6. RED AND LATERITIC SOILS : WORLD SCENARIO

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ABSTRACT

Calcareous, neutral and acid red soils, red lateritic soils, latosols and lateritic soils *sensu lato* are defined on the basis of their mineralogical composition and profile development. Their geographical distribution is discussed. Their origin is interpreted, considering successively palaeoclimates and continental drifts, tectonic movements and land-form development since the Early Tertiary period and the soil transformations during the Quaternary period. Finally, it is shown that in the tropics there are specific continental soil geographic distribution patterns which are controlled by parent material, land-form, and past and present climates.

INTRODUCTION

Many soils within the tropics or in tropical, subtropical, equatorial and Mediterranean climatic zones contain significant amounts of clay minerals—dominantly kaolinite—and they are frequently characterized by moderate to high amounts of 'free' iron oxides. These oxides which include hydroxides and hydrous oxides, either occur in the form of amorphous gels, discrete particles as coatings on sand grains and on peds, or form part of the soil matrix as microaggregates, cemented aggregates of a few centimetres in diameter, or cemented continuous soil layers. Such mineralogical composition has a wide effect on soil properties. Many of these soils have a red colour. They are obviously subject to variations in other soil-forming factors, such as topography, vegetation, parent material and rainfall.

The oxides do not form in arid zones though they may be present there; if they do occur, they are remnants from older climatic conditions. In wetter areas and if there is good drainage, aluminium oxides occur. The group of soils referred to as Red and Lateritic soils generally comprises various tropical soils with soil-forming processes controlled mainly by Fe, Al, Si geochemistry. These processes must involve both fersiallitic and ferrallitization (Robinson, 1949; Aubert and Duchaufour, 1956).

This paper will be concerned mainly with origins and causes of the distribution pattern of the Red and Lateritic soils within the tropics. It will deal with various processes involved in their formation; consequently, it will tentatively give an understanding of the factors controlling their general distribution. Soils of large areas of deserts and mountain ranges in the tropics will not be discussed here, since in the desert, soil-forming processes are different and, due to erosion, soil development in the mountains is very slow.

Sources for soil map information were several published small-scale soil-maps and general papers (FAO, 1974; McFarlane, 1976; Camargo, 1981; Eschenbrenner *et al.*, 1984; Cochrane, 1986; Tavernier and Sys, 1986; Volkoff, 1986; Zhao and Shi, 1986; Bourgeon, 1992).

RED AND LATERITIC SOILS: FORMATION AND GEOGRAPHICAL DISTRIBUTION

Mineralogy and Geochemistry of the Soil Materials

The mineralogical composition of the soil clay fraction results from chemical weathering processes, the direction and intensity of which depend on the bioclimatic environment.

General Weathering Processes

The chemical weathering of rocks takes place by hydrolysis in a neutral or slightly acid environment, when water is charged with carbon dioxide, or through acidolysis in more strongly acid environment, due to organic acids.

Some elements are partially or totally released from the parent rock and solubilized. The released elements may remain independent (as calcium carbonate or ferric hydrates) or recombine to produce specific new minerals (clays) which will constitute the major part of the soil plasma. Both unweathered and unweatherable primary minerals form the skeleton grains.

In tropical humid climates strong hydrolysis leads to the rapid destruction of all the weatherable minerals and a massive neogenesis of clays and ferric hydrates. Different minerals can be formed depending on the degree of hydrolysis: gibbsite (allitization) in strongly leached environment, 1/1 clay (monosiallitization) when silicon and aluminium are recombined in the form of kaolinite in moderately leached environment, and 2/1 clay (bisiallitization) when smectites as beidellite and nontronite are neoformed in less leached environment (Pedro, 1989). Smectite lattices will integrate part of the iron released from primary minerals whereas very little or no iron will be included in gibbsite or kaolinite crystals. In these latter cases, the totality of the iron released separates in the form of 'free' oxyhydroxides.

When the hydrolysis is less aggressive, either because the climate although humid is colder or because it is hot but dry, weathering is of partial type (Pedro, 1989). Only the more weatherable minerals are hydrolyzed and many primary minerals remain unweathered. There is a discrete individualization of secondary clays, and the soil clay plasma is essentially composed of phyllites that are inherited from the 'parent rock' and subsequently transformed to minerals like illite and vermiculite. The neoformations involve mainly either calcium carbonates and ferric hydrates in neutral or slightly acid environment, or aluminium hydrates in strongly acid environment where organic acidity is present.

The Ferrallitic and Fersiallitic Systems (Table 6.1)

The paragenesis of kaolinite and Fe-oxide might be opposed to that of smectite and Fe-oxide when the weathering is total and when all the weatherable minerals are hydrolysed. A "ferrallitic system" and a "fersiallitic system" should then be characterized by kaolinite and smectite, respectively. Actually, intermediate situations exist, in which kaolinite and smectite will identify the fersiallitic system that is, in this case, the fersiallitic system *sensu lato*.

When the weathering is partial the presence of inherited 2/1 phyllites involves only an "apparent bisiallitization" (Paquet, 1970) even though smectite is absent.

Moreover, by addition of an aluminium layer, inherited 2/1 phyllites may transform into 2/1/1 minerals with an average Si/Al ratio of 1/1, which is identical to that of the phyllites of the kaolinite type. The weathering process then appears to be of the ferallitic type because of this "apparent monosiallitization" but it nevertheless belongs to the fersiallitic type.

Ferrallitic Weathering and Ferrallitic Materials

All the minerals are hydrolysed. There is a massive neoformation of kaolinite. Kaolinite is associated with gibbsite when the desilication is strong.

Some differentiations in the materials should be related to the size of kaolinite crystals and to the degree of hydration (kaolinite/halloysite differentiation).

