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The Weathering Profile above Crystalline Basement Rocks under Tropical Weathering Conditions and in the context of Hydrogeology.

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<u>Part I</u> Initial appraisal - the scope, scale, data sources and approach of the report.

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Part I

Initial appraisal

- the scope, scale, data sources and approach of the report.

Systematic study of tropical weathering is very strongly biased in favour of the often spectacular lateritic crusts, including bauxites. Papers published annually on these have reached three figure proportions and the subject is now unlikely ever to be comprehensively reviewed. Theories of formation abound and, without adequate (or sometimes any!) data about the deeper parts of the profile and the weathering progressions therein indicated, genetic theorisation is comparable to reading the last chapter of a ten chapter book and guessing what the first nine chapters were about. The paucity of data on the lower parts of these profiles is the inevitable result of the unfortunate fact that those concerned with their nature and genesis, academic geologists and geomorphologists, simply do not have the means of acquiring the data they need. They are mainly restricted to (a) natural profile exposures, almost invariably free-face exposures where indurated carapaces occur and (b) man-made exposures provided, most often, by mining companies who stop digging at a depth defined by profitability. The International Geological Correlation Programme, Project No. 129, Lateritisation Processes, stressed the importance of more clearly establishing the genesis of the economic laterites in order to use genetic criteria for exploration and to develop deposit modelling for ore body assessment. Sadly, exploration of these materials is and threatens to remain notoriously conservative, with a clear preference for drilling more frequent shallow holes in order to explore a deposit more carefully rather than drilling more deeply in the hope of establishing genetic criteria which might offer the possibility of reducing the number of shallow holes. Thus the prospects for improving our knowledge of the deeper parts of these profiles remain poor. This may appear of little concern to hydrogeologists since the economic deposits predominantly cap ancient elevated profiles, situated on plateaux or on smaller mesas which are entirely vadose in their hydrological regime. In fact these elevated profiles are very useful for establishing weathering relationships which are highly relevant to the low level weathering profiles, those of more concern to hydrogeologists. Under the more aggressive leaching conditions, which pertain in the high level profiles, weathering reationships and variables are in effect exaggerated. They are more clearly identifiable there, than in low level profiles where, in most cases, very similar relationships occur but at a more subdued and subtle level. These relationships would pass largely unnoticed in the low level profiles not only because they are less pronounced, but because data on these profiles are, if anything, more sparse than on the lower parts of the high level profiles.

Systematic studies of the low level tropical weathering profiles, particularly where no laterites occur, are remarkably few. This appears at first rather puzzling because it is often equally informative to consider why something has not developed in a given locality (eg laterite crust) as why it has in another. That this kind of study is a serious omission can clearly be seen : we have long established criteria for development of laterite - low relief (stable landsurface), with a stable water-table which oscillates seasonally in response to a seasonal rainfall regime - yet vast areas in the tropics fulfil these criteria and they are quite without laterite crusts. No-one has ever given serious consideration to the question of why they are absent, or in what way the development of these crust-free profiles differs from those which do have a crust. Reluctantly, we must blame the negative results syndrome. It is easy to have papers published on "Why I think there is a laterite or bauxite here". "Why I think there is no crust here" or worse still "There is no crust here and I have no idea why, although according to the established criteria there should be" are unmarketable theses.

Although systematic studies of tropical weathering profiles, and in particular the low level profiles without carapaces, are few, there are numerous 'casual observations' comprising a peripheral part of other studies. These vary enormously in quality, ranging from drillers logs describing kaolinite as chalk, by virtue of its colour, to carefully analysed profiles with no contextural information whatever. Nevertheless there are sufficient pieces of the jigsaw puzzle available, to enable them to be arranged into reasonable hypotheses worthy of systematic testing.

These fragments of the story, relevant to establishing the hydrological pattern of tropical weathering profiles, come from a range of sources.

1. There are a limited number of in-depth studies of profiles or groups of profiles in catenary reationship.
2. There is indirect evidence for processes, likely to be operating at depth, from studies of shallow profiles, that is from processes deduced to be operating higher in the profile.
3. Indirect evidence of subsurface processes may be gleaned from geomorphological studies of landsurface features.
4. There are numerous laboratory studies of element mobility and mineral stability, as well as a few studies of whole rock responses to weathering.
5. There are virtually innumerable scattered fragments of information in unpublished reports - well drilling programmes, dam site exploration, geochemical exploration etc.

This report is unable to incorporate much of this last category of sources. Their analysis must form an integral part of any regional study designed to examine the validity of the hypotheses emerging from the other sources or the relevance of any particular hypothesis to the region in question. The first four source categories provide the basis of this report.

The laboratory studies have produced something of a problem. There are many interacting factors which affect weathering and element mobilisation and inevitably laboratory studies predominantly treat these in isolation. This is in itself rather dangerous, but even more unfortunate is the result that the factors most easily brought into the laboratory are those most thoroughly studied. At the head of the list is the influence of pH. When vast numbers of publications are concerned with one factor this assumes the role of main factor. This is very much the situation we have had until very recently. One of the most valuable products of IGCP-129 was the opportunity provided by the International Seminars for free exchange of information and it must be said that the best of this was outside the formal paper sessions. From this it has emerged more clearly that we must, if progress is to be made, free ourselves of our long impalement on the concept of tropical weathering profiles as essentially the product of pH-controlled differential leaching. Examples were provided of papers, by life-long field workers, which never reached the light of day. Valuable observations have been turned down ("This is surely impossible.") by predominantly desk-bound academic referees, with the latest geochemical text-books within arm's reach, on the grounds that mobilities indicated by field work did not 'fit the established rules'. Examples are too frequent to be dismissed as observational errors. It is hoped that the successor project to IGCP-129 will see a serious beginning to real efforts to find out how, in nature, the rules are circumnavigated.

To say that something cannot be correct simply because we do not know how it has happened is scientifically unacceptable. This report freely incorporates observations of processes for which we have as yet no explanation but which certainly exist. They have important implications for groundwater quality.

The geomorphological studies are inevitably concerned, in the main, with the development of landsurface features. Since the advent of 'stratigraphical geomorphology', erosion and deposition have been more frequently studied as interdependent processes. This has resulted in considerable emphasis being placed on mechanical removal of material from weathering profiles, profiles from which components have obviously gone. These systematic studies have, almost inadvertently, demonstrated the hitherto unsuspected importance of chemical removal of profile components. If there is no reasonable mechanical means of removal, it must be concluded that 'chemical' removal is involved, since there is no alternative, whether or not we know how the materials are mobilised and whether or not groundwater analyses have identified their presence there. In effect we can deduce what must have gone into the groundwaters from what is left in the profiles. Moreover, from detailed studies of textural and mineral evolution of the shallower profiles and the upper parts of the more mature profiles, we can place order on the removal of material. Studies of textural evolution allow us to deduce, for example, that textural component A (and its associated mineral and chemical assemblage) formed first and that subsequently leaching conditions changed so that component B (with a different chemical and mineral assemblage) then formed, then C etc. Chemical changes associated with this sequence allow us to deduce which chemical components must have been released into the groundwaters at which stage in the leaching history, and what is being released today. Since these stages of leaching are directly controlled by the geomorphological history, this latter is in fact an important starting point for understanding not only the configuration of saprolite bodies and associated profiles but also the potential groundwater content. What still remains in the groundwater today depends on its movement, a long-term process difficult to study directly. Study of what is in the groundwater, against a background of knowledge of what has gone into it at what time should considerably add to our knowledge of groundwater movement rates and directions.

This report treats the various aspects of weathering profiles systematically, drawing data, interpretative argument and conclusions from these varied sources, wherever it is found to be appropriate to discussion of the hydrogeological implications.

In Part II of this report, topics are considered in the following sections:

<u>Section 1</u> <u>The geographical distribution of tropical weathering and its implications for the genesis of weathering profiles, past and present.</u>

<u>Section 2</u> <u>Profile depth</u>

- 2.1 "Characteristic" and "exceptional" depths.
- 2.2 Constraints on deep weathering.
- 2.3 Nature of the basal surface of weathering.
- 2.4 Concepts of 'deep' and 'advanced' weathering.

<u>Section 3</u> <u>Factors affecting weathering</u>

- 3.1 Climate
- 3.2 Nature of the parent rocks
  - 3.2.1 Chemistry
  - 3.2.2 Mineralogy
  - 3.2.3 Textures
  - 3.2.4 Structures
- 3.3 The influence of geomorphology on weathering history
  - 3.3.1 Regional patterns of deep weathering and erosion surfaces.
  - 3.3.2 Dating landsurfaces.
    - Breaks of slope
    - Continuity of laterite sheet
    - Mesas and pediments
    - Cartographic analysis
  - 3.3.3 Valleys
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  - 3.3.5 Special sites
    - Enclosed basins on the basal surface of weathering.
    - Inselbergs.
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<u>Section 4</u> <u>The nature of the profiles</u>

- 4.1 Mineral progressions
- 4.2 Chemical progressions
- 4.3 Structural progressions
  - 4.3.1 Grain size variations
  - 4.3.2 Voids
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<u>Section 5</u> <u>Genesis of the profiles</u>

- 5.1 Profiles with an Fe-rich, lateritic crust.
  - 5.1.1 Water-table oscillation
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  - 5.1.3 Lateral enrichent
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  - 5.1.5 Residual enrichment
    - Pedogenetic laterites
    - Groundwater laterites
- 5.2 Profiles with an Al-rich, bauxitic crust
- 5.3 Deeply weathered profiles with no residual concentration in the upper horizons.
- 5.4 Profiles with Si-enriched horizons (silcrete)
- 5.5 Profiles with a calcareous upper horizon (calcrete)
- 5.6 Profiles with gypsum crusts.

Part III of this report is concerned with recommendations for research.

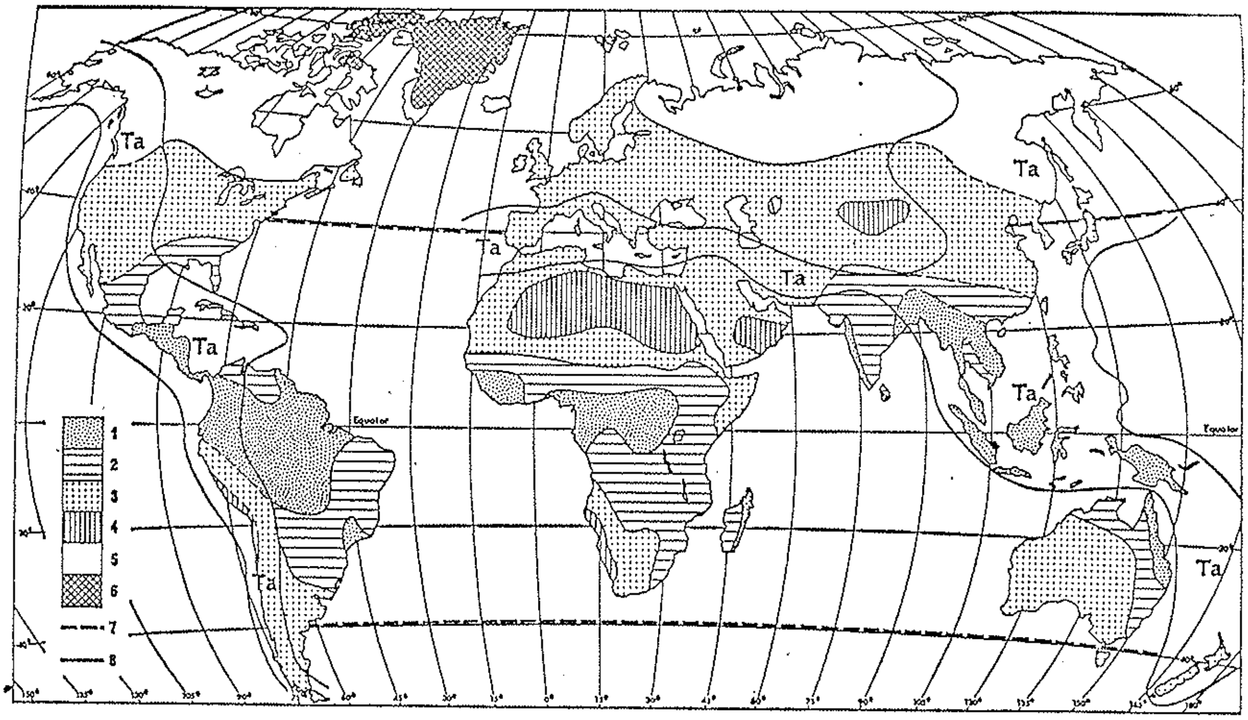
Part II

Tropical weathering profiles

Section 1

The geographic distribution of tropical weathering and its implications for the genesis of weathering profiles, past and present.

Global patterns of "types of weathering" are shown in figure 1. Tropical weathering is distinctive in that it is predominantly chemical and on this map the area where there is active chemical weathering today is essentially that designated Zone 1 and Zone 2 in the key.



Distribution of the principle types of weathering on the earth's surface (mainly after Pedro 1968, with additions from Strakhov 1967)

1. Zone of allitisation (kaolinite plus gibbsite); 2. Zone of monosiallitisation (kaolinite); 3. Zone of bisiallitisation (2:1 lattice clays–montmorillonite, illite); 4. Hyper-arid zone without significant chemical weathering; 5. Zone of podsolisation; 6. Ice-covered areas; 7. Approximate limit of red weathering crusts (after Strakhov); 8. Extent of tectonically active areas (TA) within which 'climatic' weathering types are modified.

Figure 1

Zone 1 In these areas high rainfall and temperature promote the most advanced and deepest weathering. In general terms weathering advancement follows the progression:

Primary minerals (fresh rock) → 2:1 minerals (Smectites) Stage 1 → 1:1 minerals (Kaolins) Stage 2 → gibbsite (Al hydroxide) Stage 3

Weathering advances →

This is an up-profile as well as temporal progression. The key of the map describes zone 1 as "zone of allitisation (kaolinite + gibbsite)" meaning that the progression has advanced to stages 2 and 3 in the diagrammatic representation of the stages shown above, under the existing climatic regime, i.e. weathering products of stages 2 and 3 occur in the highest part of the profile, at the surface. Since the transition from smectites to kaolins involves release of the bulk of the available Fe, kaolin formation is commonly associated with the formation of Fe-rich laterite crusts. So, in effect, at the surface in zone 1 we may have either a gibbsite-rich horizon or a horizon of kaolinite and iron accumulation.
Zone 2 In these areas of "monosiallitisation" the implication is that the progression does not proceed beyond kaolinite formation. Thus the surface horizon should comprise an Fe-rich, kaolinitic material. So the only difference between zones 1 and 2 is that in zone 1 there may be gibbsite formed (since Fe and kaolinite are common to both zones). The distinction between zones 2 and 3 is that in zone 2 the 1:1 clays form, but in zone 3 weathering does not go beyond the 2:1 clay stage.

The reason why a more recent version of this map is not available is not because recent research has confirmed the distinction of these zones but because we are not able to produce one, even though we know it to be incorrect in many respects. The distinction between zones 1 and 2 is very far from clear. In fact, within the area they encompass, there is an intricate and quite unmappable, on a global scale, mosaic of presently forming surface materials which may be either Fe-rich or Al-rich. For example, in the E. Ghats of India (in theory "monosialitisation") gibbsite (bauxite) is certainly forming today. It also appears to be presently forming in the Darling Ranges of West Australie (theoretically zone 3, 2:1 clays). Previously, profiles of this sort (i.e. ones that don't fit the scheme) were dismissed as "fossil" profiles which formed under different climatic conditions, but recently it has become clear that they are indeed presently forming and this has forced the recognition that site factors may ultimately over-rule the climatic factors.

In short, of zones 1 and 2 it can only be said that :
(a) the weathering stage may reach either gibbsite or kaolinite and iron
(b) increasing heat and humidity tend to favour gibbsitisation
(c) site factors are ultimately more important than climatic, in determining the nature of the weathering product, which is unmappable on a global scale.

The justification for zone 3 is the general failure of weathering to proceed beyond the 2:1 clay mineral stage, but within that zone the differences in weathering profiles are enormous. In cool temperate regions, although there may be abundant rain, temperatures are low and it is this which retards weathering. Near the boundary with zone 2, by contrast, temperatures are very high and if weathering is retarded, it is by lack of water. In these areas there is often a conspicuous crust of calcrete or silcrete, as the uppermost profile member. The weathering transition from zone 2 to zone 3 is particularly intriguing as we still have very little idea why it is that in some cases laterite (zone 2) gives way to calcrete in drier areas (zone 3), as in Kenya and Tanzania, while in others, e.g. Australia, the laterite gives way to silcrete in zone 3 areas. Since calcrete and silcrete are typical weathering products of the drier parts of the tropics, profiles with these should also be included in this report, despite their place in zone 3.

