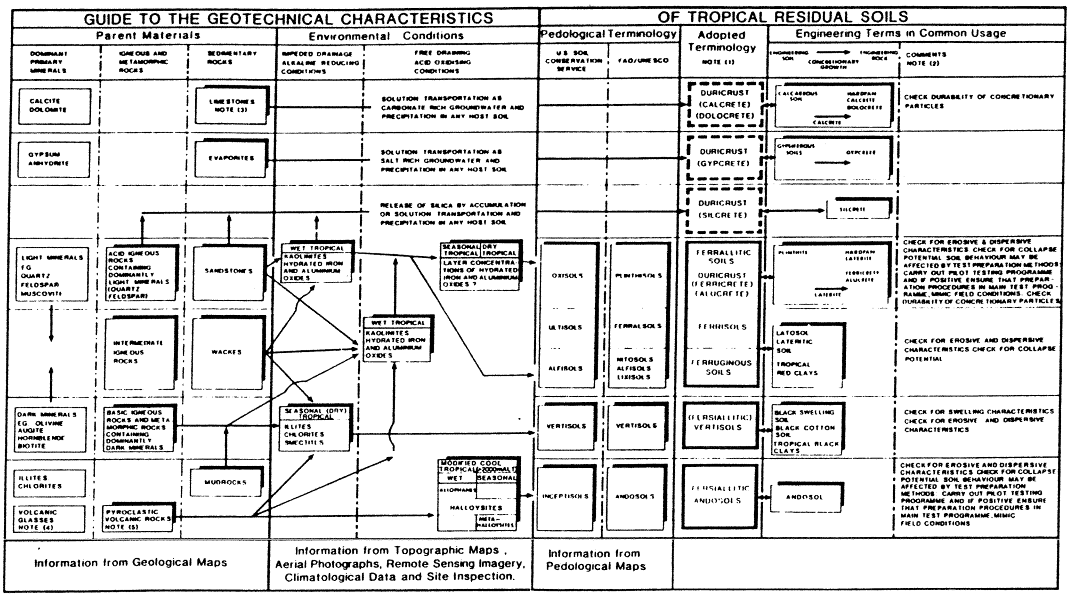

Fig. 9 Guide to the geotechnical characteristics of tropical resiudal soils (after Anon 1990).

General: The figure is intended for general guidance to assist the prediction of the potentially most likely soil group to be found under any particular combination of parent materials and environmental conditions. Many parent materials and environmental conditions exist as gradational or intermediate phases between those shown. The principles implied in the figure should be applied in such situations.

Note (1): These terms should be used as qualifying terms to support a full and detailed soil description, e.g. Firm dark grey-brown slightly silty Clay with occasional rootlets and fine gravel calcareous nodules (VERTISOL).

Note (2): The notes in the final column are intended as an early indication of typical behavioural characteristics associated with certain soil groups.

Note (3): The flowpath indicated relates to pure limestone which pass into solution and leave a residual karst landscape. For impure limestones (e.g. argillaceous) the reader should refer to flowpaths from the appropriate primary minerals.

Note (4): Volcanic glasses may include dark minerals such as olivine, augite, hornblende and biotite.

Note (5): Other extrusive volcanic rocks are included under acid, intermediate or basic igneous rocks, as appropriate.

piedmont regions from bicarbonate moved laterally from adjacent limestone hills with a more humid climate. See also Figs. 6 and 7.

(vi) *Drying*. Even partial drying at moderate temperatures may change the structure and physical behaviour of tropical residual soils. Some of these changes are chemical and are not reversed when the soil is remixed with water. They are reflected in changes, sometimes drastic, in the index properties derived from plasticity, shrinkage and particle size tests, or in particle density. Engineering properties such as compaction characteristics, compressibility and shear strength can also be affected (e.g. Frost 1976).

Changes in properties can be caused by:

(a) alteration of the clay minerals on partial dehydration (e.g. loss of intra-particle water);

(b) aggregation of fine particles to form larger particles which remain bonded together even on re-wetting.

Clay soils often aggregate to more silt- or sand-sized particles, with a lower plasticity; although in some instances the opposite can occur. Oven-drying from 105 to 110° frequently has a substantial effect on soil properties but drying at a lower temperature (e.g. 50° C), and even partial air-drying at ambient laboratory temperature can also produce significant changes.