Under wet tropical climate, with alternate dry and wet seasons, and when the weathering is total, the neoformed clays consist of smectites which are "low-charged" clays with layer negative charge (designated as X) < 0.5. The negative charge is balanced by the overall positive charge of the interlayer cations of which Ca^{2+} is dominant.

Under drier and cooler tropical climates, when weathering is not complete, the inherited 2/1 phyllites are "high-charged" 2/1 clays with $0.5 > X > 0.9$ (Pedro, 1993). The differentiations occur according to the nature of the interlayer cations and the accumulation of non-silicate minerals, for example $CaCO_3$. As we move to the driest environment, the interlayer cations of the 2/1 phyllites will be gradually dominated by K^+, Ca^{2+}, Mg^{2+} and Na^+, and will be progressively associated with increasing amounts of $CaCO_3$. Under wetter and colder climate, partial acidolysis of inherited and transformed micas leads to a redistribution of aluminium and individualization of aluminium-interlayered clays (Al-vermiculite or AlOH-2/1 clay).

The Soil Materials

On these principles the following soil materials can be defined (Table 6.1)

a) vertic materials with low charged clays (smectites) resulting from total hydrolysis and bisiallitization;

b) neutral and calcic fersiallitic materials resulting from a partial weathering where K-containing high-charged 2/1 clays (mainly illite) are associated with kaolinite or with low-charge clays (smectite); interstratified illite-smectite and kaolinite-smectite may occur;

c) acid fersiallitic materials resulting from partial weathering in which kaolinite or kaolinite and gibbsite are associated with high-charged 2/1 clay, illite and AlOH vermiculite;

d) kaolinitic material resulting from total hydrolysis and monosiallitization; and

e) oxidic materials with gibbsite resulting from total hydrolysis and allitization.

In the vertic materials, the iron released from parent rock minerals is included in the clay mineral structure. In the fersiallitic materials, the major part of the iron is accumulated as 'free' iron oxide. These latter materials may be regarded as "red fersiallitic" materials, kaolinitic and oxidic materials being considered as lateritic materials.

Geographical Distribution

Kaolinitic materials are widespread in all the humid areas between the tropics; they are found under both Wet Equatorial climates and Tropical Wet-Dry climates. They develop from granite, gneiss, schist, sandstone, shale, limestone and sandy-clay or clayey unconsolidated sediments. Oxidic materials are associated with kaolinitic materials and are differentiated according to the parent rock composition, occurring mainly on mafic rocks.

The phyllosilicates occur all over intertropical and subtropical zones. Materials with smectite are basically found under wet-dry to semi-arid tropical climate and under Mediterranean climate, where they develop from crystalline and sedimentary rocks. Acid fersiallitic materials are found under wet subtropical and under wet tropical climates. The former types are mainly determined by the nature of the parent material that may be shale or soft micaceous-clay sediment; the latter types may form over a wide range of parent rocks.

However, the climatic zonation is never clearly followed; kaolinitic materials are found not only in wet areas but also in semi-arid and arid zones as it occurs in South America, in Africa, in India and in Australia; smectite-rich materials are always restricted to relatively dry climates; acid fersiallitic materials are found under a wide range of wet climates in some tropical sites, they cannot be clearly differentiated from kaolinitic materials.

Nature of Pedological Fabrics

Great soil units can be defined using morphological features which result from the way the soil components are linked in the soil after the pedoplasmation of the materials resulting from the weathering (Pedro, 1989). The macroscopic expression of the linkage is the soil structure. Subsequent properties of these associations control the vertical differentiation of the soil profiles.

The main distribution features within tropical soils are related to the degree of the structuration and the kind of the structure present in the B horizon, and to horizon development through textural contrast in the profile.

Table 6.1. Weathering processes and mineralogy of the soil materials

	Ferrallitic system		Fersiallitic system s.l.		
Weathering process	Typical total hydrolysis weathering		Intermediate partial weathering		Typical total hydrolysis weathering
	Allitization	Monosiallitization	Apparent monosiallitization	Apparent bisiallitization	Bisiallitization
Specific minerals	Gibbsite	1/1 clay (kaolinite)	High charged 2/1 clay (usually interstratified clays)		Low charge 2/1 clay (non-tronite, beidellite)
	Al hydrate and Fe hydrates	H and Al (1/clay) and Fe hydrates	AlOH 2/1 clay)	K (2/1 clay)	Ca (2/1 Al-Fe clay)
Material type	oxidic	kaolinitic	acid fersiallitic	neutral fersiallitic	vertic

Major Pedological Features

The texture may be uniform throughout the profile, or the clay content may increase with depth. The structure of the B horizon ranges from massive to strongly structured with polyhedral units.

In many soils, the clay content in the soil profile increases with depth. It is generally assumed that this is the result of the vertical translocation of the fine particles through the profile during the wet season. The topsoil has a sandy or loamy texture and a fine granular to subangular blocky structure. The lower horizons, i.e., the B horizons, are more strongly structured with polyhedral peds that have smooth shiny faces. This B horizon will be defined as an argillic B horizon.

However, one of the most usual features may be described as a moderately deep to deep profile with a uniform sandy clay texture; the structure is well-developed with medium to fine angular polyhedral peds which have smooth and earthy faces and low coherence when moist; the peds are clearly more friable than in the soils described above.

Another major type consists of a deep profile with a uniform sandy clay to clay texture and a massive to incomplete subangular blocky structure in the B horizons. Although massive, these B horizons are porous and have an earthy fabric; when moist they easily break into fine granular fragments (like pseudosand). This is the oxic horizon (Soil Survey Staff, 1975) that is a specific feature of tropical soils.

Transitional types between these three most typical features are often found.

Major Soil Differentiations

On the bases defined above, several pedological types can be defined (Table 6.2):

1) Vertisols: smectitic or vertic materials; the texture is uniform and the structure is well-developed.