For another reason, these 'marginal' area must also be included. By virtue of their proximity to zones 1 and 2, very commonly they have in the

past been subjected to the weathering conditions present there today. The reasons for this are:
(a) climatic change has widened and narrowed the climatic belts at various times or the belts have swung north and south of their present position
(b) continental drift has moved areas in and out of the various climatic zones.
Thus, the marginal and even desert areas have, in the past, known the conditions that pertain to zones 1 and 2.

To what extent climatic change or continental drift are expressed in the present profiles depends entirely on their age. The older the landsurface, the wider the time-span encompassed in profile development. Thus, (see figure 2), in a situation where we have, for example, three landsurfaces, or erosion surfaces, the youngest only may have a profile development which relates to present conditions (climate x). Where an older landsurface survives, present weathering conditions and profile development are superimposed on an original profile which may have developed under different conditions (y). The oldest surviving landsurface may have a profile which results from an even earlier set of conditions, (z), with both y and x superimposed on this.

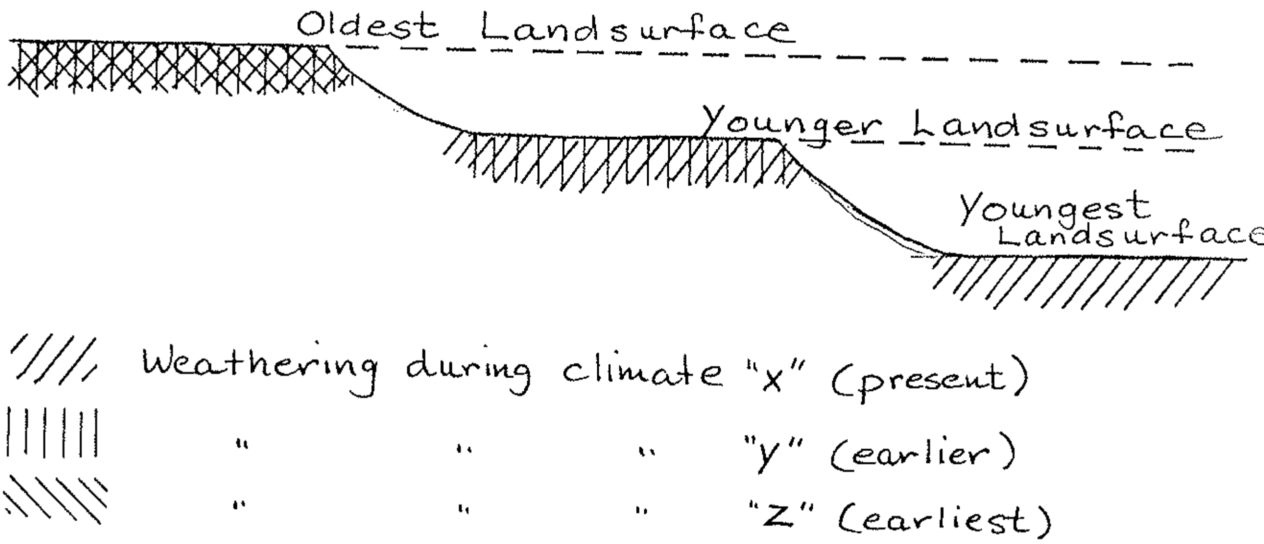
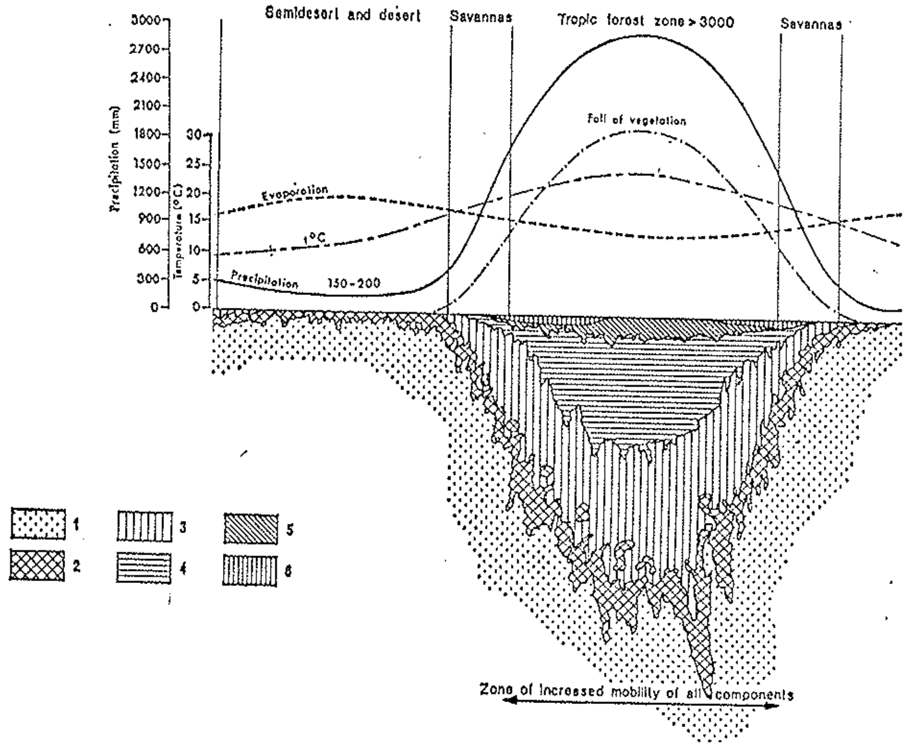


Figure 2

The sequence x - y - z, in figure 2, may have been hot and humid - alternating seasons - dry. It may have been the reverse, or any other combination. How then can we even begin to consider making generalisations about tropical weathering profiles? In effect, how can we generalise about a situation in which the separate tropical zones, as indicated in general form in figure 3, have swept backwards and forwards right across the whole tropical belt at different times, giving endless permutations and combinations of weathering conditions, variably expressed on landsurface facets of different age?



Sketch of the formation of weathering mantles in areas that are tectonically inactive (from Strakhov 1967)

1. Fresh rock; 2. Zone of gruss eluvium, little altered chemically; 3. Hydromica-montmorillonite beidellite zone; 4. Kaolinite zone; 5. Ocher, Al_2O_3; 6. Soil armour, $Fe_2O_3+Al_2O_3$

Figure 3

We can justify attempting to generalise by virtue of the fact that the effects of the hot and humid weathering (particularly zone 1) dominate very strongly indeed. Given a situation, for example, where hot, humid conditions were succeeded by less humid or dry, the effect is to 'fossilise' the older profile, with only relatively minor modifications in the upper horizons, (the product of the drier regime which penetrates less deeply). Thus some calcretes 'top' profiles of zone 1, rather like the icing on the cake. The essential features are still zone 1 features. Conversely, if a profile develops under a rather arid regime which is then followed by a humid one, the effects of the latter very quickly overtake those of the former, in effect wiping them out. Thus only the humid - dry change is likely to be expressed in the profile and this only as a relatively surficial effect. In essence most, if not all, tropical profiles predominantly express the effects of the wettest period, with modifications, if these are in the direction of increased aridity. So the tropical weathering zones (incorporating present and past) and the profile development effects, can be reduced to core areas in which it has been permanently wet and other areas where the profile features which developed during the wet period are relic and have surficial modifications.

Understanding of the weathering of zone 1 is of overall importance. It is this phase which dictates depth of weathering, configuration of weathering front, mineral and chemical progressions, texture and void development etc. From the point of view of water renewal rate in deeply weathered profiles it is important in which zone the profile now occurs, but from the point of view of the essential nature of the profiles it is very often not of great importance.

Section 2 Profile depth

2.1 'Characteristic' and 'exceptional' depths

2.2 Constraints on deep weathering

2.3 The nature of the basal surface of weathering.

2.4 Concepts of 'deep' and 'advanced' weathering.

2. Profile depth

2.1 "Characteristic" and "exceptional" depths.

Recorded variations in depth of weathering are enormous. Locally, deep weathering may be very deep indeed. Mendelssohn (1961) found slight alteration of basement complex rocks at depths of over 1,000m in the Zambian Copperbelt. Ollier (1965, 1969) cited over 120m of alteration found during tunnelling for the Keiwa Hydro-electric project. Widespread decomposition extends to 100m in some areas and depths of over 30m are very common.
Thomas (1974) regards 30-45 m as the characteristic range over basement rocks on Gondwanaland, with greater depths being characteristic of basic rocks and metasediments -90 to 100 metres are given as examples. Both inter- and intra-regional variations in depth of weathering are large and depend on the interplay of several factors which affect it. The factors which facilitate weathering nevertheless act within a fundamentally constrained system.

2.2 Constraints on deep weathering.

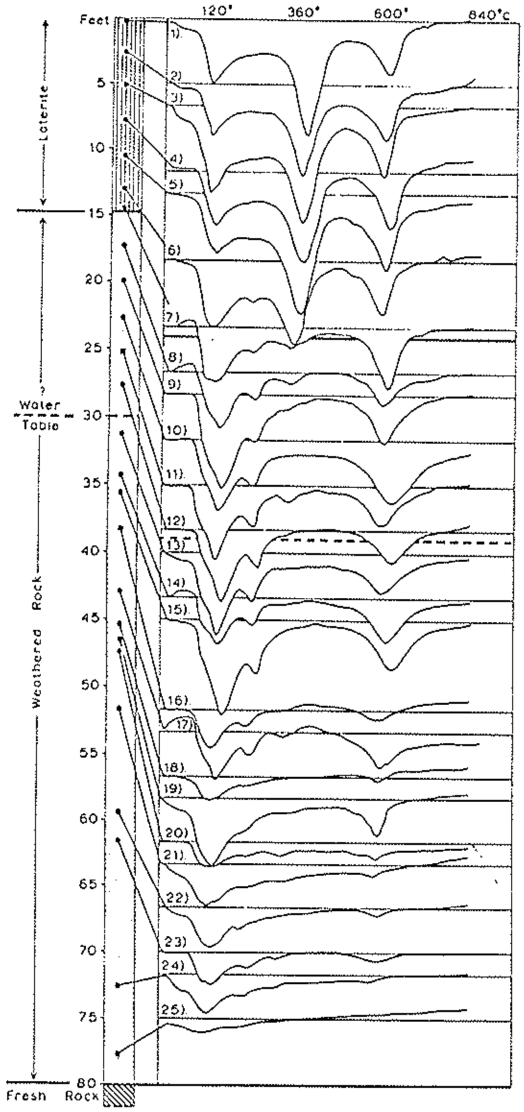
If there are in fact "characteristic" depths of weathering, this in itself implies that constraints operate to limit deep weathering, constraints which eventually over-ride the variations in depth of weathering induced by site factors, rock type etc. (see section 3).

The depth of profile can be limited at either the top or the bottom. Clearly, only where surface erosion of the weathered profile (surface lowering) is slower than lowering of the weathering front can profiles deepen. In the case of the low relief surfaces developed over continental basement complex areas, surface erosion is extremely slow and this is unlikely to provide the main constraint. It appears to be essentially at the weathering front that depth constraints are applied.

Until about the '50s, it was widely believed that weathering virtually stopped under saturated conditions below the water-table. Nye (1955) showed that rock alteration (decomposition of feldspars) penetrated below the water-table. This and other similar observations initially drew the response that the water-table was formerly lower and has risen (eg. de Swardt, pers.com.). However, it is now known that such an explanaton is untenable. Weathering clearly proceeds well below the water-table.

Acceptance of this was followed by attempts to differentiate between alteration under vadose and phreatic conditions. Lelong and Millot (1966) followed de Lapparent (1941) in recognising a 'zone d'alteration inferieure' below the water-table in which plagioclase and other silicate minerals alter to sericite and ferro-magnesian minerals to chlorite and a 'zone superieure d'alteration' where kaolinite and other clay minerals were formed.

Although these two types of secondary mineral assemblage do occur in some deeply weathered profiles, I am in some doubt that it is correct to link them with two innately different weathering situations, i.e. below and above the water-table. There are many profiles in which the graduation from the 'inferieure' to the 'superieure' assemblage does not clearly co-incide with the water-table (using the criterion of pore saturation to delimit this). In many cases, if we are provided with data on mineral progressions in a profile, it would be difficult to place the water-table. For example, the mineral progressions in the weathering profile at Busia, Uganda (parent material amphibolite) show that kaolinite (ca. 600 degree endotherm) appears at over 70 feet, while the water-table is at about 30 ft. and at this point there is no significant change in the mineral progression, which is continuous throughout the profile (figure 4).



Mineral progressions in the weathering profile (differential thermal analyses). Low temperature endotherms attributable to smectites dominate the lower part of the profile, kaolinite endotherms becoming more pronounced up-profile. The laterite is dominated by goethite and kaolinite.

Figure 4

Thus, although it is often maintained that kaolinite formation is exclusive to freely draining situations (eg. Thomas 1974) there is little doubt that it can form below the water-table. It is possible that some of this may be neo-formation of kaolinite from Al and Si leaching down into the phreatic zone, but on balance the continuous gradation of 2:1 clay minerals to kaolins in the profile indicates origin by leaching, even below the water-table. We seem here to be dealing not with innately different weathering but different rates which may be reflected as different stages in the progression. Thus, if there is a very clear change in the rates of weathering below and above the water-table (slow and fast, respectively) then Lelong and Millot's distinction may exist. Where the rates do not change abruptly at the water-table the distinction is not clear. It is noteworthy that the Busia profile lies close to the Kyoga-Victoria watershed where fairly rapid groundwater renewal would be expected.

This theme of reduced rates of weathering at increased depths appears to provide the only reasonable constraint on the depth of the weathering profile, hinging upon the rate at which solutes are removed. If, with depth, removal of solutions becomes slower, then weathering rates become slower and when solutions reach saturation concentration weathering must stop. In effect this could provide a constraint on depth of weathering which ultimately over-rides depth variations which are caused by other advantages and disadvantages eg. those lithological. In the hypothetical situation shown in figure 5, it is postulated that there is no mechanism for the removal of solutes. "Highs" and "lows" develop on the basal surface of weathering in response to the variations in susceptibility, to weathering, of the rocks. In effect, the development of this relief would be a self-destructive system. Higher concentrations of solutions in the "lows" (where the more easily weathered rocks occur) would slow down the weathering below them, in comparison with the "highs". Ongoing weathering would increase concentrations in the "lows", continually favouring preferential solution of "highs", but at a progressively slower rate as the overall level of concentration rises. Thus the relief on the basal surface of weathering might be expected to flatten. The ultimate stable, virtually flat, basal surface of weathering is probably never attained, the situation in (c) being a more realistic end stage, since some evacuation of solutes by virtue of landsurface slope must inevitably occur.

Does this postulated "no removal of solutes" situation really exist? In favour of existence are:

1. the fact that many authors are willing to ascribe a "characteristic" depth of weathering to extensive low relief areas
2. the fact that there is great variability in water quality in proximate wells, this implying that discrete basins exist, which do not have connectivity - eg the situation in (c) of the hypothetical case.

In short, it seems that where there is no removal or poor removal of solutes, weathering depth is limited, and conversely, weathering can proceed to enormous depths provided some means of evacuation of solutes exists.

The implications for water quality are that in extensive low relief areas, in which a "characteristic" weathering depth exists, shallow basins which occur within the "characteristic" depth range may contain very old water with high concentrations of solutes. Within such an area, any significantly deeper basins might be expected to contain younger and cleaner water by virtue of the deduced system of renewal that their "exceptional" depth indicates.