As a general rule it should be assumed that all tropical residual soils will be affected in some way by drying. Classification tests should therefore be applied to natural soil with as little drying as possible, at least until it can be established from comparative tests that drying has no significant effect on the test results. The method of preparation should always be reported. Suggested preparation procedures are given (Anon 1990).

(vii) *Disaggregation.* Disaggregation of tropical residual soil should be done with care and with regard for what is meant by 'individual particles'. The aim should be to separate individual particles without crushing or splitting. For soils in which particles are held together by cement the extent of disaggregation may be limited to that achievable by finger pressure. In some soils it might be preferable to soak in water overnight (with a dispersant if appropriate) and to apply no additional mechanical force.

(viii) *Classification and engineering behaviour.* The engineering behaviour of tropical residual soils is described in more detail in Anon (1990). Certain special behavioural characteristics which are summarized here to demonstrate the utility of the proposed classification:-

In the **fersiallitic vertisols** group, behaviour is dominated by the volume changes exhibited by smectite clay minerals when they are subjected to changes in natural moisture content. This behaviour is described in detail in Anon (1990). Several methods of prediction of swelling potential are available, based on results of index tests.

In the **fersiallitic andosols** allophanes together with halloysites and metahalloysites of the kaolin group influence engineering behaviour, viz:-

Soils containing metahalloysite possess aggregations of clay particles which can be dispersed by manipulation during testing. Aggregates may be reformed unless the soil is oven-dried at 105° C, which removes all interparticle water and collapses the aggregated structure.

Soils containing hydrated halloysite lose water of hydration or water on drying. This occurs when the relative himidity falls below 50% or the temperature rises above 50° C. The loss of water of hydration in a pure halloysite is equal to 14% of the dry soil weight. Drying causes aggregates to form and the soil then behaves like the metahalloysite described above.

Soils containing amorphous allophane form aggregates on drying. This is an irreversible process caused by loss of interparticle water and water from the amorphous clay mineral and is accompanied by large reductions in porosity. The effect can be so marked as to change the soil from a 'clay' to a 'sand'.

In the **ferruginous, ferrisol and ferrallitic** soil groups variable quantities of sesquioxides affect the results of standard laboratory tests in several ways, viz:-

Aggregation of clay-size particles. The sesquioxides within the fine fraction of tropical soils coat the surface of individual soil particles because of the electrical bonding between the negatively-charged kaolinite and the positively charged hydrated oxides. The coating reduces the ability of the clay minerals to absorb water and can also physically cement adjacent grains, thus producing aggregates of increased size. Both factors reduce plasticity, but intensive remoulding of the soil breaks down aggregates and the sesquioxides coatings, with an attendant increase in plasticity. This is important when relating laboratory testing procedures to construction operations. Field operations of excavation, transport and placement are unlikely to break down the fine soil aggregates to the extent that plasticity is affected. The degree of working required to prepare laboratory specimens for Atterberg limit determinations is, by comparison, very much greater. The plasticity of the construction material may thus be lower than would appear from the standard Atterberg or other laboratory tests on remoulded samples.

Irreversible changes in plasticity on drying. Soils which contain hydrated oxides of iron and aluminium may become less plastic, i.e. exhibit lower Atterberg limit values on drying. This is partly because dehydration of the sesquioxides creates a stronger bond between the particles, which resists penetration by water. The process cannot be reversed by re-wetting. The effect is observed during air-drying but is more pronounced on oven-drying at higher temperature.

Loss of water of hydration on drying. The water of hydration in the sesquioxides of iron and aluminium may be driven off by oven-drying at 105° C, the standard temperature for testing temperate region soils. This water normally takes no part in the engineering performance of the material but is reflected in the results of tests undertaken to temperate country standards at a higher moisture content.

Collapse characteristics or decrease in volume upon addition of water and with no addition of load. Susceptible rocks have high void ratios but relatively low moisture content and hence they may be identified by determining whether the natural void ratio is higher than the void ratio at the liquid limit. This indicates a soil that is susceptible to changes in structure with saturation. Another method, used by Jennings (1965), makes use of the consolidation test. These matters are more likely fully described in Anon (1990).

Duricrusts provide a unique problem to the engineer because they do not necessarily represent a material that behaves as a 'rock' in the engineering sense. They are essentially concretionary particles in a host soil, as a honeycomb structured material of coalesced concretionary particles or as an indurated horizon. In any event they exhibit variable engineering properties within a deposit and require detailed description, evaluation and quality control. Particular care should be given to the evaluation of particle strength; unless fully mature duricrusts may be relatively weak and hence can be considerably changed by handling and processing.