2) Neutral and calcareous fersiallitic soils: mixed high-charge and low-charge 2/1 clay materials; clay-illuviated B horizon (Chromic Luvisols; Alfisols)

3) Acid fersiallitic soils: high-charge 2/1 clay but without low-charge 2/1 clay materials; clay-illuviated B horizon (Orthic Acrisols; Ultisols)

4) Ferrallitic soils without oxic horizon: kaolinitic materials, uniform texture and structured B horizon (Ferrallic Cambisols, Nitosols; Kandisols)

5) Ferrallitic soils with oxic horizon: kaolinitic and oxidic materials; with uniform texture and massive B horizon (Ferralsols; Oxisols)

6) Neutral, texture-contrasted kaolinitic soils: kaolinitic materials but small amount of inherited 2/1 phyllites (like illite) can be found; clay-illuviated weakly structured B horizon (Ferric Luvisols; Ultisols).

7) Acid, texture-contrasted kaolinitic soils: kaolinitic materials but small amount of inherited 2/1 phillites (as Al-vermiculite) can be found; clay-illuviated, weakly structured B horizon (Ferric Acrisols; Ultisols).

Of the above soils, only the fersiallitic and ferrallitic soils will be discussed, leaving out Vertisols that have low chroma and very low 'free' iron oxide content and cannot be considered as 'red soils.'

Table 6.2 Main soil types and their equivalents

Soil types	Equivalent names in:		
French System	Common	FAO Legend	U.S. System
Vertisols	Vertisol	Vertisol	Vertisol
Fersiallitic soils	Neutral and calcic Red soil	Chromic Luvisol	Alfisol
Neutral and calcic Acid	Acid Red soil	Orthic Acrisol	Ultisol
Ferrallitic soils (soil with texture-uniform profile) without oxic horizon	Lateritic Red soil	Ferrallic Cambisol, Nitosol	Kandisol
With oxic horizon	Latosol	Ferralsol	Oxisol
Transition Ferrallitic/Fersiallitic	Lateritic soil	Ferric Luvisol	Ultisol
Neutral kaolinitic soil with texture-contrasted profile	Acid Red soil	Ferric Acrisol	Ultisol
Acid kaolinitic soil with texture-contrasted profile			

NEUTRAL AND CALCAREOUS FERSIALLITIC SOILS (NEUTRAL AND CALCIC RED SOILS)

Neutral and calcareous fersiallitic soils are composed of 2/1 phyllites (as illite) associated with variable amounts of smectites. The cation exchange capacity of this material is always relatively high (> 24 cmol (+) kg^{-1} clay). These soils are shallow to moderately deep, brown to red in colour. There is a marked increase in the clay content from the surface to the B horizon. However, the upper horizon is never strongly leached. Its texture remains sandy loam to sandy clay loam. The B horizon has an angular blocky structure. Clay coatings are usually found on faces of peds; consistence is firm to hard when dry.

The pH values range from 6 to 7. They may be over 7.5 in the subsoil if it is calcareous. The base saturation is 50 per cent or more. Exchangeable bases are dominated by Ca.

The total amount of free iron oxides is usually small.

Acid Fersiallitic Soils and Acid, Texture-contrasted, Kaolinitic Soils (Acid Red Soils)

Both soils are identified by an acid reaction (they are often strongly acid in their upper part) and a red or yellow, clay-illuviated B horizon. They may contain a considerable proportion of 2:1 phyllites in the form of illite that may be associated with vermiculite; the illite: vermiculite ratio generally decreases in the upper part of the profile. Both illite and vermiculite are partially or entirely transformed to Al-vermiculite.

However, because most of acid fersiallitic soils have their mineralogical composition typically dominated by kaolinite, and because they gradually evolve towards the acid, texture-contrasted, kaolinitic soils, the acid fersiallitic soils cannot be easily differentiated from the latter and they will be considered together.

This soil category has a moderately deep to deep profile. The A/B boundary is usually clear and there is often some yellowish mottling in the lower part of the B horizon in the deeper profiles. The A horizons are generally loamy, with a weak blocky structure. The B horizon is clay loam to clayey. Its structure is moderate, medium to fine blocky. The consistence is friable to firm when moist and the soil usually sets hard on drying. Clay coatings are not frequent.

The major analytical data of these soils may be related to those of the Ultisols which have been extensively described (Buol and Sanchez, 1986). The pH values are approximately 5.5 or less. The cation exchange capacity is low (< 24 cmol(+) kg^{-1}). The base saturation is less than 50 per cent. Acidic cations (hydrogen and aluminium) are dominant.

The total amount of free iron oxides may be relatively high.

Ferrallitic soils without oxic horizon (or Lateritic Red soils)

Even though some of these ferrallitic soils are shallow, most profiles are moderately deep to deep, underlain by a slightly soft and mottled, light grey, yellow and red saprolite. Horizons are poorly developed. They are uniformly red or less commonly red brown or red yellow in colour and have a uniform texture throughout the profile.

These soils are chiefly characterized by their structure profile. The upper part is weakly structured with medium to fine subangular polyhedral peds. The B horizon has a strong structure with shiny-faced polyhedral units up to 1 cm in diameter which progressively break into smaller units with earthy faced peds which have low coherence when moist.

The clay mineralogy is dominated by kaolinite (occasionally with some halloysite in the subsoil). They normally contain both haematite and goethite gibbsite is present in some soils.

The texture ranges from sandy clay loam to heavy clay. The soil pH ranges from neutral to acid. The exchange capacity is low (< 24 cmol (+) kg^{-1}). The base saturation is less than 50 per cent, and exchangeable calcium and potassium contents are very low in both surface soils and subsoils.