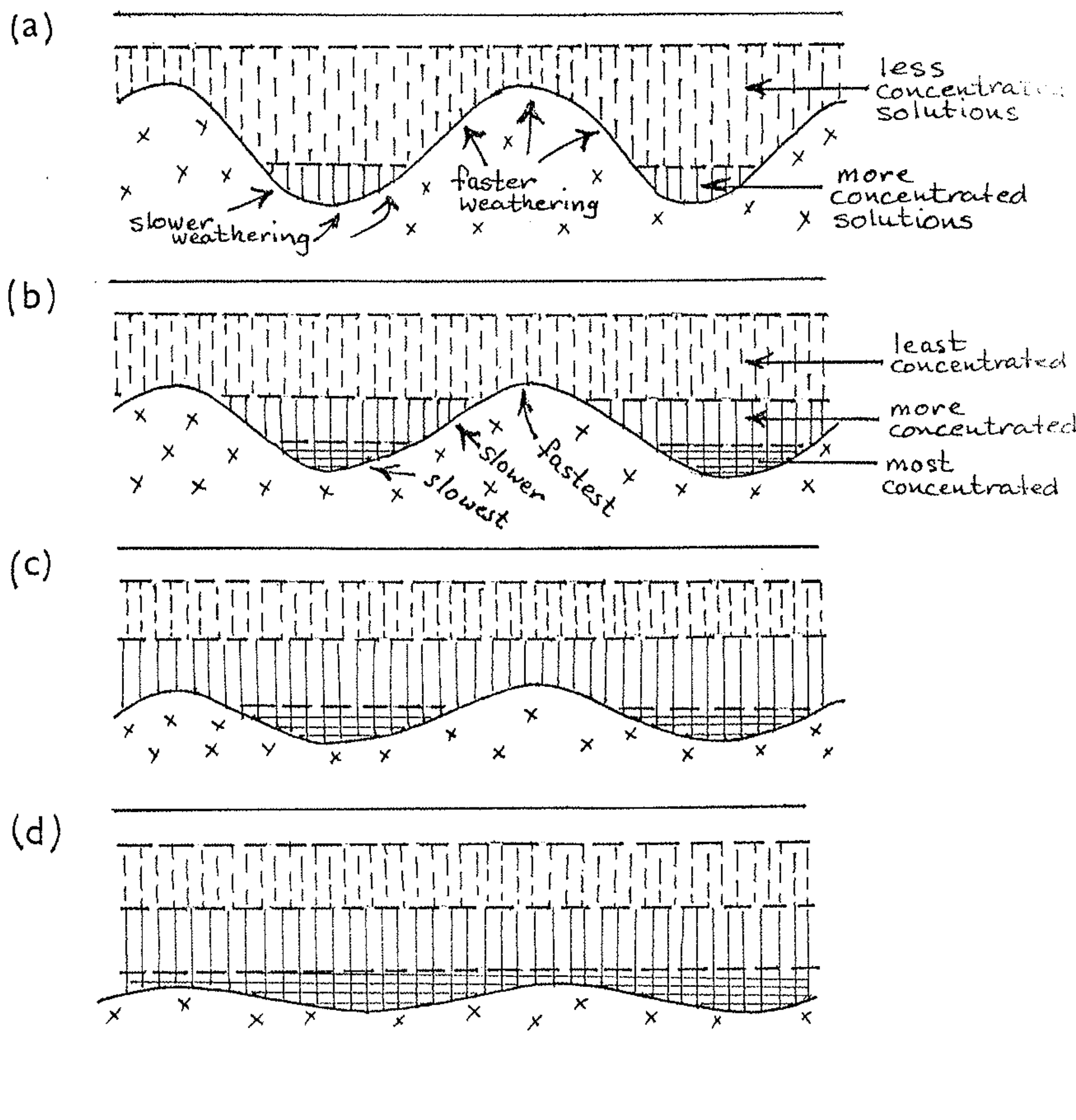


Figure 5

2.3 Nature of the basal surface of weathering

The basal surface of weathering or weathering front, the junction between fresh and weathered rock, is not as simple a concept as was supposed when the terms were coined.

It varies from a very sharp junction indeed, to a gradation so extended that the transition is difficult to place.

Some tentative generalisations on this can be made.

1. The junction tends to be sharper where more basic rocks are involved and more diffuse over acidic rocks.

2. There is some indication that more diffuse weathering fronts tend to occur where the minerals in the rock have a wide range of susceptibility to weathering. For example, a granite containing biotite or plagioclase feldspars would be expected to have a more diffuse junction than one in which orthoclase feldspar is the most susceptible mineral, since the biotite to quartz range of susceptibility is greater than the orthoclase to quartz range (see section 3.2.2). By contrast, quartz-free rocks with a narrower range of mineral susceptibility, eg basic extrusives, would be expected to have a sharper junction.

This generalisation only takes the earlier one a step further, but it points to a need to look at the accessory minerals, not just the range of dominant minerals if we are seriously concerned with precisely defining where, in the profile, weathering really begins.

3. Similarly, sharper junctions may be associated with narrower ranges of crystal size rather than wider ranges.

4. It is also clear that the <u>rate</u> of weathering is important. Where the rate is faster the junction is sharper. This is expressed in the form of a progressively more diffuse junction with depth (figure 6).

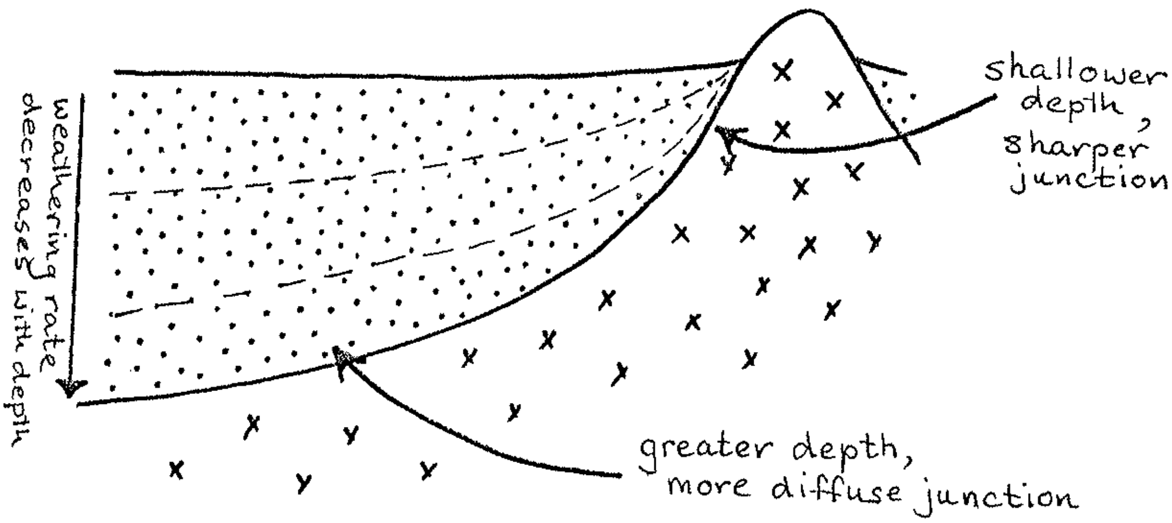


Figure 6

It is also seen by the much more abrupt junction associated with core stones 'suspended' in the well-weathered saprolite, than lower in the profile (figure 7). This may be of some use in the problem

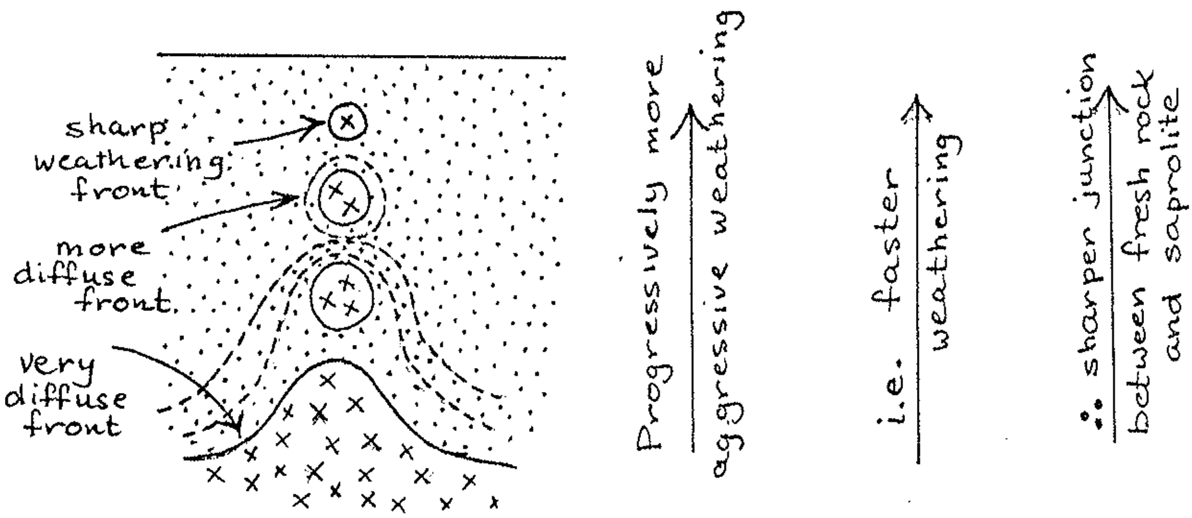


Figure 7

of deciding whether the basal surface has been reached during drilling or whether only a core stone has been encountered, particularly with quartz-rich rocks.

The effect of weathering rate in determining the sharpness of the junction appears also to be expressed where the extreme 'lows' of the basal surface owe their existence to fractures or fissures which particularly facilitate leaching, as indicated in figure 8.

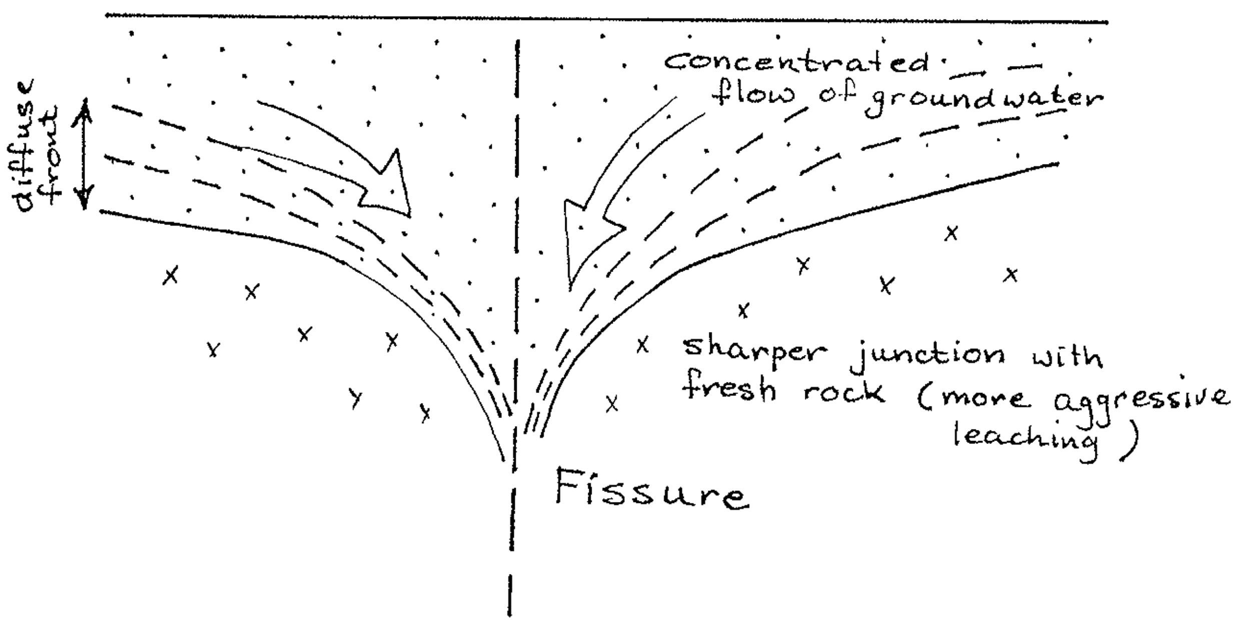


Figure 8

With water resources in mind, the question must be asked: "Does it matter, to precisely identify the weathering front in terms of 'here weathering has begun and here it has not'?" In one respect the answer seems to be "no", in that the initial stages of weathering (hydration) may be isovolumetric, the secondary minerals filling the space occupied by the primary minerals (Thomas 1974). So the development of porosity or permeability need not co-incide with this point in the profile. It may well be higher. Consequently a geophysical technique which locates the actual weathering front could not be used to define the lower limit of the groundwater body within saprolite and, conversely, a technique which locates the base of water-bearing saprolite need not define the basal surface of weathering as such.

This leads to another problem. In some cases fissuring of the rocks is so well developed that although the basal surface of weathering can be identified to the extent that fresh rock is encountered, fairly consistently, at a particular depth, yet the main water body lies below this in the weathered fissures (Ugandan bore hole records), as shown in figure 9.

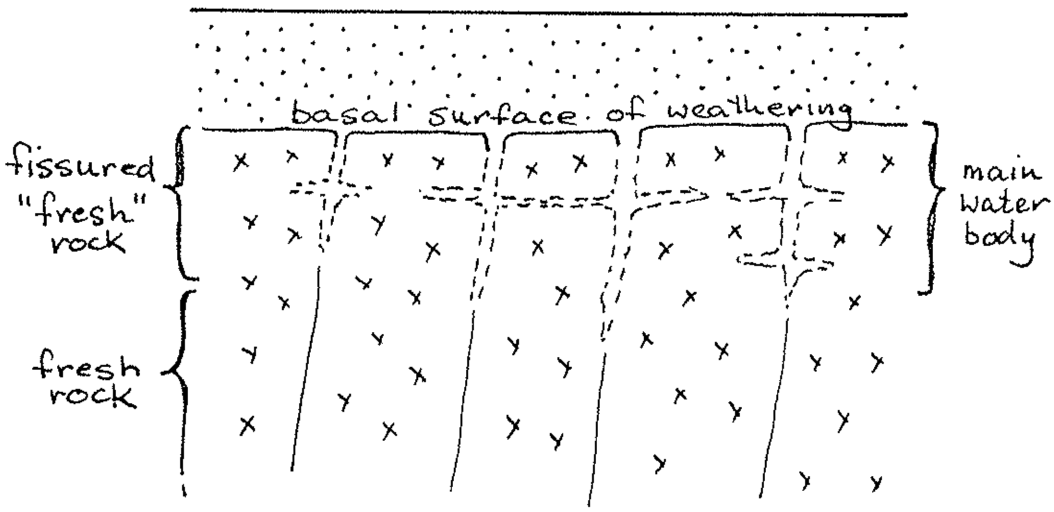


Figure 9

A related problem occurs with horizontally disposed beds. More resistant beds (to weathering) may present a convincingly continuous pseudo-base, with extensive weathering of lower beds beneath this (figure 10). The effect can be well seen in Madras, India, where a series of tunnels and chambers have been excavated out of 'interstratified' weathered horizons, between horizons of fresh rock (to provide accommodation for a monastic community).

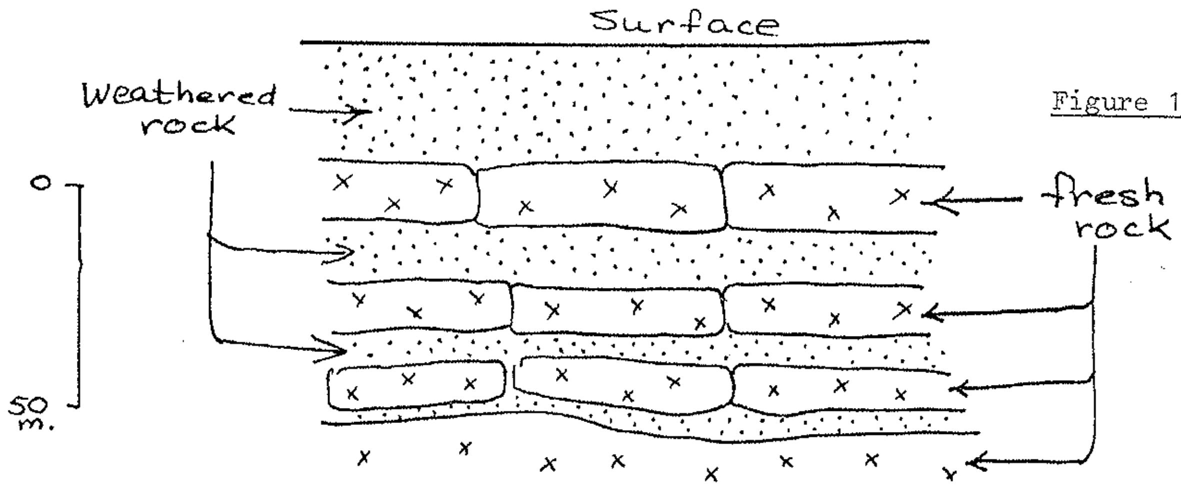


Figure 10

A similar effect, but on a smaller scale, can be seen in the lateritised extrusives exposed along road cuttings north of Nairobi (figure 11).

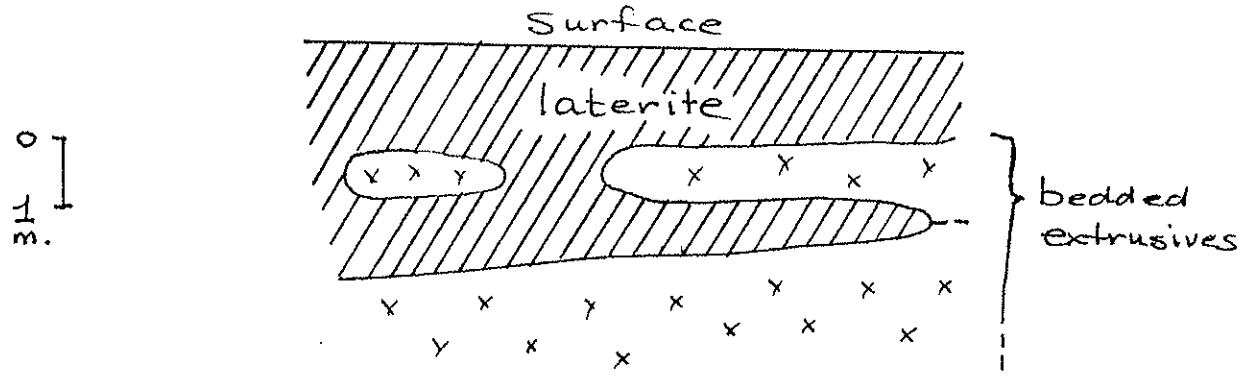


Figure 11

There the pedogenetic laterite (formed by repeated solution and deposition - see section 5.1.5) has developed preferentially along certain horizons leaving suspended 'roofs' of fresh rock above. A similar effect must be expected to occur with metasedimentary rocks.