Clearly, the properties described above render the soil behaviour susceptible to the methods used to prepare specimens for laboratory tests. Early identification of such behaviour is necessary and a pilot testing programme should be carried out to determine the need for modification of standard test procedures.

Table 2 summarizes, with much simplification, the characteristics that individual clay species bring to a particular soil. The influence such species has on the behaviour of the soils will vary considerably with the circumstances, depending on moisture content, clay proportions, cementing and so on. Therefore this guide must only be considered very approximate.

2.3.2 Definitions

The following principal definitions accompany Fig. 9. See also the Appendix glossary.

Duricrust: an indurated material produced by low-temperature physico-chemical surficial and pene-surficial processes, formed by cementation or replacement of bedrock, weathering deposits, unconsolidated sediments, soil or other materials. Various common forms are defined by their principal components, e.g.:

Alucrete: a form of indurated deposit often called 'bauxite crust', containing Al and Fe in residual laterite deposits. The Al may occur in sufficient quantity to be of commercial use. It may be subdivided on the basis of degree and type of induration. It may also be detrital, reworked or pedogenetic.

Calcrete: an indurated deposit mainly consisting of Ca, Mg carbonates. The term includes non-pedogenetic forms produced by fluvial or groundwater action; they may be pedogenetic by lateral or vertical transfer. Subdivisions are usually made on the basis of degree and type of cementation (e.g. powder, nodular, concretionary). May be called caliche locally.

Ferricrete: a form of indurated deposit consisting of accumulations of sesquioxides, mainly iron, within one or several ferruginous or ferrallitic soil horizons. It may form by deposition from solution, moving laterally or vertically, or as a residue after removal of silica, alkalis, etc. The term 'carapace' is sometimes used for moderate induration and 'cuirrasse' for high induration. It may be pedogenetic by retention or accumulation of minerals and by segregation within vadose profiles. Texture may vary from pisoliths to massive, blocky or sheet form. Groundwater forms are pisolitic.

Gypcrete: an indurated deposit mainly consisting of calcium sulphate dihydrate. The main subdivisions are based on the degree and type of induration (e.g. powder, laminated) but also include desert roses in dune sane. It may include non-pedogenetic forms such as windblown gypsum dune sand but is normally pedogenetic by vertical transfers (Goudie 1973).

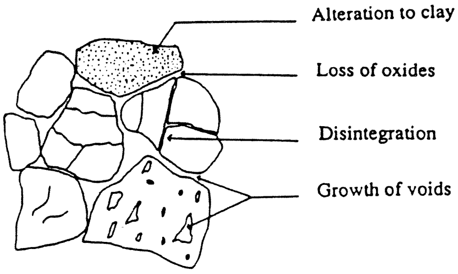

Fig. 10 Fabric of weathered rocks (after Ebuk 1991).

Silcrete: an indurated deposit mainly consisting of silica (SiO_2), which may be formed by lateral or vertical transfer of silica and which may include pedogenetic, groundwater or leached varieties. Commonly they are poor in Fe, Al, Ca, K, Mg and P. Subdivisions may also be made on the basis of the dominant fabric type (Langford-Smith 1978; Summerfield 1978, 1983).

Fersiallitic vertisols: Vertisols: 'cracking clays' show a wide range of seasonal volume change, and usually contain clay minerals of the smectite/montmorillonite group. Clay-humus complexes are often incorporated to some depth by topsoil falling down the cracks, hence the common name of black cotton soil.

Fersiallitic andosols: Soils, often clays, derived partly or wholly from volcanic deposits and often dark coloured, essentially amorphous allophane-humus complexes. They have an enormous water-holding capacity which exceeds 100% and can reach 200% in hydromorphic tropical andosols, but prolonged desiccation can lower this capacity, often irreversibly. They have high exchange capacity and are very clay and iron rich; they indurate on drying.

Fersiallitic soils: (sensu stricto): initial phase of development of tropical soils, with some reddening. Formed in sub-tropical of Mediterranean climates where weathering is weaker than in the ferruginous soils, and does not affect quartz, alkali feldspars and muscovite. Main clay mineral is smectite but kaolinite may form in well drained areas. 2:1 clays are dominant by both transformation and neoformation and the cation exchange-capacity of the clays is greater than 25 mEq/100 g. Where vertical development is incomplete they form brown fersiallitic soils; where complete, saturated or almost saturated complex, red fersiallitic soils and when complex, desaturated and degraded, acid fersiallitic soils.