Ferrallitic soils with oxic horizon (or Latosols)

Latosols are usually deep or very deep, with a uniform profile which gradually evolves downwards into a soft saprolite, with its characteristic light grey, yellow and red mottling. Their properties are determined mainly by the parent rock and the rainfall. There are major variations in the soil colour which ranges from dusky red to red-yellow and pale yellow. There are also significant changes in the oxic B horizon thickness which may range from 1 to 3 m.

The characteristics of these soils have been thoroughly described by Eswaran *et al.* (1986).

Although kaolinite is the only clay mineral found, latosol mineralogy varies considerably because significant amounts of iron and aluminium oxides may be present. Generally both haematite and goethite are found, and gibbsite is occasionally present. Haematite is normally absent in the yellow latosols, as is goethite in some dark red latosols.

Many latosols contain ironstone nodules, which form an iron gravel layer at a depth that varies in the profile. This layer may be very thin or 2 to 3 m thick. In a few soils, a massive iron duricrust is observed.

The texture ranges from sandy clay loam to heavy clay.

Most of these soils are moderately to strongly acid. The exchange capacity is usually low (< 15 cmol (+) kg^{-1} clay). They are extremely low in base status at depth and are normally strongly unsaturated, exchangeable calcium and potassium contents being very low in both surface soils and subsoils.

NEUTRAL, TEXTURE-CONTRASTED KAOLINITIC SOILS (OR LATERITIC SOILS)

These soils vary in total depth of the profile, in thickness of the individual horizons, and in texture of the A and B horizons.

They range from moderately deep to deep (1 to 3 m) and in the latter case, often have an extended B3 horizon which is coarsely mottled red, light grey and yellow brown. This mottled horizon grades downward into a soft saprolite composed of kaolinite, iron oxides, and some inherited micaceous clays (like illite) in partially preserved rock structures.

The deep subsoils are generally mottled and often have impeded or slow internal drainage. The A horizons range from grey to brown, and from sand to loam; they have a weak crumb structure. The A/B boundary is usually gradual. This transition portion of the profile is massive, pale yellow to ochreous, and grades into a clay-loam to clay, red-yellow B horizon. The structure of the B horizon is weak to moderate, medium to fine blocky, and its consistence is commonly firm even when moist. The upper part of the B horizon are often mottled with light yellow. This mottling usually reflects slow drainage and a seasonal saturation of the upper part of the profile.

Typically, the underlying horizon has a reticulate pale, red and ochreous mottling. Many of the red mottles are incipient ironstone nodules. Usually, this horizon must be regarded as a "plinthite." It is sandy clay or clayey with a weak to moderate, medium to coarse blocky structure. Clay coatings are more easily identified in pores than on the faces of peds.

One of the main distinctive features of these soils is the iron oxide concentrations in the form of nodules or concretions and hard crusted layers. Normally, ironstone nodules are present above or within the mottled clay. Plinthite may harden to a vesicular iron duricrust.

The clay fraction of the soil is strongly kaolinitie, with goethite and haematite; small amounts of illite may be found in the lower part of the profile. The ironstone nodules, concretions and duricrusts are mainly composed of goethite, or both goethite and haematite with varying amounts of quartz and kaolinite.

The soil reaction is usually neutral to moderately acid on the surface, and mildly to moderately acid at depth. Cation exchange capacities are usually low (< 15 cmol (+) kg^{-1} clay); exchangeable calcium and potassium contents are very low in both surface soil and subsoil.

Geographical Distribution of the soil types

NEUTRAL AND CALCAREOUS FERSIALLITIC SOILS

Neutral and calcareous fersiallitic soils occur throughout areas of dry tropical climate on all the continents. The larger areas are found around the Mediterranean sea and in the southwestern part of North America (Fig. 6.1). They are mainly red but they turn predominantly brown in the mid-latitude areas.

ACID FERSIALLITIC SOILS (AND ACID TEXTURE-CONTRASTED KAOLINITIC SOILS)

Acid fersiallitic soils are preponderant in subtropical areas with fairly humid climate in South China, in the Southeast of USA and in the Southeast of South America. They also occur intermittently in the intertropical areas in the East and on the footslopes of the Andes in Argentina, Bolivia, and Peru. They occur on flat or gently sloping situations or on gently sloping or on moderate or steep slopes.

FERRALLITIC SOILS WITHOUT OXIC HORIZON (RED LATERITE SOILS) AND FERRALLITIC SOILS WITH OXIC HORIZON (LATOSOLS)

Ferrallitic soils without oxic horizon are found all over the wet equatorial zones where rainfall is fairly uniformly distributed throughout the year and where the natural vegetation is evergreen tropical rain forest. Ferrallitic soils with oxic horizon are not restricted to this climatic zone; they are more largely distributed throughout both wet tropical climates under rain forest, and wet dry to dry tropical climates, under savannah and sclerophyllic shrubs.