It is also possible that a similar effect is more widespread than is realised, the result of 'sheeting'. Pressure release fractures, running parallel to the surface, are common on fresh rock exposures. Evidence that they occur under saprolite is sparse, but this may be for want of looking. Thus, even in situations where the disposition of the strata might not indicate weathering parallel to the basal surface of weathering, it may very well occur in association with these fractures.

This range of possibilities clearly points to the need to establish precisely what is being identified by geophysical techniques. Present opinion on the usefulness of seismic methods or resistivity, to locate the basal surface of weathering or base of water-bearing saprolite, is remarkably varied. Some claim inordinate success from a particular technique while others denounce it as close to useless. Both are likely to be right. Our present problem is to link these variable results with particular types of weathering front. We still do not have any clear idea which type of weathering front responds to identification by what technique and whether that identification is in fact relevant to identification of the lower limit of water-bearing material.

2.4 Concepts of 'deep' and 'advanced' weathering.

Advanced and deep weathering are not synonymous. Relatively thin profiles may be highly advanced in that the mineral progressions have reached an extreme stage, e.g. crusts very rich in Fe_2O_3 (up to 70%) or bauxitic crusts may rest directly on fresh rock. In effect the whole weathering profile consists of the minerals characteristic of the last stage of the weathering progression. At a less advanced stage such profiles would have been thicker and contained minerals pertaining to earlier stages of weathering, although in some cases of extremely aggressive leaching the transformations are very rapid and the earlier stages of the weathering progression may be confined within a range of less than 1mm from the fresh bedrock.
The relationship between advanced and deep weathering can be seen in low relief areas, e.g. Busia, Uganda. The basal surface of weathering rises under the interfluves. The weathering profile in thicker downslope, as shown in figure 12. Yet the residual materials are richer in higher

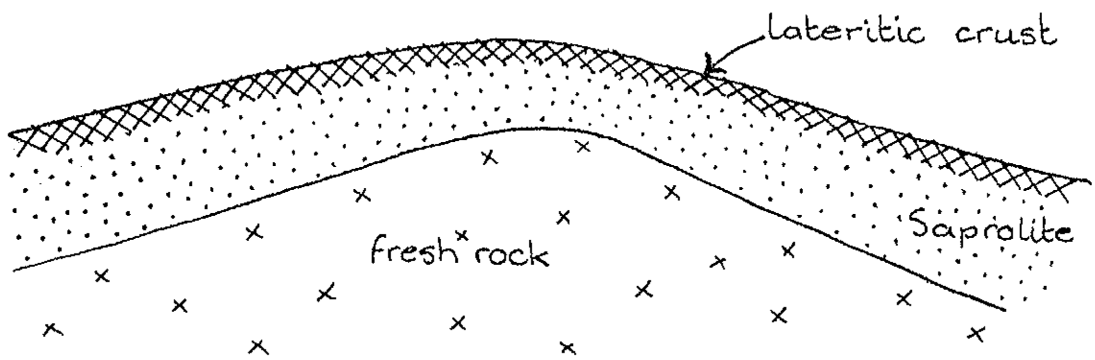


Figure 12

catenary positions. If we calculate the column of rock consumed to provide the residuum, consumption is greater on the interfluve and the palaeosurface elevation is higher (figure 13).

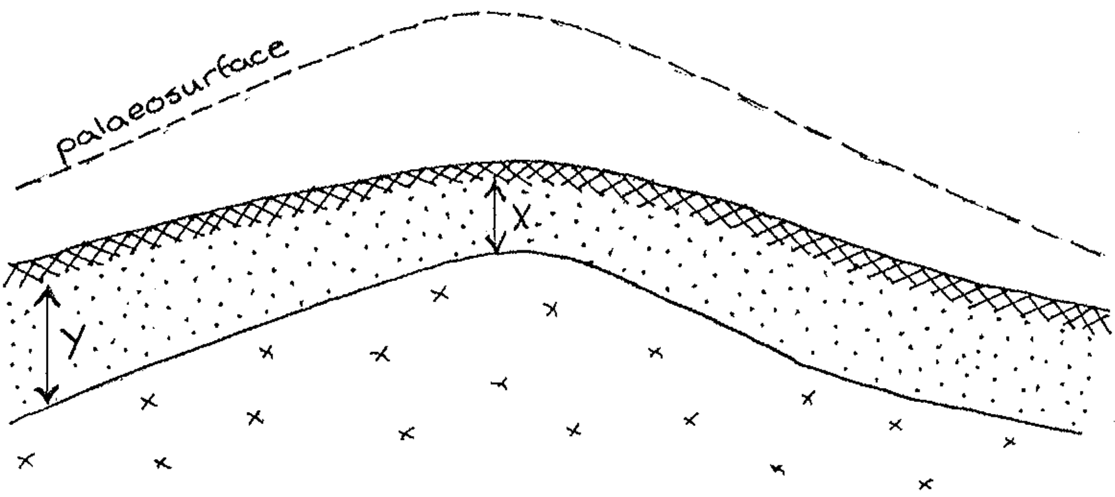


Figure 13

Thus weathering is shallower but more advanced at X and less advanced but deeper at Y.

In a two-cycle situation, the older profiles may be relatively thin and rich, with deeper, less advanced weathering on the younger surfaces (figure 14). This situation usually occurs where the older surface

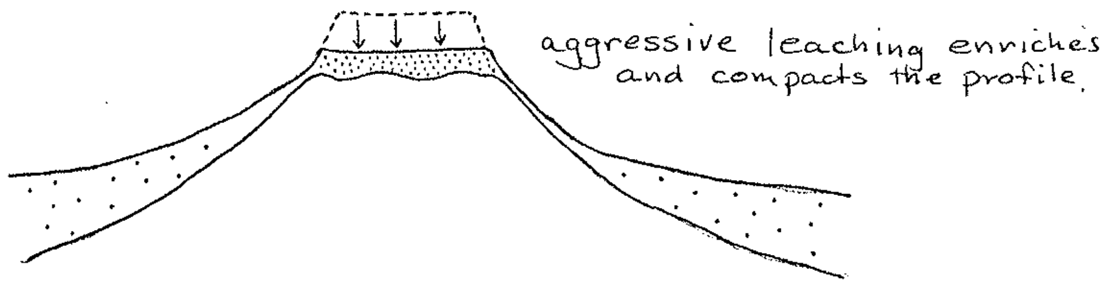


Figure 14

is strongly dissected, so that it survives only on relatively small mesas or plateaux, through the profiles of which leaching is very aggressive. A very high permeability of the weathering mantle is also necessary for such profile contraction. Where older plateau remnants are more extensive, in central areas weathering apparently continues to deepen the profile slowly but towards the margins the shedding of water from the old profile tends to facilitate deeper weathering at lithologically favourable sites and this has the effect of increasing the relative relief on the basal surface of weathering (figure 15), the 'highs' of which become exposed to form nascent inselbergs as the scarp retreats.

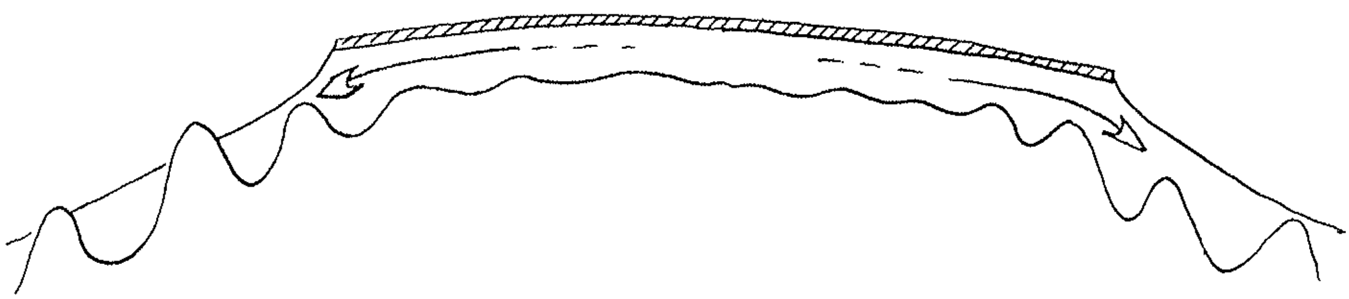


Figure 15

These variations in the development of ancient profiles, in response to incision, clearly relate to the frequency of drainage lines and any elevated landsurface can therefore express different profiles in areas where drainage patterns differ (e.g. Ghosh & McFarlane 1984).

For the extensive development of deeply weathered profiles, the weathering must be slow and sustained. The requirement of slow weathering is, as already indicated, to limit the possibility of very aggressive leaching compacting and concentrating the profile. If slow weathering is to be deep it must be sustained for a very long time. In effect this means that a low relief landsurface must survive as such for a long time. Where large expanses of ancient landsurfaces survive in elevated positions it may be true to say that the older the landsurface the deeper the weathering. However, an older landsurface may have shallower profiles for two reasons: compaction and advancement of the weathering profile after elevation and a shorter period during which it existed as a low relief surface at low altitude. Since characteristic weathering depths are frequently associated with surfaces of different ages within a given region, it is therefore important to establish the relative ages of the landsurfaces present (see section 3.3). Depth of weathering is, for example, an important diagnostic criterion for landsurface recognition in Uganda (McFarlane & Brock 1983).

Section 3 - Factors affecting weathering

3.1 Climate

3.2 Nature of the parent rocks

- 3.2.1 Chemistry
- 3.2.2 Mineralogy
- 3.2.3 Textures
- 3.2.4 Structures

3.3 The influence of geomorphology on weathering history.

- 3.3.1 Regional patterns of deep weathering and erosion of surfaces
- 3.3.2 Dating landsurfaces
  - Breaks of slope
  - Continuity of laterite sheet
  - Mesas and pediments
  - Cartographic analysis
- 3.3.3 Valleys
- 3.3.4 Interfluves
- 3.3.5 Special sites
  - Enclosed hollows on the basal surface of weathering
  - Inselbergs
  - Enclosed depressions on the land surface
  - Dambos

3.1 Climate

It is widely believed that weathering is more extreme in tropical areas because it is more rapid there. Since most chemical reactions increase exponentially with temperature, a rise of 10°C is cited as increasing reaction rates 2 or 3 times (Van't Hoff's rule). A 15°C or 20°C difference in soil water temperature between temperate and tropical zones would be expected to increase at least 4 times, the weathering rate. It is also known that biological activity increases with temperature. Thus, given that rainfall is in abundance, to remove dissolution products, high temperatures would be expected to favour rapid weathering.

Nevertheless, as is often the case with natural environment studies, attempts to demonstrate the obvious tend to present problems. Ruxton and Berry (1961a) attempted to quantify depth of weathering in terms of climatic zones and suggested 30m is expected for humid tropics, 25m for wetter savannas, 6m for drier savannas and less than 3m in arid zones. By contrast, Melfi and others (Melfi et al. 1983) indicated a range of 1.5m to 2.7m in climatic areas ranging from semi arid to humid sub tropical (table 1).

Profile	Location	Soil classification	Profile depth (m)	Rainfall ($m\ a^{-1}$)	Mean annual temperature (°C)	Climate	Topography	Natural vegetation cover
GAL-1	Alagoas State (Santana do Ipanema)	Regosol	1.5	0.5–0.75	25	Semi-arid with rainfall concentrated in 3–4 months	Low rolling plateau slightly dipping eastwards	Savannah
GBA-2	Bahia State (Campo Formoso)	Regosol	2.2	0.5–0.75	25	Semi-arid with rainfall concentrated in 3–4 months	Low rolling plateau slightly dipping eastwards	Savannah
GSP-9	São Paulo State (Apiai)	Red-yellow podzolic	2.7	1.2–1.5	21	Sub-humid with 3–4 months of dryness	Atlantic plateau (950 m) dips stepwise toward the Atlantic Ocean, with deep straight valleys trending eastwards	Semi-deciduous forest
GPR-2	Paraná State (Antonina)	Oxisol	1.5	1.4–1.5	18	Humid, sub-tropical	Serra de Paranapiacaba (1000–1200 m)	Sub-tropical forest
GPR-4	Paraná State (Ponta Grossa)	Red-yellow podzolic	2.6	1.4–1.5	18	Humid, sub-tropical	Serra de Paranapiacaba (1000–1200 m)	Sub-tropical forest
GRS-2	Rio rande do Sul State (Encruzilhada do Sul)	Red-yellow podzolic	1.8	1.4–1.6	16	Humid, temperate	Serra do Sudeste—a massive (35,000 km²) granitic feature rises to 500 m; pronounced (10–15%) relief, where granite outcrops, and rolling topography where rocks are at depth	Grasslands

Table 1

Such attempts to link rainfall with depth of weathering are faced with two problems which, singly or in combination, render any conclusions of doubtful validity. First, since climatic belts have shifted, or varied in width, it is probably invalid to assume that the weathering depth and characteristics in any particular climatic belt directly reflect the present climatic conditions alone (the exception being the 'core' forest areas). Second, such comparisons can only be made with some success if it is absolutely certain that the ages of the surfaces in different areas are exactly the same. As with such attempts to link rainfall with weathering depth, attempts to link temperature with weathering depth (eg. Leopold, Wolman & Miller 1964) have also been unconvincing (Thomas 1974).

Despite inability to demonstrate or 'prove' the generalisation that high temperatures and humidity promote weathering, I am quite sure that it is valid. Nevertheless, there is persistent dispute about this (eg. David 1964). It is argued that the weathering rate (desilicification) in the tropics is no more rapid than in temperate regions. The difference is claimed to lie in the longer time available for weathering in the extra-glacial areas. The low Si content of tropical streams was cited in support of this, but since streams are the tip of the iceberg, as far as removal of weathering products is concerned, this argument is invalid. Low Si content of groundwater has also been used to support the argument, but, as indicated later, this assumes that true solution dominates and expresses a faith in the analytical techniques which may not be justified. Since we now know of well developed laterite and bauxite profiles of undoubted Pleistocene age I don't think the argument can be sustained. (In India, Coca Cola bottle tops are reported to be submerged in indurated laterite!) Nevertheless it persists. For example, the study by Melfi and others (op.cit.) of granite weathering in Brazil concluded that surface temperature has little influence on the rate of Si removal. However, sample areas are very widely separate indeed, spreading along a 3,000 km belt, and as already indicated, it is very doubtful if such comparisons are reasonable unless the ages of the landsurfaces are demonstrably identical and there has been no climatic change.

In short, I do not think that there is as yet any valid evidence to support the thesis that tropical weathering is no faster than temperate weathering. The existence of very young but very highly weathered profiles in the tropics, to my mind, says it all. Having said that, it must also be acknowledged that time is an obvious asset which many parts of the tropics clearly enjoy.

Of the climatic parameters affecting weathering in the tropics, I would place greatest importance on rainfall and since the swing or expansion and contraction of the climatic zones involve considerable changes in precipitation, it becomes important to establish, if possible, the age of the surface and its leaching history in terms of precipitation changes. These are fundamental to an explanation of the weathering profiles and upon their effects must then be superimposed the effects of the other factors, discussion of which follows.

3.2 Nature of the parent rocks

I entirely agree with the opinion that we will not be able to understand, let alone predict, the susceptibility of rocks to weathering, without much additional information (eg Thomas 1974, Aleva pers. com.). The problem is that we have four variables - chemistry, mineralogy, texture and structure - and we are not yet able to assess how these compete or complement one another.

3.2.1. Chemistry The sequence of mobilities of metal cations in rocks has been established, as shown below. This sequence results from the works of Anderson and Hawkes (1958), Denman and Anderson (1962), Harris and Adams (1966) and Loughnan (1968). In theory, this allows us to rank common rocks in terms of weatherability (if chemistry is the over-riding factor), as shown in table 2.

(1) Most mobile Ca^{2+}, Na^{+}, (Mg^{2+}) (K^{+})
(2) Intermediate K^{+}, Mg^{2+}, Si^{4+}, Fe^{2+}
(3) Least mobile Fe^{3+}, Al^{3+}

MOST STABLE
↑
Pegmatite
Porphyritic granite
Alkaline granite, mica schist and quartzite
calc-alkaline granites with two micas, gneiss
granodiorite
diorite, gabbro
microgranite, dolerite, amphibolite, pyroxenite
microdiorite, microgabbro and metamorphic schists
green rocks
↓
LEAST STABLE

Table 2

In practice, however, such ranking does not provide a good guide to relief development (eg. Rougerie 1960) because mineralogical, textural and structural influences may over-ride that of chemistry. For example, the availability of an element for leaching depends a great deal on its site within a mineral lattice and the resistance of the mineral to dissolution. In the case of olivine, for example, magnesium and ferrous ions are held on the edges of isolated tetrahedra and are easily detached. In the case of alkali feldspars the mobile ions of potassium and sodium are held in a framework of linked tetrahedra which hinders their escape. Nevertheless, within a limited situation, weatherability can sometimes be related directly to minor chemical variations, for example within the feldspars, in an area of granitic rocks, since the feldspars form a continuous series with almost infinite gradations in composition.