Ferruginous soils (sensu stricto): soils of an intermediate phase between those formed by fersiallitization and those by ferrallitization. Weathering of primary materials is stronger than in fersiallitic soils but not as pronounced as in ferrallitized soils. There is some removal of soluble silica by drainage. Neoformed clays are usually kaolinitic but some 2:1 clays persists; lessived gibbsite is absent. Horizons are often in the form of a kaolinitic saprolite, and the development is strongly influenced by age.

Ferrallitic soil (sensu stricto): final phase of development of thick soil profiles in hot, humid climates in which most primary minerals, even quartz, are affected by total hydrolysis. Oxides of iron, aluminium, silica and bases are liberated but iron and aluminium are retained in the profiles while the bases and some silica are removed in solution; neoformed kaolinites are poor in silica. Main characteristics are quartz, gibbsite, haematite or geothite. An argillic horizon is generally absent.

3. SOIL OF THE SAPROLITH

Weathering grade IV (i.e. saprolith) is defined as 'more than 50% of the rock material decomposed and/or disintegrated to soil. Fresh/discoloured rock present as discontinuous framework or corestones', BS 5930 (1981) Table 10. this is illustrated schematically herein as Fig. 2. Its behaviour is not that of the true tropical residual soil exemplified by weathering grade VI, although its description is appropriate to classification in the Duchaufour system.

As weathering progresses from weathering grade III to VI, there is a reduction in bulk density and skeletal density due to the alteration and disintegration of minerals as well as the generation of voids of different sizes and shapes. Voids generally grow large with an increasing degree of weathering. This results in a relatively more open fabric and ultimately most of the minerals are weathered to clay and the clay, together with the voids, strongly influences the engineering properties of the soil (Table 2). Particle size distribution shows the continuous disintegration and alteration of grains into clays and clay size particles with increasing degree of weathering.