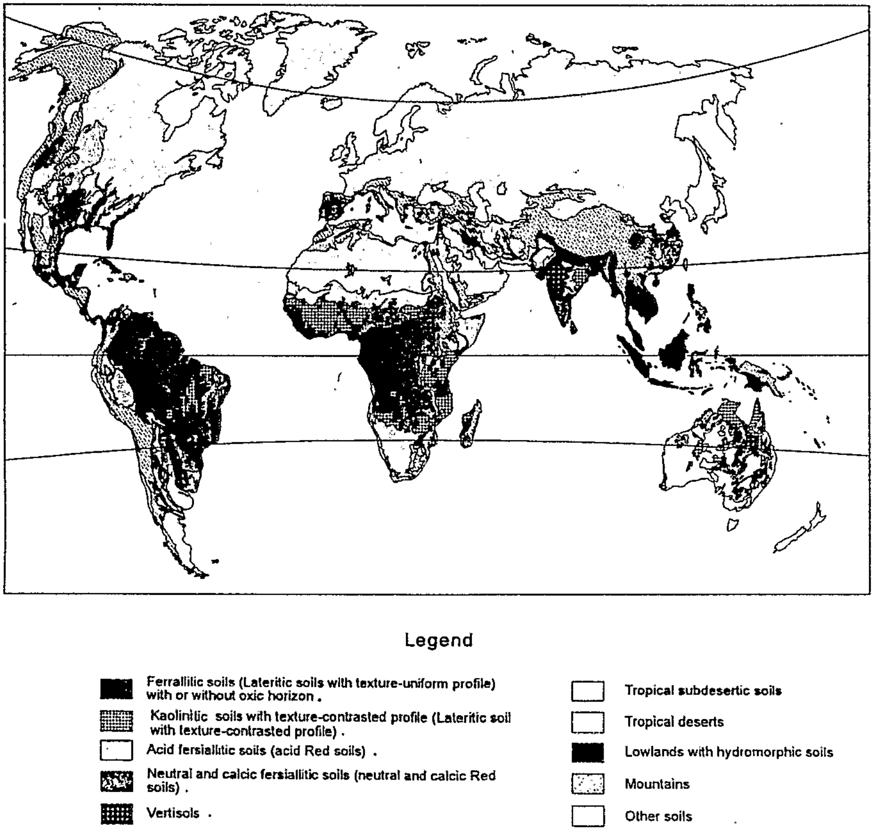

Fig. 6.1. World Soil map showing distribution of the major soil types in tropical and subtropical zones

Ferrallitic soils without oxic horizon are widespread in wet equatorial parts of South America, Africa, Southeast Asia and the Pacific. In India and Australia, they occur sparsely in the higher rainfall areas. They are mainly found in mountainous and undulating landscapes, often with convex slopes, where they alternate with ferrallitic soils with oxic horizon (Latosols), which are often found on flat or gently undulating situations.

Latosols are common in Central Africa and Central America and widespread in South America where they occupy large areas under moderate to low rainfall, in addition to the tropical rain forest. They are mainly observed on flat or moderately sloping topography.

NEUTRAL TEXTURED-CONTRASTED KAOLINITIC SOILS (KAOLINITIC SOILS WITH CLAY-ILLUVIAL B HORIZON)

These soils have a widespread distribution in the tropics, but occur mainly in Africa. They are almost exclusively confined to areas of relatively high rainfall (1000 to 1500 mm annually) where a wet season alternates with a dry season, and where they support a typical savannah (as in South America or in Africa). Nevertheless, these soils are also found in the semiarid (as in India) or the arid (as in Australia) areas.

This kind of soil develops on flat or gently undulating plateaus or on lowlying lands. The landscape is characterized by extensive gentle concave slopes extended below scarps fringing tabular plateaus where an iron duricrust is frequently exposed.

INTERPRETATION

Soil formation is a very slow process requiring thousands and even millions of years to develop a mature profile. Many tropical soils have evolved over a long period of time; most of them started their development during the past million years. Over one million years may be required for the formation of a 1 m thick kaolinitic saprolite. For that reason, the very thick saprolites (several tens of metres) are found only on very old land surfaces which have been exposed to weathering for extended periods of time. However, the age of the surface may be different from that of the weathered material and from that of the soil itself which may be significantly younger.

The environmental factors which determine the nature of the soil may have remained relatively constant over a long period of time—the continuing soil development having led to progressive changes in the soils and to the formation of specific features within them, such as an iron accumulation in the form of a thick massive duricrust—but it is evident that most areas experienced a succession of different climates which induced changes in soil genesis. Consequently, studies of soil development and of its changes in time must consider the climatic and tectonic events that took place in the Tertiary and Quaternary Periods.

a-Palaeoclimate and continental drift

It is assumed that the general world has changed many times in the past and that it was warmer than the present climate during a major part of the Tertiary period (Frakes, 1979). The latitudinal drifts of the continents which followed the fracturing of

Gondwanaland are also responsible for important climatic changes at a continental scale. The warm conditions were maintained in tropical and subtropical areas throughout most of the Tertiary period. However, all continents were not subject to exactly the same climatic effect.

At the time of the super-continent Gondwana, which was composed of South America, Africa, Madagascar, India, Australia and Antarctica, the Equator crossed through Africa from Mauritania to Egypt and northern South America. Also, at that time, India and Australia, together with Antarctica, were located in middle and low latitudes, south of the Tropic of Capricorn. Both the temperature gradients from the equator to the poles and the oceanic and atmospheric circulation patterns were quite different from the present ones.

Following the disruption of Gondwana land the position of the continents changed during the Tertiary period subjecting them to a series of climatic changes. Gondwanaland had begun to disintegrate in the Cretaceous, after a fracturing period during the Jurassic. South America had started moving away from the eastern part of Africa which moved to the North. Meanwhile, Australia first moved to the East together with Antarctica, and subsequently moved to the North, away from Antarctica. Similarly, India, Which had lain between western Australia and Africa for a hundred million years also became separated and moved northwards, at a greater rate than Australia (Veevers *et al.*, 1971; Parrish *et al.*, 1982; Beckmann, 1983a and 1983b)

From the Cretaceous to the end of the Tertiary, all continents, except Antarctica, moved through a series of climatic changes and were subjected to long periods of a continuously wet and warm climate favourable to ferrallitization, and of a wet climate but with a distinct dry season propitious for the formation of hard massive lateritic duricrusts (Kumar, 1986; Tardy *et al.*, 1991). But geographical differentiations at the regional scale exist because of the differences in their history; some continents have indeed been more exposed than others.

At the end of Tertiary, the overall temperature became cooler and closer to the modern values. The most important feature of the Quaternary was the recurring changes of climate associated with generally cooler conditions and intermittent warmer intervals.