3.2.2. Mineralogy In the case of crystalline rocks, ion bonding strength or weakness appears to be important. In general, the higher the temperature of crystallisation, the more readily the mineral may be disintegrated by hydrolisis. This variable susceptibility can also be expressed in terms of $Si:O_2$ ratio. The ratio decreases as substitution of Si by other cations increases. The lower the ratio the more susceptible to weathering is the mineral. The two groups of silicate minerals, the ferro-magnesian minerals and the feldspars, can be generally ranked in order of susceptibility and this series (after Polynov 1937 and Goldich 1938) corresponds with the Bowen Series (order of crystallisation from a silicate melt), as shown in table 3.

Olivine
1:4* Pyroxene (Augite)
1:3 Hornblende
4:11 Biotite
2:5 Orthoclase–Quartz–Muscovite
3:8

Calcic-Plagioclase 1:4 Sodic-plagioclase 3:8

Least stable ——————→ *Most stable*

* Ratios are given for $Si:O_2$.

Table 3

Again, in practice, this order is not adhered to in natural weathering. Biotite, for example, frequently weathers more rapidly than hornblende (eg Eggler et al. 1969). This has been attributed to the large size of the crystals which tend to be fractured in the fresh rock (Thomas 1974). (Biotite is rather weak and during the final stages of crystallisation when the very hard quartz and orthoclase crystals are battling for elbow-room the biotite tends to be a casualty...).

In the case of granitic rocks, susceptibility to weathering appears to depend to a considerable extent on (a) presence of biotite and (b) nature of the feldspars.

The susceptibility of biotite is well seen in hand specimen - apparently otherwise unaltered rock is spotted with the reddish weathering products of biotite dissolution. It appears that the initial penetration of moisture (where fissures are absent) is along grain boundaries and along twin planes. These become etched by dissolution. As soon as this penetration reaches a biotite crystal it is rapidly altered. Early alteration apparently involves expansion which mechanically prises apart the rock, thereby facilitating further penetration of moisture along adjacent grain boundaries, to reach other isolated biotite flakes and so on. Thus, the effect of the presence of biotite is two-fold. It facilitates deep penetration of weathering without much change in mineralogy and it facilitates disaggregation of the rock to form gruss (see Section 4.3). There are good indications that the gruss zone is favourably permeable. Thus a granite containing biotite might be expected to yield a thicker gruss zone and this may be important for water supplies, particularly if the biotite granite is fractured as this would be expected to deepen the penetration of gruss formation, extending the thickness of this basal zone. This favourable permeability appears to be in essence the result of mechanical weathering - the physical prising apart of the rock by expansion of a few dispersed weathering grains. The effect appears to be reduced when weathering advances because, when the other rock minerals are weathered, the material is generally more competent and lacks susceptibility to mechanical disruption. It is only because the bulk of the rock is still unaltered and incompetent that the disruptive effect of biotite is so clearly marked.

The nature of the feldspars also greatly affects granite weathering (eg Rougerie 1960). Dissolution of Na and Ca feldspars (plagioclase) is more rapid than that of the K-feldspars (eg Melfi et al. 1983) and of these the first to be affected appears to be the calcic plagioclase (Thomas 1974). Ruxton and Berry (1957) observed that 'when part of the plagioclase has decomposed, and the orthoclase is beginning to be attacked, the rock breaks down into platy fragments of decomposed granite called gruss'. It seems then, that in the absence of biotite, it is the plagioclase, especially calcic, that functions as 'gruss-maker'. However, in such cases a gruss horizon is likely to be thinner. In effect, the wider the range of weathering susceptibility of the minerals the greater the depth of weathering and in particular the depth of gruss horizon. When the orthoclase has weathered to kaolins, the saprolite stage is reached (see Section 4.3) and, although the material retains the original rock structures and textures, it can be completely disintegrated by hand into sand and clay.

3.2.3. Textures It is said that in finer rocks the decay of one mineral has generally less effect (Thomas 1974), but it is difficult to be sure of this because it is based on comparisons of very different rocks, eg. granites and basalts (chemically different and with minerals which have a different range of susceptibility).

Setting aside the role of the early weathering of a particular mineral, there is evidence that coarse grained rocks weather more rapidly in the sense that penetration of weathering is more rapid (i.e. deep as opposed to advanced weathering). This is attributed to the smaller total surface area of the grains, in relation to volume. Where grains are smaller and therefore where rather more surface dissolution is required to achieve deep weathering, depth penetration is slower. This can be seen, for example, at Pocos de Caldos, an alkaline extrusive in Minas Gerais, Brazil. There the fresh rock penetrates higher in the profile (figure 16) where the grain is finer (Aleva, pers. com.).

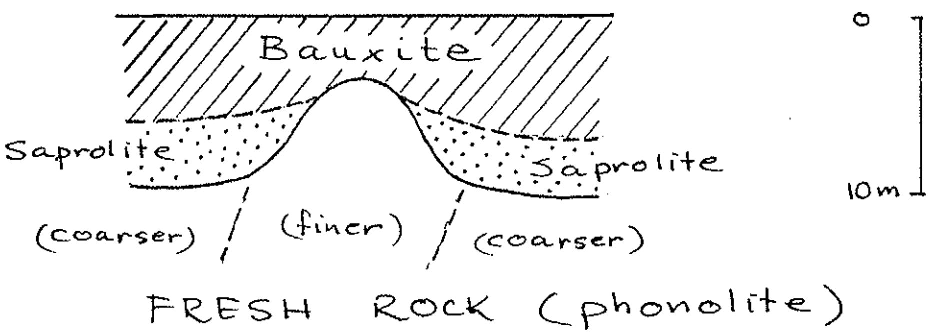


Figure 16

Conversely, although depth of weathering is favoured by larger grains, advancement of weathering is favoured by smaller grains, i.e. progress through the mineral progression (see Section 4.1) is more rapid.

3.2.4. Structures

Joints The presence or absence of joints is well known to influence the resistance of rocks to mechanical erosion. Clearly they also facilitate chemical weathering, providing relatively easy entry points for leaching solutions. For the purpose of this discussion joints can be grouped into three classes. Syngenetic joints and fractures may occur within granitic bodies (sheet joints) aligned with the margins of the intrusion. Similarly orientated joints may also occur in the stressed country rock. Their scale varies greatly. They may be sufficiently well developed to allow macroscale entry of water, which greatly facilitates weathering, or they may be microscale - "potential joints" only identified by zones of fractured or cleared (stressed) crystals or layers of tiny fluid inclusions in grains (Chapman 1958, Bisdom 1967, Birot 1962). These joint systems may be very deep but the depth to which their presence facilitates penetration of moisture is not known. Post-genetic joints are of three kinds. Joints may result from tectonic deformation of an area. Pressure release fractures follow the topography. They are well known on inselbergs and they appear also to occur beneath the saprolite on the relatively flat intervening plains. To what extent the depth of the saprolite affects their development is not known. At abrupt changes of slope on the basal surface of weathering, two differently orientated joint systems may intersect to give a zone with more frequent fractures. As suggested elsewhere, such intersection may contribute to the 'sharpening up' of emerging inselbergs, by facilitating weathering around their base. A separate system of micro-joint formation, weathering fractures, as already indicated, can be recognised where the weatherability of a single mineral far exceeds that of the remainder of the rock minerals and where its weathering and expansion fractures the rock to form gruss. These latter two joint classes - pressure release and weathering joints - are more frequent and variable in direction (and therefore intersection) where rocks are more heterogeneous. Thus, the most homogeneous granites, the 'mantle' granites (I granites), formed by differentiation, are likely to have a wider and simpler fracture system than the S granites (orogenic granites) and would be expected to be more resistant to weathering. Within the S granite class, there are granites and granites and we should expect to find a rather variable but generally greater susceptibility to post-genetic jointing and weathering, depending on, for example, the occurrence of xenoliths and migmatite zones. The variable topographic relationships between granites and country rock could well be explicable in terms of variations in susceptibility to fracturing. For example in much of West Africa, granites stand as inselbergs between more deeply weathered plains underlain by metasediments, while in south and west Uganda the metasediments form the topographic highs, with the more deeply weathered granites forming arenas within the metasedimentary areas (figure 17). From the work of Acworth (1981) it emerges that in N Nigeria, the heterogeneity of the metasediments leads to extensive fracturing which has apparently facilitated weathering. In contrast, in S Uganda, the grade of metamorphism of the Buganda Series is low (the basal quartzites still show ripple marks) and the individual sedimentary facies are thick and uniform. Such massive, relatively homogeneous 'welded' sediments are likely to be relatively less susceptible to fracturing and this could well be an important factor in their superior resistance, in comparison with the granite.

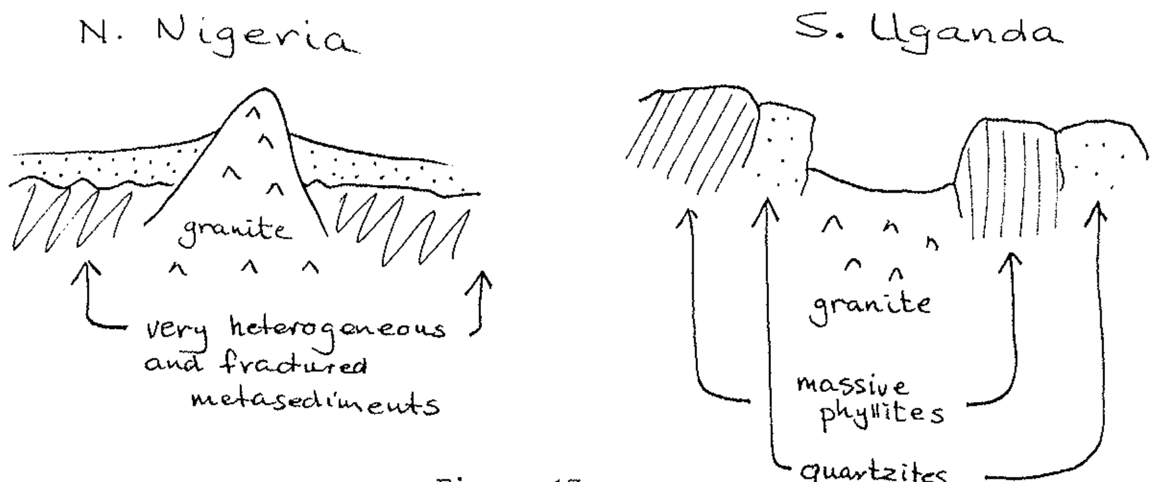
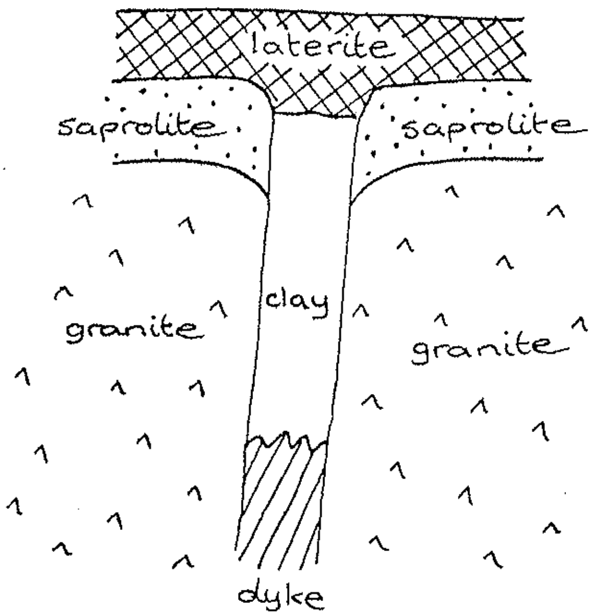


Figure 17

<u>Dykes</u> Where these occur in granitic areas they are commonly found to be much more deeply weathered (figure 18).



<u>Figure 18</u>

It has been suggested that the dykes also facilitate the weathering of the granite itself by introducing a lateral weathering attack on the granite body in addition to the normal vertical attack from the surface downwards. Hence a granitic area with dyke swarms might be expected to weather more deeply than one with no swarms. However, because dykes weather to form sticky, rather impermeable clays, zones of deeper weathering attributable to this may not be favourable for groundwater supplies, being, in effect, riddled with clay walls which may limit lateral recharge to the extraction area.
Such dykes may also have a much wider significance for regional depth of weathering because of this tendency to weather into very tight, sticky, almost impermeable clay. Thus, a dyke positioned across a groundwater drainage basin, even though completely weathered itself, introduces a limiting factor for groundwater evacuation which may restrict depth of weathering on the upstream side. The effect would be very similar to that produced by bands of fresh rock (figure 19).

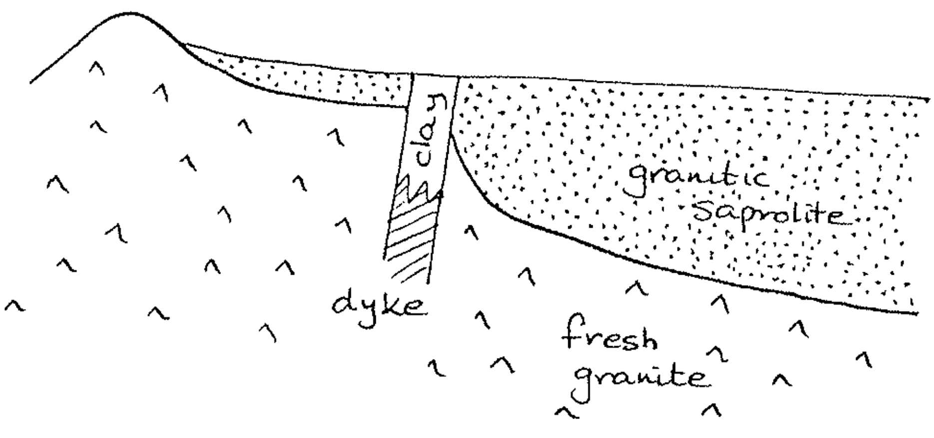


Figure 19

A kaolinised (clay) dyke, aligned in the direction of the groundwater flow could well be expected to effectively divide the drainage basin into chemically separate and quite distinct units (figure 20).

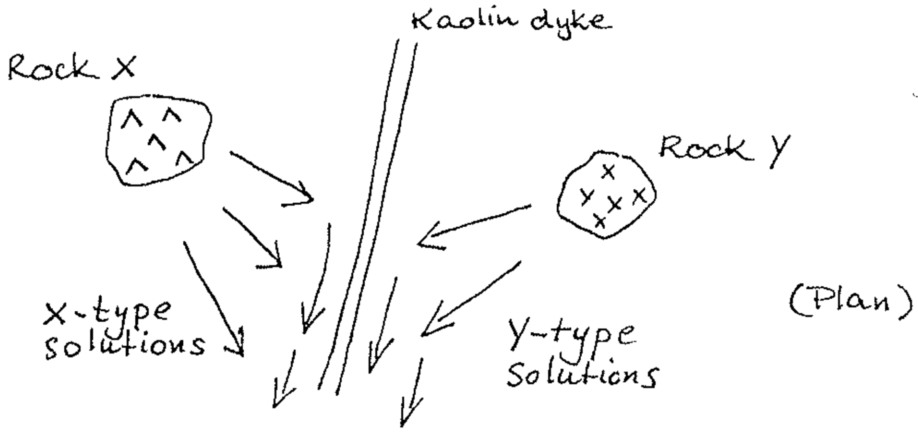


Figure 20

This relative impermeability of kaolinised dykes thus introduces an interesting range of possibilities for water quality and depth of weathering. Two parallel dykes, for example, could 'confine' a discrete groundwater drainage system, chemically distinct from waters outside their confines (figure 21).

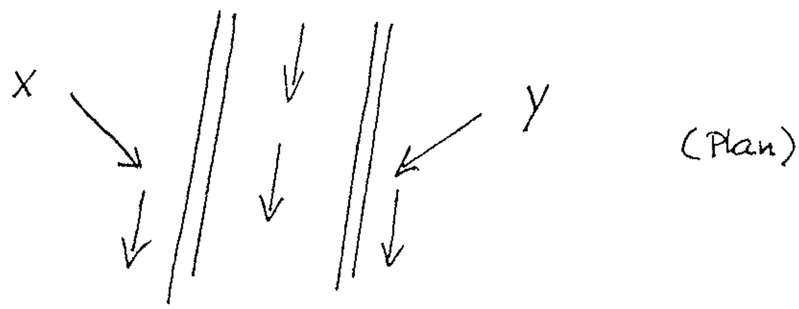


Figure 21

Other structures Gaskin's study (Gaskin 1975) of synclinal structures associated with bauxitised residua in Tonkolili, Sierra Leone, provides a most interesting insight into structural influences. The situation is a plateau, with free drainage and thus the effects are more extreme than would be expected in a plains situation, but they are likely to occur there also, albeit at a more subdued level. The synclines comprise rocks with variable feldspar content and hence different proportions of clay in the weathering product. The more felspathic rocks yield relatively impermeable horizons which, in a pitching syncline, channel the water in such a way that the more permeable (originally less felspathic) horizons are most extensively leached, particularly in the lowest part of the syncline (figure 22).