In weathering grade IV, i.e. approaching a true

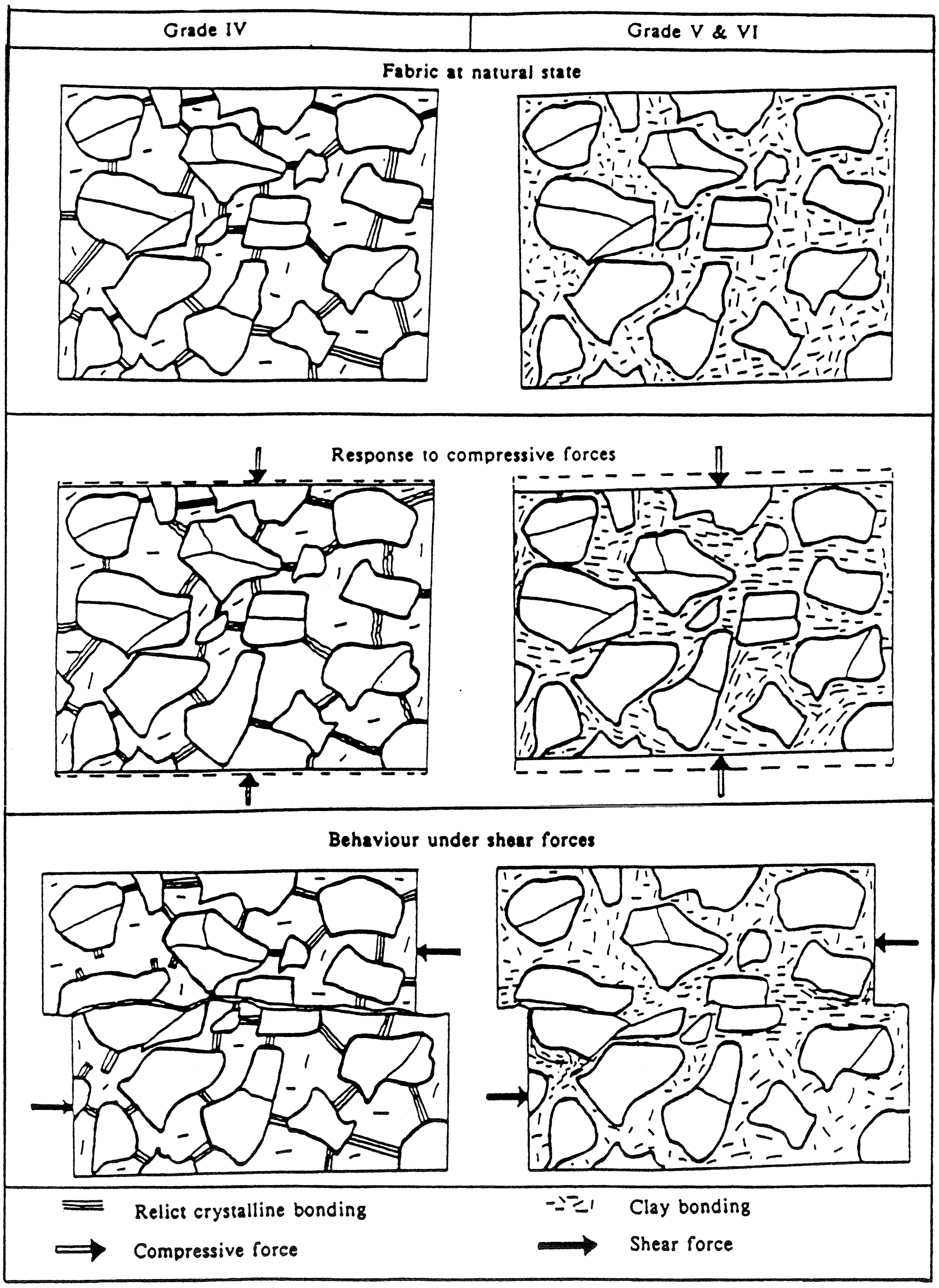

Fig.11 Idealized model of the influence of fabric on the engineering behaviour of weathered rocks (after Ebuk 1991).

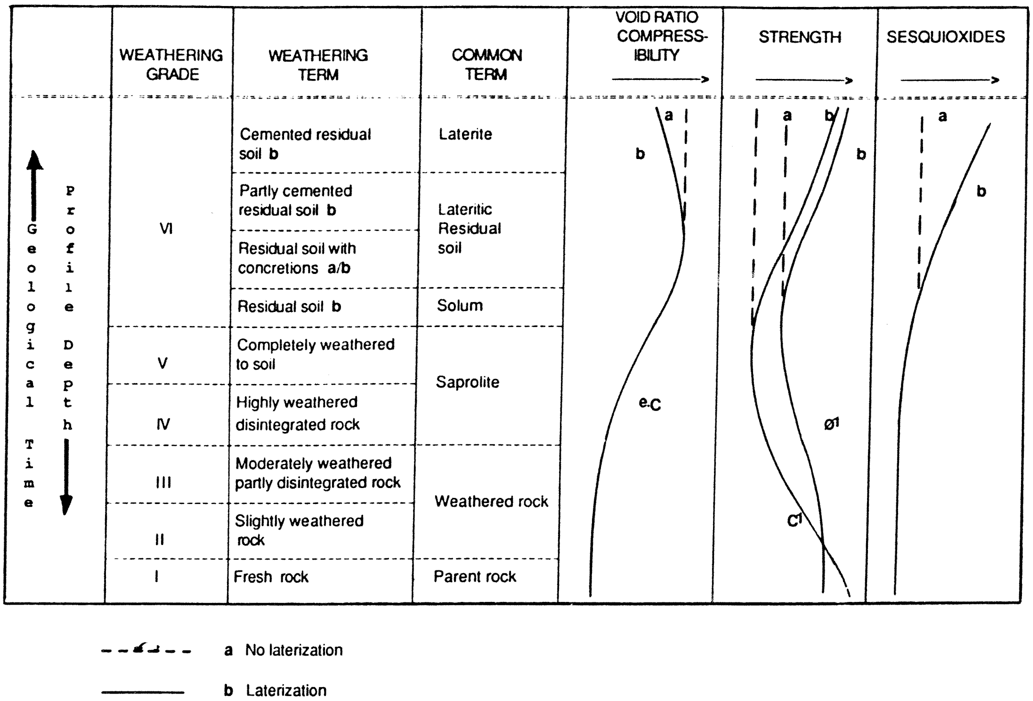

Fig. 14 Geological and engineering changes occurring in an idealized composite weathering profile (adapted from Blight 1991).

bring together the weathering grade and residual soil terms as used in this paper, and to relate these to idealized changes in engineering properties which occur with the progress of weathering and residual soil development.