In the mid-latitudes, particularly in the northern hemisphere, glaciations together with their associated periglacial conditions effectively removed most of the deep soils and the weathered rocks that had formed during the Tertiary period. However, in the tropical areas, the extensive, thick, kaolinitic soil covers which had developed in the wet and warm periods during the Tertiary and the Quaternary were maintained; they are seen in vast regions of America, Africa, India and Australia. They also occur elsewhere, as in equatorial areas of both South America and Africa, where prevailing environmental conditions remained constant over all this geological period and where the range of weathering situations would have persisted. But they may also occur in many presently arid areas in Central America, South America, Africa, India or Australia, where they are assumed to have formed under more humid conditions and are now fossilized by a change to drier climatic conditions.

Tectonic movements and landform development

Polycyclic landscapes are another characteristic of the intertropical areas. Over geologic time, erosion periods have alternated with long periods of tectonic stability. Successive uplifts produced distinct surfaces during the Mesozoic and Tertiary.

After the Jurassic period, orogenic activities were restricted to the East, South, Central and North America, to the Mediterranean zone and to Southeastern Asia, with intense folding, uplifts and formation of mountain ranges. In other parts of the globe, tectonic movements consisted mainly of gentle epeirogenic uplift movements.

During the early Tertiary, most of the shield areas were tectonically stable for tens of millions of years. All the tectonic movements were vertical, with some broad warping and some local faulting. Warm and moist to wet conditions prevailed almost continuously. Under these conditions exposed rocks were extensively weathered. When subjected to uplifts and renewed denudation, the new surfaces exposed were similarly weathered.

It appears that, from the Cretaceous to the end of the Oligocene and into the Miocene, a long process of reduction proceeded over most of the continent to produce a generalized surface which developed in South America, Africa, India and Australia (King, 1968). This main surface dates from the mid-Tertiary period, but one or two pre-Tertiary surfaces have been recognized from the early part of the Tertiary or even the Cretaceous.

The uplift in the late Tertiary and Quaternary resulted in the rejuvenation of drainage and in the formation of new surfaces. The main mid-Tertiary surface was reduced, and a succession of younger erosional and depositional surfaces were developed below it. These surfaces were further dismembered by erosion during periods of low sea level.

Cooling started in the late Tertiary and continued during the Pleistocene. The expansion and contraction of the continental ice sheets in the northern and southern hemispheres controlled a series of eustatic rises and falls of the sea level during the Quaternary. During periods of low sea level, the continental shelf was exposed to a maximum depth of more than 100 m below today's level. Lowered sea levels induced valley cutting. The effects of all the sea level changes were superimposed on those of tectonic events, not only in the coastal areas, but also inland.

A series of distinct, stepped erosion surfaces developed as a result of intermittent uplifts throughout the entire Tertiary and the early Quaternary periods in all the continents. Two major surfaces can be recognized; a Tertiary surface and an early Quaternary surface (Fig. 6.2). Their height ranges from the present sea level to 1000 m. They are at various stages of dissection. In many of them, weathering situations may have disappeared with further dissection and only remnants of older weathered materials left.

Some soils were left as relicts or were slightly modified. New soils may have formed in the lower layers of former weathered materials exposed during the erosion cycles. Modern soils have formed on more dissected slopes in unweathered parent materials. The influence of underlying rocks on soil development became evident as earlier surfaces were reduced.

Some soils have therefore existed for exceedingly long periods of time, whereas others are as young as any on younger slopes. The soil cover of the younger surface depends on both the amounts of dissection and stripping of former weathered materials,

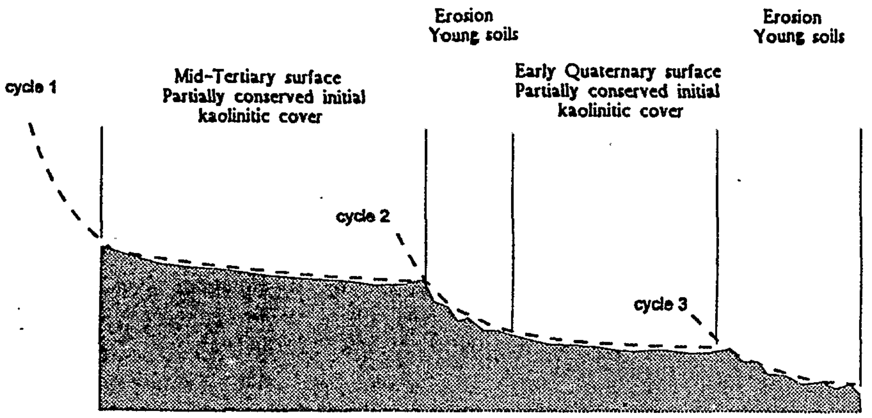

Fig. 6.2. Polycyclic landscape: generalized soil-geomorphic pattern on continental shields

and on the local climate which prevailed later. Young soils are directly determined by today's local climate. Most of them are monogenetic soils, ferrallitic or fersiallitic soils.

Soil transformations

Soils associated with Tertiary surfaces have a deeply weathered profile the main feature of which is the thick kaolinitic saprolite formed during wet palaeoclimate and during long stable tectonic periods. The soils which occur on these surfaces may be very old. The materials have been exposed on land surfaces through the several climatic changes of the Quaternary. Most of the soils are polygenetic soils and the diversity of their properties may have been inherited from the Tertiary and Pleistocene periods.

In South America and Africa, the old weathered mantle has been extensively preserved. In Australia, only relatively small remnants can be seen, the old mantle appears to have been stripped down to scattered pockets of saprolite or a few occurrences of kaolinitic materials. In most of the regions of India, the old weathered mantle has been widely removed, and exposures of fresh rock are frequent.

In Africa the deep weathered mantle is dominated by a massive iron duricrust, and is found in broad regional divides.