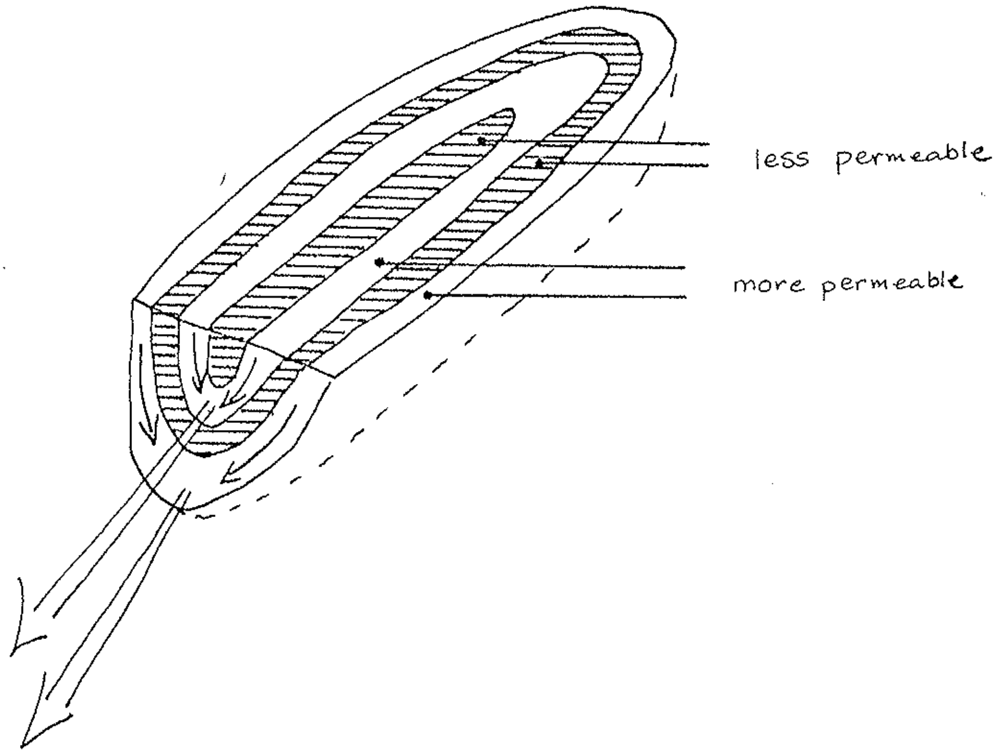


Figure 22

Gaskin's study suggests that we should place some importance on the permeability of individual saprolite 'facies' within an area of metasediments. It implies that within an overall system of solute evacuation, defined by a weathering basin, there may well be several quite distinct solute evacuation systems separated by relatively impermeable clay 'facies'. We may have to think in terms of superimposition of the effects of lithology (structural variations in permeable saprolite 'facies') on a 'normal' sequence of up-profile weathering stages, each with different permeability.
The aspect of the strata may also influence depth of weathering. For example, where beds lie parallel to the direction of groundwater drainage, weathering is sometimes shallower because water is 'shed' by the bedrock planes. Thus, on two sides of a valley the weathering is sometimes deeper on the side where the beds are truncated by the valley, apparently because the bedding planes facilitate weathering penetration (eg. Butt,1975) eg. figure 23.

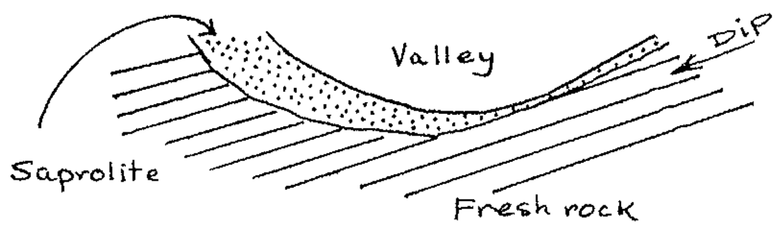


Figure 23

The relative positions of rocks with variable resistance to weathering, in relation to groundwater drainage direction, is often important. For example, in Uganda, rocks which are resistant to weathering form falls or rapids along streams and above the falls the rocks are less deeply weathered than apparently similar rocks below them, presumably because the fresh rock barrier retards the groundwater movement and evacuation of solutes (figure 24).

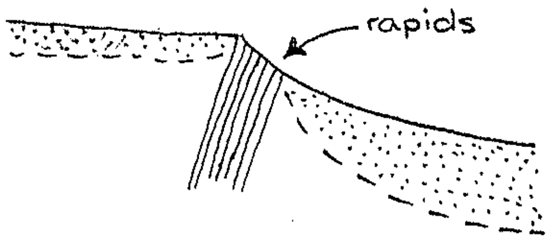


Figure 24

Similarly, phyllites 'enclosed' within quartzite ribs in upland areas are less deeply weathered than in areas beyond the confines of the ribs, presumably for the same reason - restricted evacuation of solutes (figure 25).

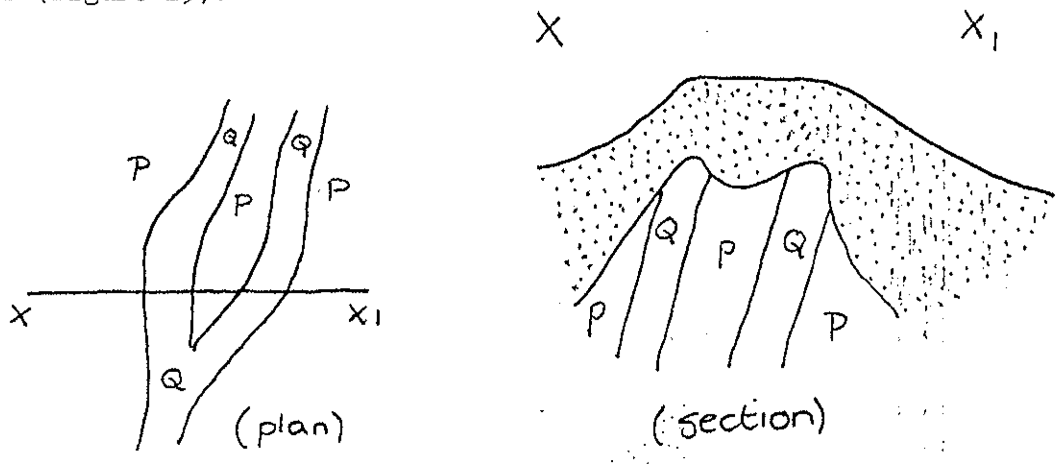


Figure 25

In short, there seems little doubt that within a given area, an understanding of weathering depths, and groundwater quality and behaviour, is heavily dependant on considerable knowledge of the geological background, upon which is superimposed the effects of the leaching history.

3.3 The influence of geomorphology on weathering history.

3.3.1 Regional patterns of deep weathering and erosion surface

I am inclined to agree with those who indicate that there is a 'characteristic' weathering depth or profile on landsurfaces of particular ages within any particular region.This may be more appropriately couched in terms of a different range of weathering depths over various rock types associated with different erosion surfaces, and if observations of weathering depth and lithology are sufficiently frequent to draw generalisations from particular topographic positions then their validity is increased.Southern Uganda provides an example. Over the Buganda Surface interfluves, quartzites are weathered to 150-200 ft. Over the Ntenga Surface interfluves, fresh quartzites reach very close to the landsurface. On the Kasubi and Tanganyika Surfaces, quartzites ribs stand as 'inselbergs' in interfluve areas, reaching up to 150 ft and nearly 300 ft above these respective surfaces (McFarlane and Brock 1983). Within a given region, I think such generalisations can be made and when faced with statements to the effect that, intra-regionally, weathering depth is significantly different at different places on a planation surface of a particular age, I would be inclined to look first for an explanation in terms of one of two things - either (a) differential post-incision leaching or (b) polycyclic surface development.

(a) Since leaching does not stop when a surface is incised, it is possible that deformation may favour deeper weathering in certain areas. For example, if a low relief surface has a characteristic weathering depth and in one area it is gently upwarped, deep weathering may be facilitated by the freer drainage in the elevated parts (figure 26).

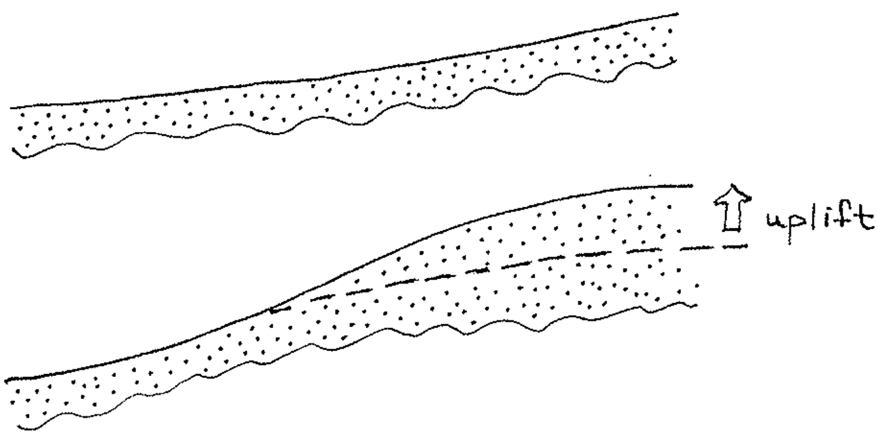


Figure 26

Such an event can be detected by a study of the incision of the drainage lines. Similarly, as already indicated (section 2.4), the depth of weathering and relative relief on the basal surface of weathering may increase towards the periphery of an extensive, elevated, erosion surface remnant, the result of accelerated deep weathering where the groundwater gradient responds to incision of the landsurface (figure 27a). It may sometimes be possible to identify the locus of this change in weathering depth because profile compaction or enrichment sometimes results in a slight change of slope on the landsurface itself (figure 27b).

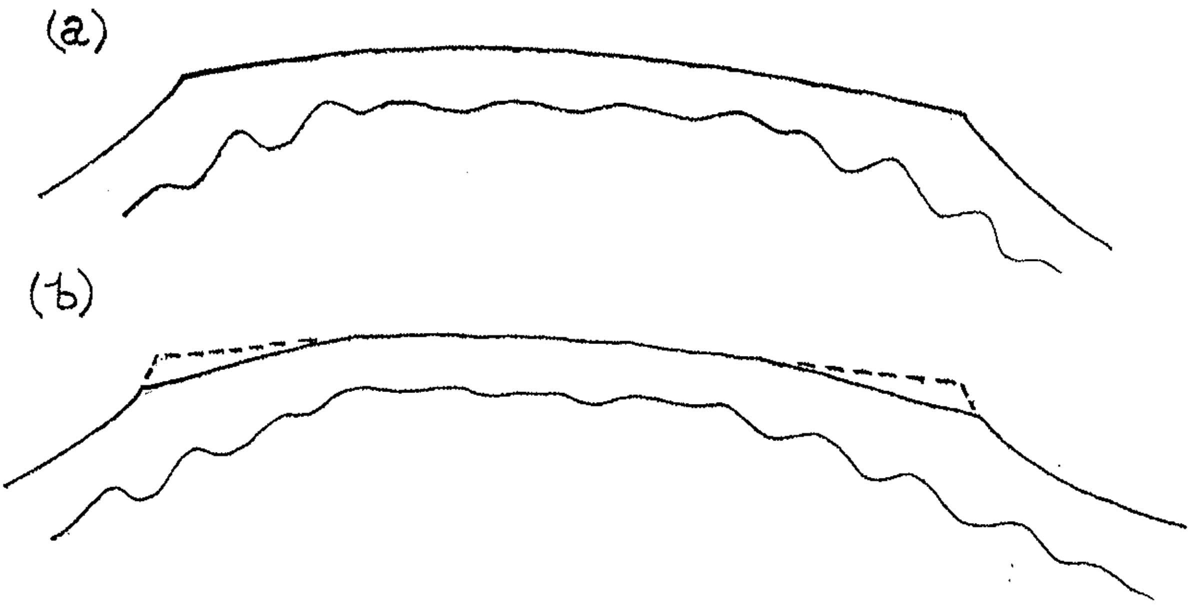


Figure 27

Weathering profiles are very closely related to the leaching history and there is often a surface expression of this. The changes of slope involved may be very slight indeed, but can now be detected by cartographic analysis (section 3.3).
(b) King's masterly overview of world morphological events (King 1962) inevitably painted with a rather broad brush. The major surfaces he identified may be polycyclic. Wayland's PIII, in Uganda, provides an example. It was formerly thought to be end-Tertiary and is now understood to be considerably older and possibly equivalent to King's African Surface (Bishop & Trendall 1967). This major erosion surface is in reality a multiplicity of surfaces with small vertical separation. Changes of slope bounding the facets are often so slight as to go undetected on the ground and on air photos, but may be identified by cartographic analysis. The occurrence of such polycyclic facets may have profound results for depth of weathering. For example, where landsurface movement (lowering) is faster than the lowering of the basal surface of weathering, the depth of weathering may be least on the youngest surfaces (figure 28).

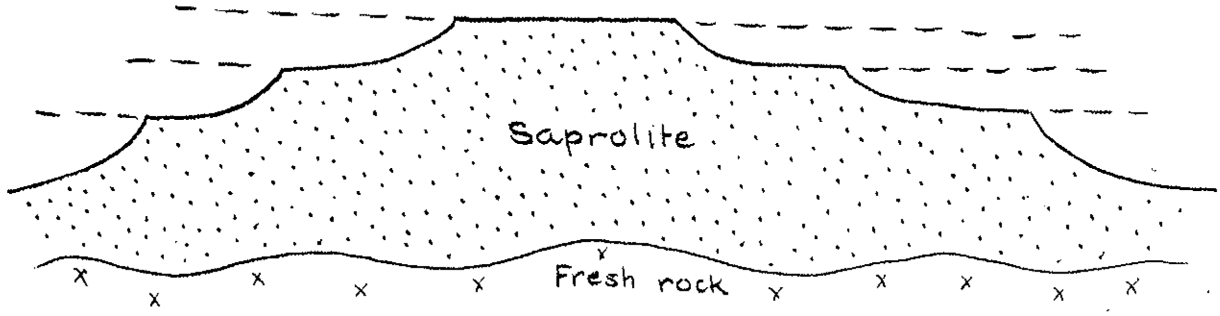


Figure 28

Where lowering of the basal surface of weathering is accelerated by the increased freedom of drainage, as a result of the increased 'shedding' from the 'highs' on the basal surface of weathering, the profile may become deeper under the younger surfaces (figure 29).

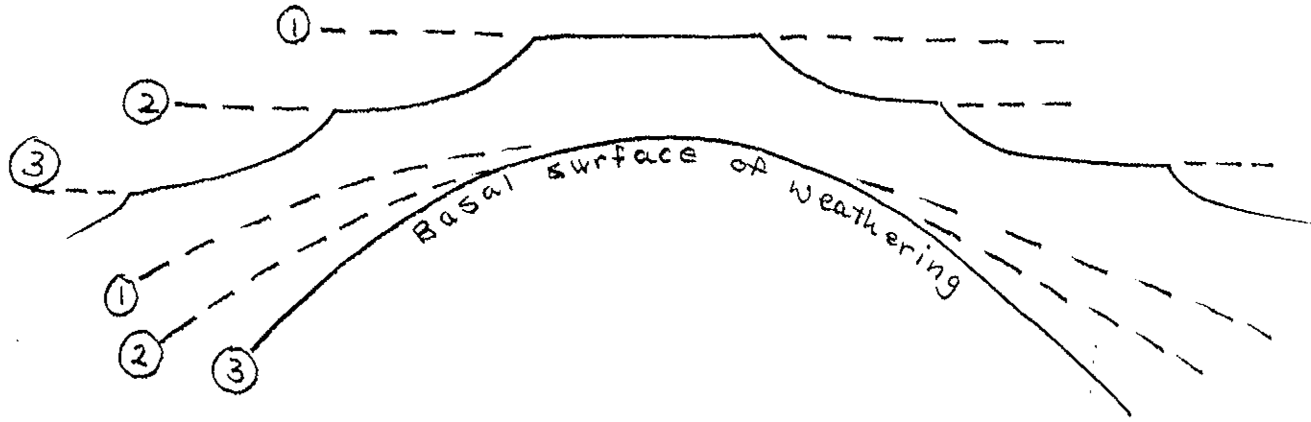


Figure 29

In essence, we are looking at a rather delicate balance between the rate of landsurface lowering and the rate of lowering of the basal surface of weathering, so any evidence of a change in the rate of landsurface lowering must be taken as likely to have an important effect on depth of weathering. Relationships between depth of weathering and landsurface facets on a polycyclic surface of very low relief have never been examined. The means of recognising and analysing their polycyclic nature was not until recently available (see section 3.3).