Glossary of terms
(see also 2.3.2 in the text for definitions of principal terms used in this paper)

Accretionary soil : A thick soil formed by simultaneously slow deposition of sediment and pedogenesis, often occurring on footslopes where colluvium accumulates.

Allite: A ferrallitic soil formed in hot, humid tropics in which aluminium oxides predominate.

Allophane: Poorly crystallized aluminosilicate clay formed in fersiallitic (andosols) soil by rapid weathering of volcanic glass.

Alumina: Aluminium oxide.

Andosol: Porous soils of low bulk density formed by rapid weathering of volcanic ash and containing complexes of humus and imperfectly crystallized aluminosilicate clay (allophane).

Bauxite: Ore of aluminium oxide.

Black cotton soil: Common name for soil which exhibits large volume changes on wetting and drying, caused by the presence of abundant smectite clay minerals.

Catena: Soil sequence influenced by topographical control especially where movement of water and fine particles occurs down a slope.

Cation exchange capacity: The total number of ion exchange sites in a soil, principally on clay and humus particles which can be temporarily occupied by positively charged ions (Ca, Mg, Na, K, etc.).

Collapsible soil: Soils whose structure can collapse when wetted.

Colluvium: A fine sediment of variable texture formed by run-off and creep on slopes and frequently found on hillslopes where it may overlie a residual soil.

Corestones: Residual blocks of hard rocks surrounded by soil formed by spheroidal weathering of well jointed igneous rock. Can be >10m diameter. Used to indicate grade of weathering.

Etchsurface: An irregular surface formed by erosion of a deep residual soil mantle to expose much of the underlying basal weathering front of bedrock.

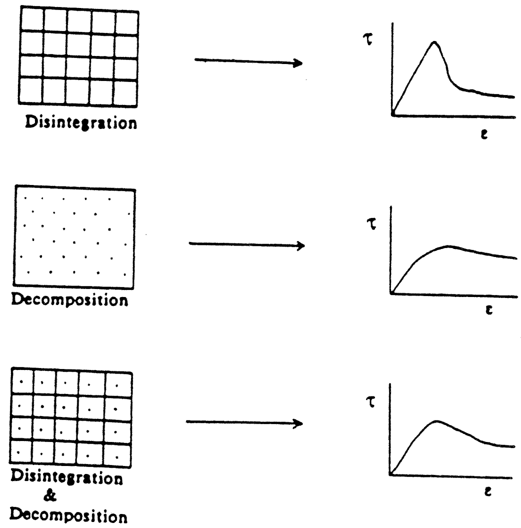

Fig.12 Effect of weathering type on shear behaviour (after Ebuk 1991)

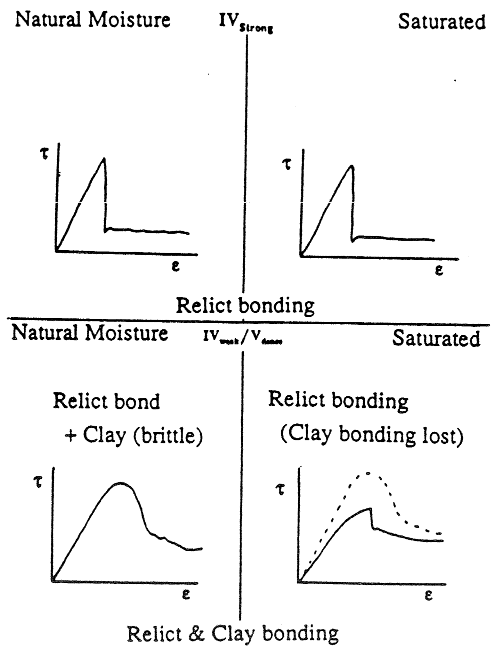

Fig. 13 Effect of bonding types on shear behaviour (after Ebuk 1991)

tropical residual soil, the major factor effecting the pattern of shear strength behaviour, for example, is the degree of residual bonding which is a combination of the relict structure from the parent rock and clay bonds being developed by the weathering. Variation in moisture may play a modifying role and void volume also influences the strength, but the most dominant factor is the fabric. The influence of variation in moisture arises from the wetting of secondary clay bonds which lose considerable strength between the air dried and soaked conditions. Partial saturation may lead to higher strength because of the effect of suction. Ebuk (1991) has demonstrated in grade IV granitic soils that the strength envelope is a function of cohesion, friction and dilation which is dominated by the relict crystalline structure, the texture, the clay bonding and cementation by sesquioxides. The relict structure may be little affected by changes in moisture, but the cohesion due to clay bonding and sesquioxide cementation may be totally lost on saturation. Friction is mainly dominated by particle roughness, interlocking and moisture level. Dilation is mainly controlled by differences in particle size, relative proportion of each size group, particle roughness and the strength of the relict bonding relative to stress level which in turn is influenced by moisture content. The fabric, he considers, reflects the relationship and interplay of voids, grain and degree of bonding.