In western tropical Africa, extensive stripping of the mantle in the watersheds has resulted in a complex scattering of small plateaus and residuals, separated by extensive pediments (Michel, 1973). This is considered to be the result of natural erosion accompanying landscape development in response to changes in local base level and climate during the Quaternary.

The first development consisted in the removal of the upper soil horizon by erosion and in the exposure of the ferruginous duricrust. The massive duricrusts are exposed on the plateaus, the upper slopes and the crests, while the weathering products of the duricrusts have been transported downslope. On the surface of the slope there is a loamy material; below it is a very characteristic horizon containing abundant fragments of ironstone and quartz gravel. This horizon is formed by both differential erosion of the pediment surface—the final material being moved downslope—the addition of laterite fragments broken from the escarpment to the surface. Such evolution is attributed to local base-level lowering as well as to climatic changes affecting the vegetative cover and the internal soil drainage. The mottled clay which ordinarily underlies the duricrust is regarded as forming a poorly drained horizon that is saturated with water for part of the year and where the kaolinitic clay may be easily released and transported downwards by the draining water. In more severe dry seasons, the initially vertical drainage will become lateral causing kaolinitic clay transport and leaching downslope, and to a greater accumulation of water downslope. In drier climate, the lateral water circulation will concentrate more elements that will modify weathering environment at the bottom of the slope where vertic material may occur (Boulet, 1978).

The soil sequence observed in northern Togo (Western Africa) indicate (Fig. 6.3) that, in the upper part of the slope, there is a sharp boundary with the underlying material which may be a red oxic horizon or more often a mottled clay. Further down the slope, the red yellow fine material accumulates at the surface to form texture-contrasted clayey kaolinitic soils; finally, at the bottom of the slope, there are yellowish-grey soils formed in clayey light yellow to grey micaceous weathered material, at first of the fersiallitic type, then of the vertic type (Faure and Volkoff, 1989).

Quite identical sequences may occur under wet to dry tropical climates in southeastern South America, where Latosols, formed on the early Quaternary surface (Volkoff, 1982) grade downslope to Planosols, which consist of several tens of centimetres thick, sandy surface horizons overlying vertic materials (Soubiès and Chauvel, 1984).

The soil pattern along the slope, i.e., the relative proportion of each soil type, depends on both the nature of the pre-existing lateritic material—oxic material, massive iron duricrust with or without mottled clay—and the environmental conditions (local topography and local climate).

In Central Africa, rejuvenation of drainage in upper catchments has resulted in extensive, gently undulating plains in the form of wide convex hill belts, dominated by ferrallitic soils where Latosols is the prevailing type (Tavernier and Sys, 1986). The

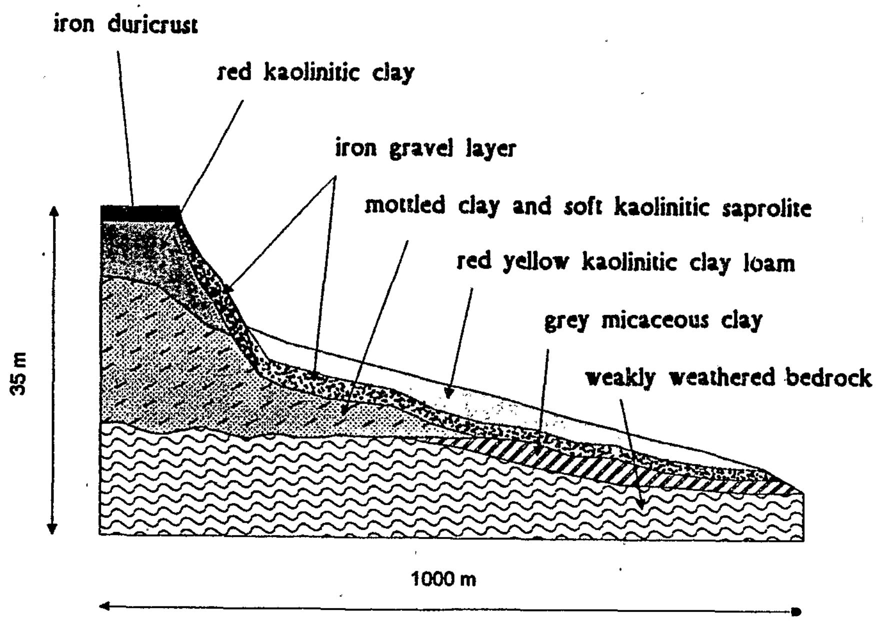

Fig. 6.3. Transect in West Africa (North Togo)

Latosols have developed on exposed lateritic material of the Tertiary surfaces (Segalen, 1967). Such evolution is usually attributed to a change of climate from alternately wet and dry seasons to uniformly wet. As observed in the north fringes of the Central African rain forest (Beauvais and Tardy, 1991), the duricrust may have been entirely crumbled by weathering and substituted by oxic material mixed with iron nodules (Fig. 6.4) which are inherited from the former duricrust (Bitom and Volkoff, 1993). Southwards, under wetter conditions in southern Cameroon (Fig. 6.5), only remnants of the former massive iron duricrust are left, in the form of blocks or as iron gravel underlying a continuous and thick oxic material (Martin and Volkoff, 1990; Bilong *et al.*, 1992). Iron gravel may form a 2–3 m thick layer.