3.3.2 Dating landsurfaces

If there are characteristic weathering profiles associated with landsurfaces of particular ages, then it becomes important to be able to recognise areas of landsurface that are similarly aged (whatever the age). The previously popular criteria for recognising the relative ages of landsurfaces are now known to be fraught with problems. Breaks of slope bounding landsurfaces. These were formerly taken, with unjustified confidence, to indicate that above the break the landsurface is older than below the break. This need not be the case. For example, if the old, deeply weathered landsurface is warped and the regime of the younger period favours pediplanation, the result is as shown in figure 30.(The sub-Elgon scarp seems to be an example.)

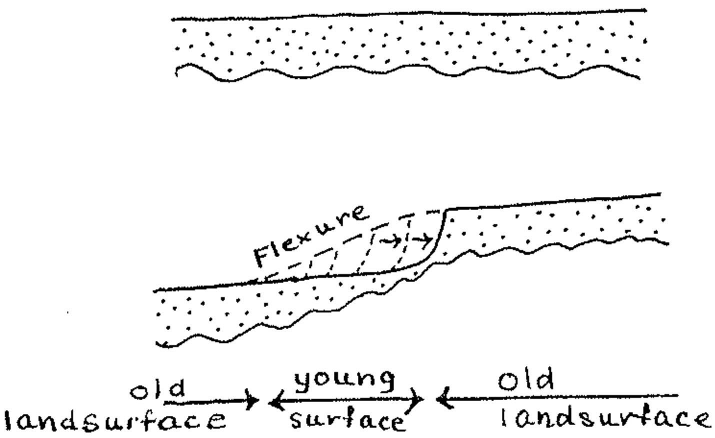
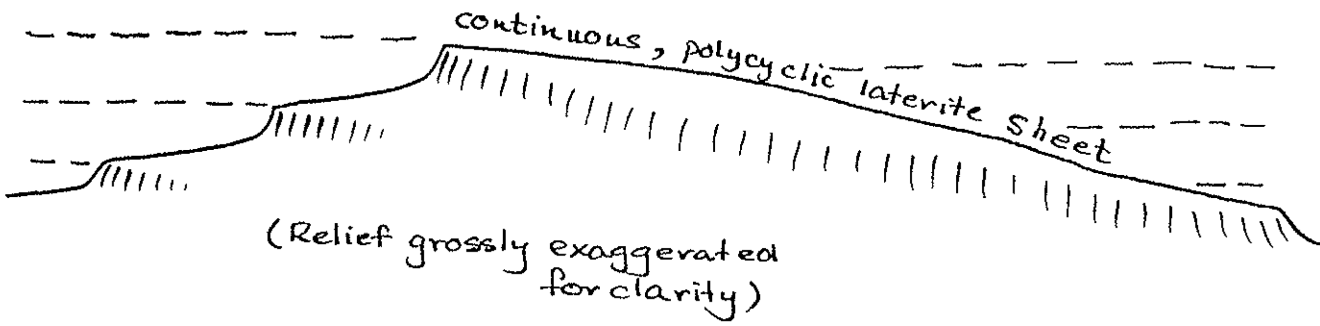


Figure 30

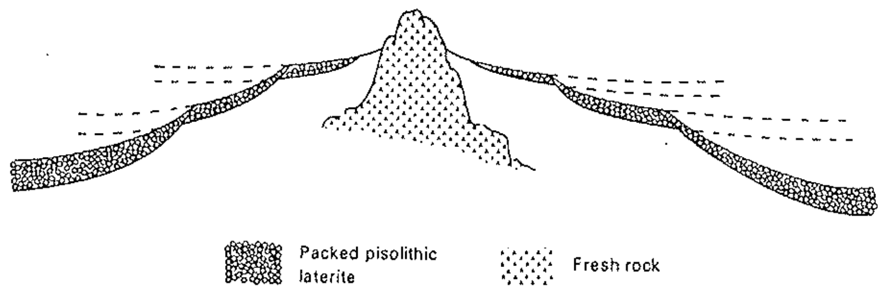
Another source of error is the belief that the break of slope which bounds a continuous sheet of laterite encloses a chronological and genetic entity, i.e. the laterite covered landsurface above the scarp is older than the surface below the scarp. These scarps may develop as polycyclic features and they may bound polycyclic surfaces, the lower parts of which are chronologically equivalent to pediments below the highest part of the scarp (McFarlane 1981).



In short, in the relative dating of landsurfaces I think that breaks of slope need close scrutiny before they can be used with confidence to delimit surfaces of different ages.

Continuity of laterite sheets

The existence of a continuous laterite sheet has been given quite unwarranted importance in landsurface recognition. The practice of regarding such a sheet as a monocyclic, genetic entity stems from the former belief that only after a planation surface has developed can laterite begin to form; the stable landsurface and oscillating water-table were seen to be prerequisites for laterite formation. Thus, every sheet of laterite was believed to 'mark' a planation surface. This is quite wrong. The development of a lateritic residuum occurs during a late stage of landsurface reduction, when slopes are low. When such a surface is incised, where slopes are steep the profile is undercut to give a scarp which breaks the continuity of the laterite, but where incision is gentle, the laterite profiles may be reworked (groundwater laterite) or may simply continue to form (pedogenetic laterite). There are now many recognised examples of polycyclic laterite sheets. For example see figure 31.



Recurrent gentle rejuvenation of an immature packed pisolithic groundwater laterite in effect protracts the early stages of the groundwater laterite familial progression, leading to the formation of very thick sheets of packed pisolithic laterite. Although these are continuous with the progressively thinner and higher sheets, changes of slope occurring between them indicate the polyphase or polycyclic nature of the continuous blanket.

The Darling Range, W.Australia.

Figure 31

The assumption that all parts of a continuously lateritised surface are chronologically equivalent has led to serious misdating of landsurfaces. If the tectonic activity (elevation), which terminated one surface and initiated another, was great, then chronologically separate surfaces were recognised (because the sheets are separated). Where tectonic disturbance was slight, the continuity of the laterite was seen to indicate a single surface (figure 32).

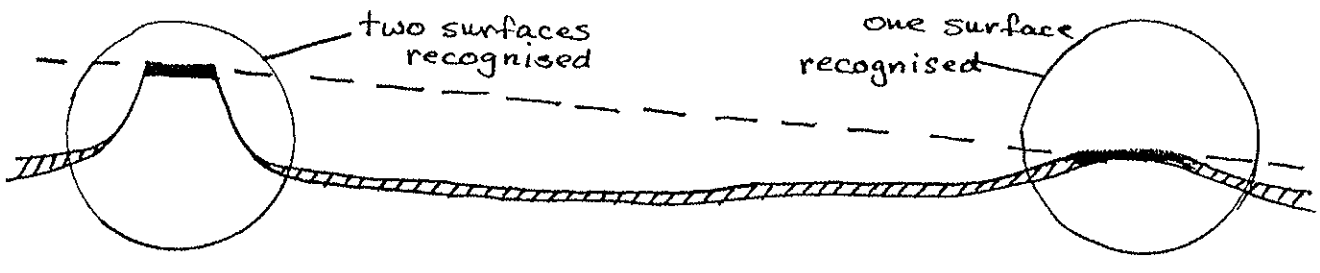


Figure 32

We are familiar with the fact that landsurfaces cannot be recognised or dated by their absolute altitude. However, where closely spaced surfaces, which may be of entirely different ages, are blanketed by continuous laterite, there is still a widespread failure to recognise that the continuity is very much a red herring.

Mesas and pediments

A major source of error in dating lateritised surfaces is the assumption that topographic position can be used. De Swardt (1964) is a protagonist of the argument that because laterite occurs in two topographic positions throughout vast areas of Africa, there are two lateritised landsurfaces, recognisable by their positions on mesas or pediments. Thus, where a laterite-capped mesa is low or high, then the surface was assumed to have been originally either high or low at those localities, or it may have been downwarped or upwarped. The fallacy of this reasoning is clear in Southern Uganda, where any of the four lateritised surfaces may occur on mesas, depending on the degree of incision (figure 33).

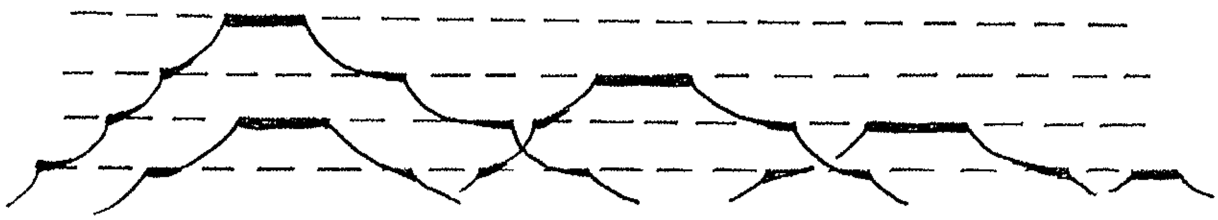


Figure 33

An example of the dating error which results can also be provided from this area. The 'high level' mesas extend no further eastwards than Jinja (figure 34).

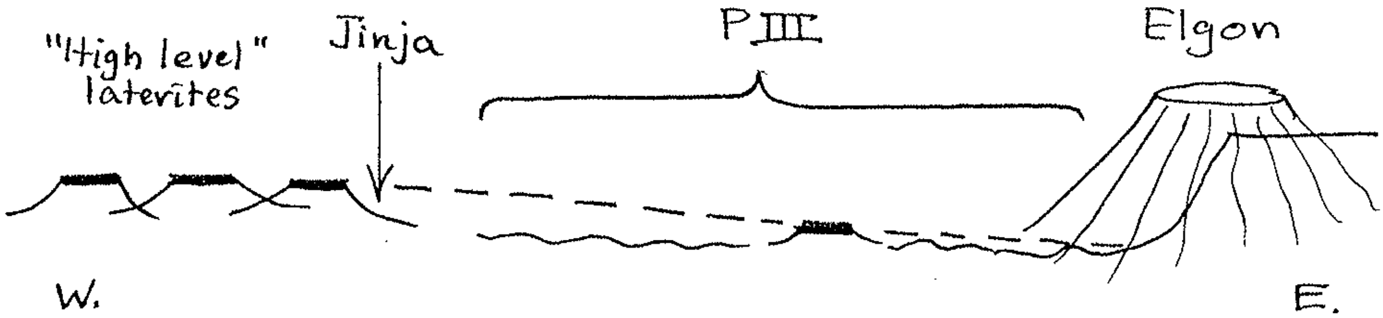


Figure 34

To the east, on PIII, occurs a single laterite capped mesa at a lower altitude. De Swardt and Trendall (1970) used this to argue that the 'high level' surface feathers out against the Elgon escarpment, as shown in figure 34, i.e. that the surface above the escarpment is older than the 'high level' laterite surface in Buganda. In fact the 'high level' surfaces are upwarped eastwards. The low mesa in the PIII area is equivalent to one of the lower laterite surfaces, the Kasubi and Tanganyika Surfaces, predominantly on pediments west of Jinja but also on mesas where incision is good (McFarlane & Brock 1983).

We simply cannot use the topographic position (on mesas or pediments) to date a lateritised landsurface.

Cartographic analysis

The relative dating of landsurfaces is by no means as easy as was formerly assumed. Sadly, study of denudation chronology has rather lapsed in the tropics, for two reasons. Decolonisation saw the departure of those concerned with denudation studies and saw something of a re-adjustment of priorities which relegated rather a lower place to what were seen to be 'white elephant' academic studies, including denudation chronology. At the same time, it fell from grace in Europe and America, with the rising popularity of 'process studies'. Thus, denudation chronology was left in rather a state of limbo in the tropics, at the point where we knew that our approach needed refining if it were to produce better results, but the climate was generally unfavourable for the examination of new approaches to the problem. Certainly we need much tighter geomorphological analyses. Many of the traditional criteria for landsurface recognition are inapplicable and the traditional cartographic analyses are inadequate (McFarlane & Brock 1983).

Recently, some progress has been made in this direction. Multifacet surfaces can now be divided into separate facets using the technique of plotting inter-contour distances, along profile lines, against altitude. A series of profile lines are drawn directly on the map, running from interfluves into the valleys. There is no need to draw the profiles. The distances between the contours are plotted against altitude categories (figure 35).

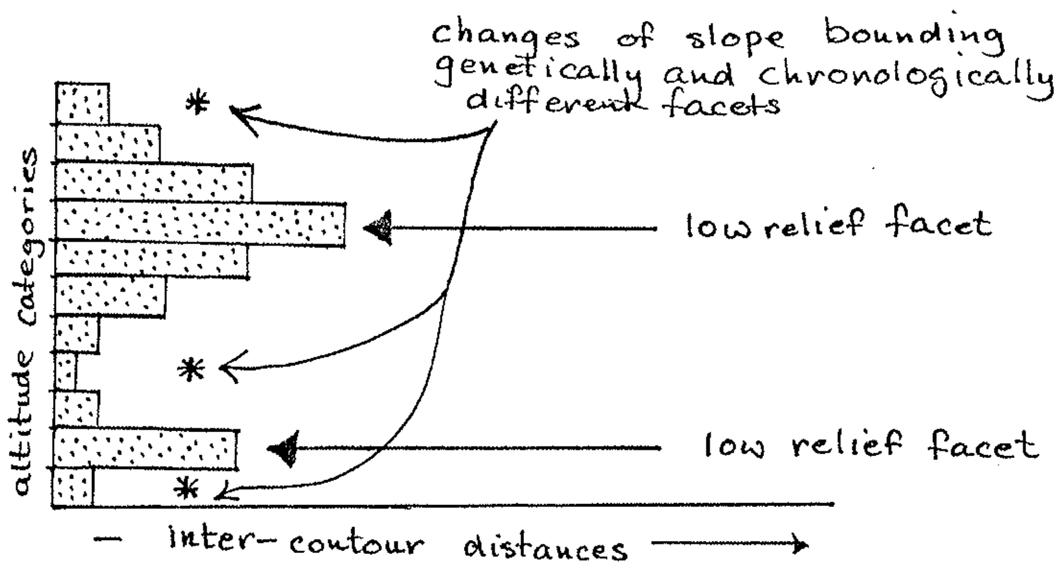
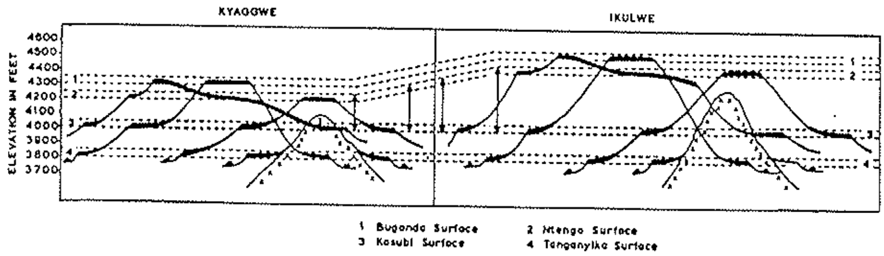


Figure 35

In effect, this gives slope variations at different altitudes. It is necessary to sum the distances for several profiles on each interfluve, to firmly establish the number of facets and their heights, since one or more facet may not appear on any particular profile line. This gives the altitude of the changes of slope. These can then be mapped, to provide a detailed chronological/genetic breakdown of the low relief landsurfaces. It was tested along a 70 mile long belt on the Kyoga/Victoria watershed, where four closely-spaced surfaces occur. Despite the fact that they are linked by detrital laterites and are tectonicaly deformed, they were identified throughout the area and the two upper surfaces were shown to have been upwarped to the east prior to the formation of the lower two. It also showed that the depth of weathering (depth to fresh rock 'highs') associated with each surface is consistent throughout the belt. In effect, the depth of weathering is a good guide to landsurface recognition (figure 36).



(McFarlane & Brock 1983)

Figure 36

Inter-regionally, depth of weathering and the nature of the weathering profile and residual crust do not appear to be good guides to landsurface recognition. The very deeply weathered and lateritised Buganda Surface now appears to be of Gondwana vintage and yet elsewhere in Africa this surface is reputed not to bear a laterite (King 1962).

3.3.3 Valleys

It is very commonly the case that, in a polycyclic situation, river valleys excavate and younger surfaces develop where the weathering profile is deepest (figure 37).