Shearing generally leads to progressive loss of bonding, grain interlocking, microfracture overriding and particle rearrangement. In the initial stages shearing is dominated by the microfractures around and through the grains as well as the breaking of residual bonds. The later stages or shearing are dominated by particle rearrangements. Fig. 10 shows Ebuk's interpretation of the fabric of weathered granitic rocks and Fig. 11 shows idealized models of the influence of fabric of weathering grade IV compared with weathering grades V/VI (VI is considered the 'true' tropical residual soil grade or solum in this paper) on their engineering behaviour.

With the progress of weathering, shear behaviour passes from domination by disintegration to that of disintegration and decomposition, finally to decomposition as illustrated schematically in Fig. 12. Fig. 13 shows the weathering grade IV shear behaviour at natural moisture content and saturated, compared with weathering grades V and VI at natural moisture content and saturated. The difference between weathering grades IV and V/VI is clearly illustrated. It must be emphasized that there is a gradation between the weathering phases and that generally there is usually no sudden change in engineering behaviour.

Fig. 14 has been adapted from Blight (1991) to

Table 1: Summary of Duchaufour soil phases, location and climate.

FACTORS/ CONDITIONS — SOIL PHASE	MINERALOGY	CLIMATE NEEDED TO REACH THE PHASE	TYPICAL LOCATIONS OF THE PHASE	FAO/UNESCO EQUIVALENTS (USA - SOIL SURVEY)
1 **Fersiallitic**	Upper soils undergo decalcification and weathering of primary minerals. Quartz, alkali feldspars and muscovite not affected. Free iron usually >60% of total iron. Main clay mineral formed is 2:1 smectite; 1:1 kaolonite may appear in older well drained surfaces. With recent volcanic ashes porous andosol soils formed which are eventually replaced by 1:1 halloysites.	Mean annual temperature (^{o}C) 13 - 20 Annual rainfall (m) 0.5 - 1.0 Dry season - yes	Mediterranean, subtropical	Cambisols, calcisols, luvisols, alisols, andosols (alfisols, inceptisols)
2 **Ferruginous** (ferrisols-transitional)	More strongly weathered soils form phase 2 but orthoclase and muscovite typically remain unaltered. Kaolinite is the dominant clay mineral; 2:1 minerals are subordinate and gibbsite usually absent. On older land surfaces and more permeable and base rich parent material, ferrisols transitional to phase 3. Partial alteration to gibbsite may occur.	Mean annual temperature (^{o}C) 20 - 25 Annual rainfall (m) 1.0 - 1.5 Dry season - sometimes	Subtropical	Luvisols, nitosols, alisols, acrisols, lixisols, plinthasols, (alfisols, ultisols, oxisols)
3 **Ferrallitic**	All primary minerals except quartz are weathered by hydrolysis and much of the silica and bases removed by solution. Remaining silica combines to form kaolinite but usually with excess aluminium gibbsite is formed. Depending on the balance between iron and aluminium, iron oxide or aluminium oxide will predominate. Soils currently take 10^4 or more years to form.	Mean annual temperature (^{o}C) >25 Annual rainfall (m) >1.5 Dry season - no	Tropical Can occur in modern savannah from previous wetter climate. Conversely, some currently hot wet areas are still only in the ferruginous phase (e.g. by climate change or by rejuvination of slopes).	Ferrasols, plinthasols (oxisols)

Expansive clay: A clay which swells when it has free access to water if it is not sufficiently restrained.

Ferrisol: Soil type transitional between ferruginous and ferrallitic types.

Ferrite: A ferrallitic soil dominated by iron oxides, which occurs mainly on rocks low in aluminium.

Geothite: A crystalline hydrated iron oxide formed in soils by residual accumulation of iron in a humid environment or by precipitation from solution.

Gibbsite: A crystalline form of aluminium hydroxide ($Al(OH)_3$) which occurs in ferrallitic soils and is the principal constituent of bauxite ore and some rocks.