The same evolution, transforming a hard iron duricrust into oxic material, may have also taken place in south America, particularly in the southeastern part of the Amazonian forest (Nahon *et al.*, 1989). But iron gravel layers are not exclusively found in Amazonian soils. They are widespread in many South American latosols, under much drier conditions than those of the Amazonian rain forest. The iron gravel layer lies

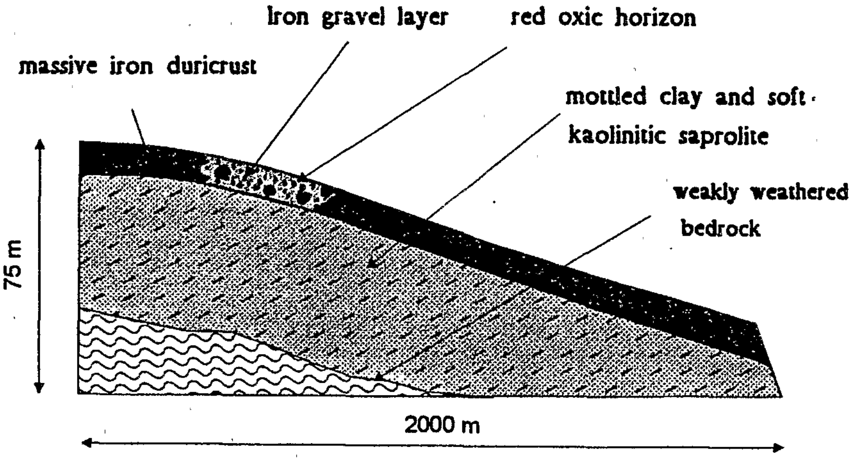

Fig. 6.4: Transect in Central Africa (Central African Republic)

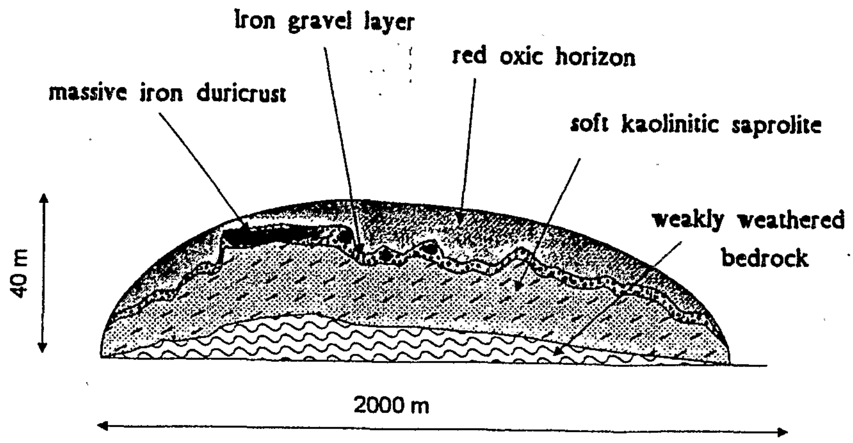

Fig. 6.5: Transect in Central Africa (South Cameroon)

above a thick and soft kaolinitic saprolite without mottled clay, and below a thick oxic horizon. It is normally thinner than in Africa. It can be assumed that the majority of these South American latosols developed under wetter climate, by means of similar processes, and that they are at present fossilized, due to the constancy of the drainage conditions.

CONCLUSIONS

Although parent materials, topography, and climates are together regarded in the tropics as the factors controlling the soil formation, climate has a predominant effect on the continental scale since its two most important components, namely temperature and precipitation, clearly determine the differentiation of fersiallitic soils (calcareous red soils, acid red soils) and ferrallitic soils (lateritic red soils and some latosols).

Locally, one of the three factors may exert the strongest influence. On steep slopes, as in mountain ranges, soils are usually shallow and develop from the weakly-weathered underlying rock; parent material such as limestone, basic rocks or some clay sediments, often leads to the formation of soils which contrast with those formed in more common materials. This is true only in the cases in which soil formation has proceeded for a short time.

Many soils within the tropics have existed for exceedingly long periods of time. In the early Tertiary, large parts of South America, Africa, India and Australia were tectonically stable and they were deeply weathered during long periods of warm and wet climate. A thick ferrallitic material was then formed, masking the variability of the rocks and homogenizing the surface materials in such a way that the effects of the modern climate are detected with great difficulty.

There are also similarities in the main landscape features in the South American, African, Indian and Australian continents. Distinct plantation surfaces developed, ranging in age from the early Tertiary to the early Quaternary. Most were affected by ferrallitic weathering, and some were capped by thick iron duricrust. These materials have been exposed to several climatic changes during the Quaternary. They may have been stripped to varying degrees, and transformed or removed with further dissection especially during more arid conditions.

Therefore, a wide range of weathering situations can be identified, regardless of the present-day climatic conditions. Latosols, which occupy a large proportion of South America, are mainly associated with the mid-Tertiary surface; similar soils, with much thinner profiles, also occur extensively on the earlier surfaces. In western Africa, texture-contrasted kaolinitic soils (lateritic soils) occur predominantly with a small proportion of neutral fersiallitic soils, on the widespread early Quaternary surfaces, but the same soils may also occur on the remnants of older surfaces. Only relics of kaolinitic materials resulting from older ferrallitic weathering are left on the mid-Tertiary surface of India, where calcareous and neutral fersiallitic soils (neutral and calcareous red soils) predominate. It also appears that most of the acid fersiallitic soils (acid red soils) of the subtropical zones of both southeastern North America and southeastern China belong to a geomorphic level which can be related to the early Quaternary surface of the southern continents.

The transformation and the dismantling of the inherited kaolinitic cover is thus one of the main phenomena taking place within the tropics. The soils formed in the kaolinitic cover depend directly upon (i) the characteristics of the inherited kaolinitic cover, which are closely related to the age of the geomorphic surface and to its history; (ii) the regional drainage which determines the erosion and water flow through the landscape, and (iii) the present climate.

It becomes evident that, owing to a very distinct history, each continent is unique in terms of soil distribution pattern. This is the reason why the world-wide complexity of tropical soils will only be understood if analysed on a continental scale.

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VOLUME I

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