Halloysite/metahalloysite: A 1:1 clay mineral related to the kaolinite group with hollow tube-shaped crystals. Hydrated halloysite can lose water irreversibly on drying to form metahalloysite.

Illite: A 2:1 clay mineral common in sedimentary rocks, siallitic and fersiallitic soils. Characterized by 10 A X-ray diffraction spacing. The aluminosilicate layers are separated by potassium ions and do not expand and contract with moisture changes.

Illuviation: Downward movement of solid particles (usually clay) through a soil profile by dispersion in percolating groundwater. An upper (eluvial) horizon is consequently depleted in the illuviated material and a lower (illuvial) horizon is enriched.

Kaolinite: Common 1:1 aluminosilicate clay mineral characterized by aluminium silicate layers giving a 7 A interlayer spacing in X-ray diffraction.

Laterite: A soil material which is impregnated with, cemented by or partly replaced by hydrated oxides of iron or aluminium.

Lateritic: Soil with some tendency to form laterite.

Leaching: Vertical (downward or upward)

Table 2: Simplified summary of clay mineral species and their characteristic engineering behaviour

CLAY SPECIES		CLAY SPECIES TYPICALLY IN:	TYPICAL ENVIRONMENT	CLAY PARTICLES SIZE, SHAPE	RELATIVE PERMEABILITY	RELATIVE COMPRESSIBILITY	RELATIVE STRENGTH	NOTES
Amorphous	Allophane	Fersiallitic soils	Mediterranean Sub tropical (on volcanic ashes)	Amorphous	Moderate	High	High	Light, wet, indurates on drying
2:1 Clays	Smectites Chlorites (swelling)	) Fersiallitic soils) Vertisols	Mediterranean Impeded drainage Basic rocks	Small, platy	Low (wet) High (dry)	Moderate	Low	) Swell/shrink)) Wet/dry)
	Vermiculites Chlorites (non swelling)	) Fersiallitic soils) Vertisols	Mediterranean	Moderate, platy	Moderate	Moderate	Low	)Possibly)Dispersive
	(Illite)	(Sediments)	(Sedimentary)	(Moderate, platy)	(Low)	(Low->Moderate)	(Moderate)	)
1:1 Clays	Halloysite	) Fersiallitic soils	Subtropical ↓	Tubular	Moderate	High	Moderate->High	) Property)) changes on)) drying
	Metahalloysite	) Fersiallitic soils		Tubular	Low	Low	Moderate->High	
	Kaolinites	) Ferruginous soils	↓ Tropical	Large, platy	Moderate	Low	Moderate	
Oxides/ Hydroxides	Iron Oxides (e.g. Goethite) Aluminium Hydroxides (e.g. Gibbsite)	Ferrallitic soils	Wet tropical	Cement	Varies	Varies	High	Indurates on drying

movement and removal of soluble weathering products from soil horizons. Downward leaching occurs in humid environments, upward in drier areas subject to fairly continuous surface evaporation.

Pedogenesis: Soil formation.

Plinthite: Laterite material containing hydrated oxides of iron and aluminium but no or only slight evidence of concretionary development. Soft when dug moist, it hardens irreversibly on exposure and desiccation.

Regolith: The superficial mantle of loose incoherent rock material formed by the sum total of physical and chemical weathering processes and of deposition by water, wind and ice.

Residual soil: The soil accumulates in situ by decomposition of rock and leaching of soluble constituents, leaving insoluble materials which are not transported any significant distance.

Saprolite: Thoroughly decomposed rock, a clay rich soil formed in place by chemical weathering of igneous or metamorphic rocks; features of original rock structure (e.g. phenocrysts) are often preserved by differences of colour or mineralogy in the clay.

Silica-sesquioxide ratio: The ratio of silica (SiO_2) to sesquioxides Al_2O_3 and Fe_2O_3 present in the soil. Often used as a crude index of the state of the weathering.

Smectite: Soil clay mineral group containing montmorillonite and other 2:1 minerals composed of aluminosilicate layers with hydroxyl ions between the layers, which consequently expand and contract as the soil wets and dries.

Soil fabric: The three-dimensional arrangement of solid particles and voids in a soil, which is either inherited from the parent material or imposed by pedogenic processes.

Soil texture: A property determined by particle shape and size distribution which determines the feel of a moist sample remoulded between finger and thumb.

Weathering: The processes of physical breakdown and chemical alteration of rock material in response to contact with air, water and organisms.

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