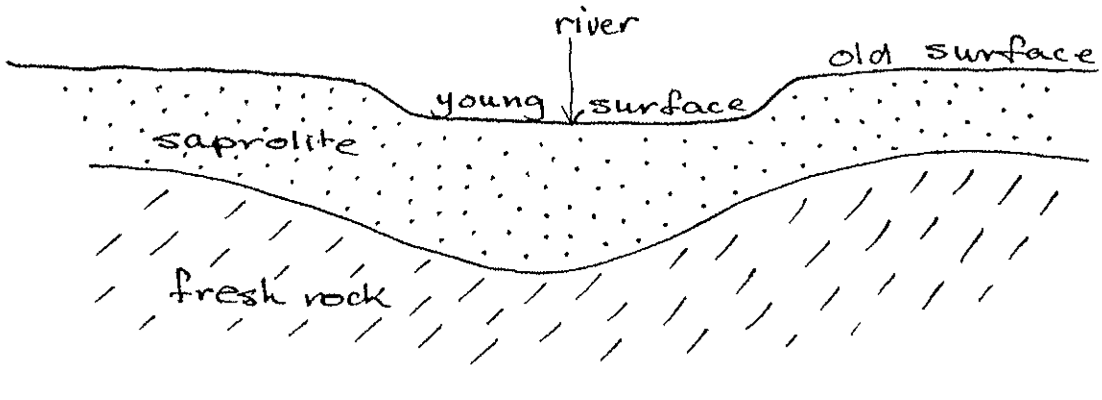


Figure 37

We are familiar with the sensitivity of rivers to variations in lithology. Soft rocks are readily excavated and form lowlands etc. But, given a situation where the rocks are 'insulated' by a ubiquitous weathering mantle, this would appear to preclude the possibility of a lithological control on the locus of younger surface development. So how do we explain the preferential incision where weathering is deepest? It certainly raises the question "is river incision so sensitive that it can respond to variations in the saprolite itself?" I am inclined to think that the answer is yes. It seems that rivers can excavate with greater ease where the underlying material has a higher proportion of clay in the saprolite. Thus, a rock which weathers to yield a higher proportion of clay (eg. a more felspathic rock) might in this way influence river incision and such rock would be expected to weather relatively readily and deeply (figure 38).

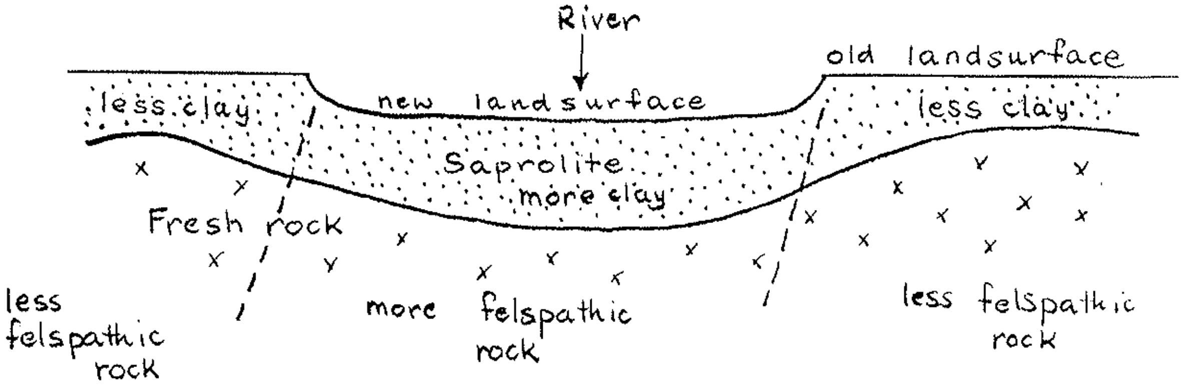


Figure 38

It is also possible that where weathering is deepest, it is also more advanced in that the later stages, with a higher proportion of clay, might be better developed in the upper horizons (figure 39). Thus the different stages of profile development associated with different depths of weathering could be a decisive factor in itself. All this is highly speculative as no-one appears to have looked for such a relationship.

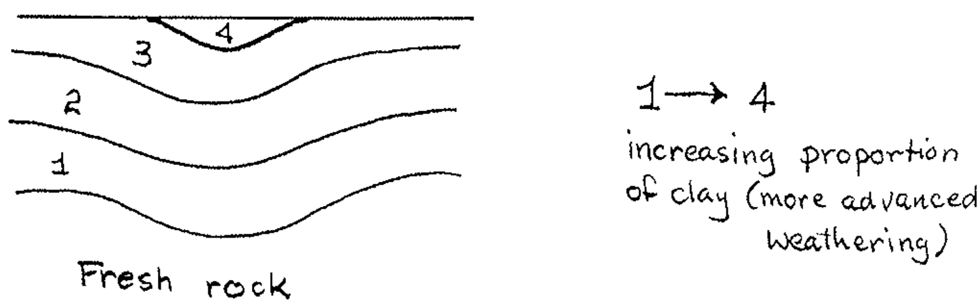


Figure 39

Thomas' study of deep weathering (Thomas 1974) raised two points which he saw as intriguing problems for further research.

1. In deeply weathered areas, fresh rock outcrops more frequently in river beds.
2. The depth of weathering often increases away from the rivers.

As concerns the first of these, I am not sure that I see the problem (but perhaps I am missing something....). Given a situation where there is an irregular basal surface of weathering and a river incises so that its bed is the lowest part of the landsurface, then the chances of fresh rock being reached by the river must surely be greatest (figure 40).

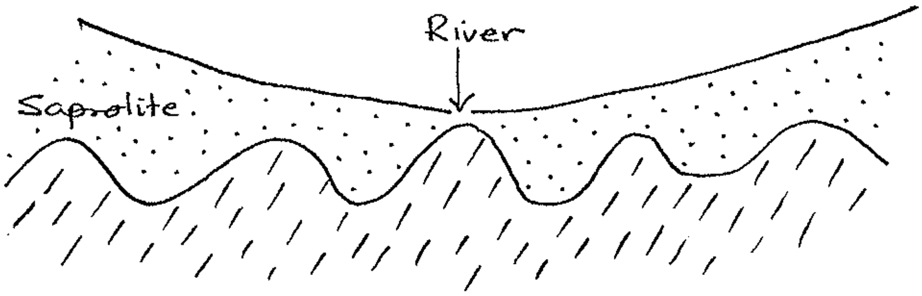


Figure 40

As concerns the second point, if a river reaches the 'highs' of the basal surface of weathering, then locally the weathering will be deeper away from the river (so what?); see figure 41.

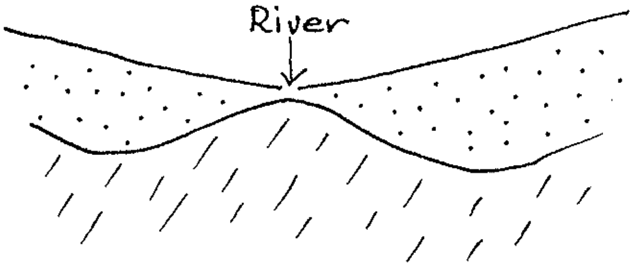


Figure 41

Further, when Thomas says that the depth of weathering increases away from the river this could perhaps merely be an expression of the fact that the landsurfaces rises away from the river. Thus, given a completely flat weathering front, depth of weathering would increase away from the river (figure 42).

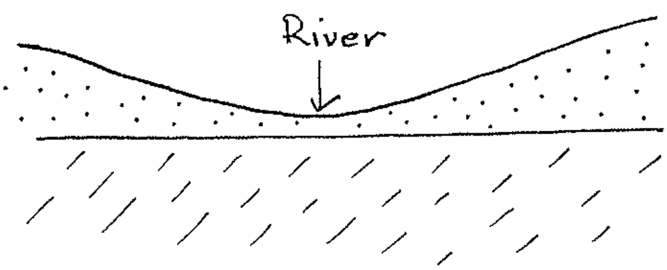


Figure 42

And, given an irregular basal surface of weathering, the average depth of weathering would increase away from the river (figure 43).

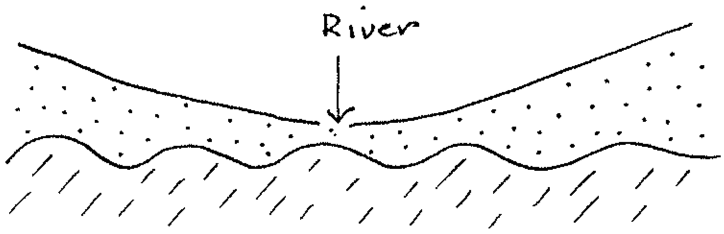


Figure 43

Thomas appears to imply that weathering is favoured away from the streams. If this is so (perhaps I misread him ?) I doubt this very much.

3.3.4 Interfluves

It is commonly observed that the basal surface of weathering rise under the interfluves, i.e. the weathering profile thins over the crest of the interfluves. This raises a 'chicken and egg' problem ; is the interfluve where it is because it is underlain by rocks more resistant to weathering or is the rise of the basal surface of weathering the result of the existence of the interfluve there ? In many cases it is clear that the lithology influences the location of the interfluve. In others it is difficult to evoke such an explanation, for example where the drainage pattern is dendritic and completely without relationship with the underlying lithology. In such cases the weathered zone appears to act as a uniform surficial layer, effectively insulating the drainage pattern from the possible influence of the underlying rocks. The rise in this case would therefore seem to reflect a catenary variation in leaching potential. It seems reasonable to explain this pattern in terms of downslope movement of groundwater, shed from higher catenary positions, so that leaching in lower catenary positions is enhanced by this addition of water from upslope. This enhancement evidently operates at the base of the profile (figure 44), deepening it, rather than operating through the entire profile (since high catena weathering profiles are sometimes seen to be more advanced and compacted).

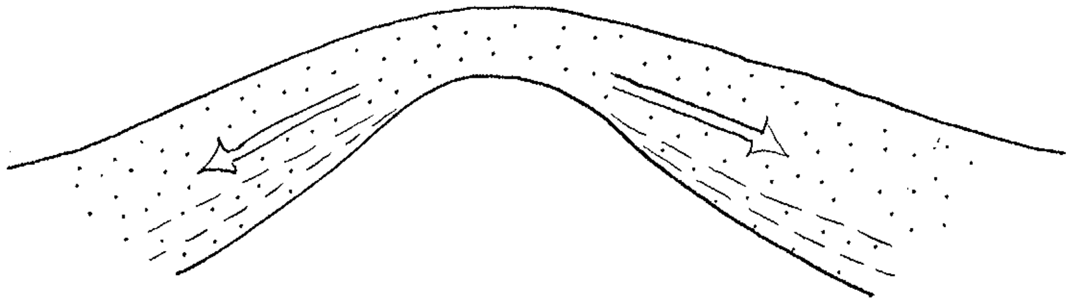


Figure 44

It also seems that repeated rejuvenation (slight) increases the effect; presumably the lowering of the base-level of erosion facilitates drainage of solutions from the lower part of the profile.

How do we know if the rise of the basal surface of weathering below interfluves is lithologically or topographically induced? As already suggested, drainage pattern provides a good indication. Dendritic patterns indicate a topographic control and divergence from this pattern suggests a lithological influence.

On any landsurface there is a tendency for a progressively more important role for lithology, in dictating the position of local interfluves, progressively towards the continental drainage divides.

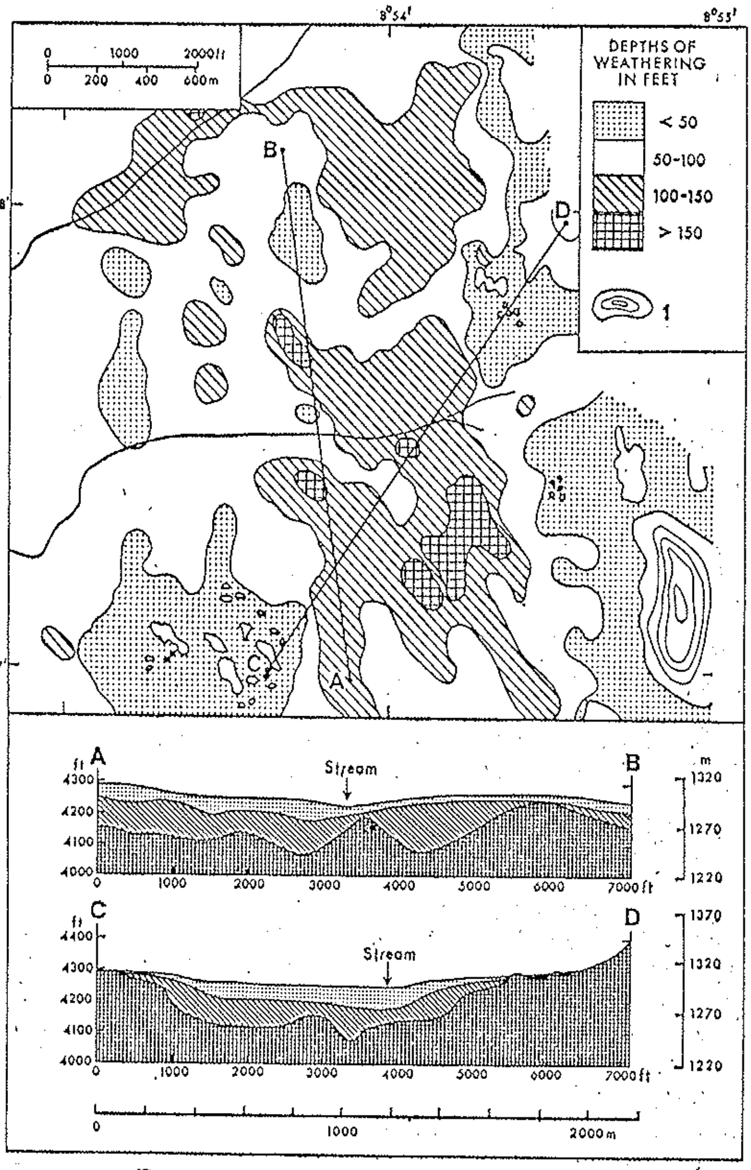
With landsurfaces of 'African' vintage, a lithological control on local interfluves along the divides is highly likely and with progressively younger landsurfaces the influence of lithology is expected to extend much further down the continental catchments. Where surfaces are young, even in the lower part of the catchments a lithological influence often occurs on local interfluve location.

3.3.5 Special sites

Enclosed basins - the "lows" on the basal surface of weathering

Thomas (1974) and others (Feininger 1971, Enslin 1961, p379) have demonstrated the existence of what appear to be large basins on the basal surface of weathering. They may reach, for example, over 150 feet deep (within a distance of about 500m of surface exposures of fresh rock) in fine-grained, biotite granite terrain near Jos, N. Nigeria. Here the area of the basins below 150 ft in depth was very varied, reaching up to 200m in diameter. It is noteable that the basins are not 'mirror images' of the inselbergs, the "highs" on the basal surface of weathering; they are much more gentle and shallow as 'topographic' features. Feininger did not draw isopleths of the basins but Thomas was able to map them (figure 45). In his study he only included records where the sampling interval was 200 feet or less (60m). In some cases the interval was 100 feet as on the Jos Plateau (Thomas, pers. com. 1984).

Other studies of the configuration of the weathering front have been surprisingly few. Faniran (1974) brought the Nigerian record more up-to-date and Brook (1978) published some regional trends for parts of the Transvaal. These broadly confirmed the results of Thomas' pioneering work in that they identified "highs" sometimes expressed as inselbergs, with intervening "lows", sometimes apparently enclosed. Thomas himself has been unable to pursue further study of the configuration of the weathering front, having made an unsuccessful attempt to secure NERC support for portable seismic work in 1971. More recently Omorinbola published the results of experimental work in Nigeria (Omorinbola 1981,1982,1983). His sample interval was very wide, giving reason to question the security of his conclusions. Thomas having



Deep weathering patterns in fine-grained, biotite granite near Jos, northern Nigeria.

1. Outcrops of unweathered granite, showing contours at 50 feet (16 m) intervals. On the cross-sections (A–B; C–D) sedentary regolith is diagonally ruled; the stippled material represents an alluvial fill.

Figure 45

paved the way, sadly there has been little further progress. One of the main problems is clearly data acquisition. Thomas confirms the existence of "lots of scattered records, but no analysis of closely spaced logs". He adds the comment that even boreholes for dam-site exploration (which we might expect to be a good source of data) "are often on a cross section and the result is almost two-dimensional".

The existence of large, relatively deep basins raises the interesting and hydrologically very important question of how the water at the base of these basins can be renewed, to maintain subsaturation concentrations and allow ongoing weathering within them.

There appear to be three possibilities.
1. In his book, Thomas cites and appears to favour the possibility that there is removal of concentrates upwards by a process of ionic diffusion. This follows Lelong's (1966) study of pore water in the zone of water-table oscillation, a study which indicated upward movement of water under conditions of non-saturation each dry season. Lelong interpreted this as diffusion, responding to a gradient of concentration. Thomas indicated that he believed this process could also act in such a way as to allow the products of hydrolysis, formed at the bottom of the basins, to migrate towards the surface. Without wishing to suggest that ionic diffusion does not operate to some extent it seems to me rather unlikely that tese basins essentially owe their existence to such a mechanism when more likely mechanisms exist.
2. Since the rims of basins are not at uniform height and the landsurface slopes, albeit gently, lateral ,movement of groundwater across the basins must surely occur. The aspect of the water body associated with these basins appears not to be known. We do not know, for example, if the gradient of the surface of the water body is unaffected by them (figure 46a) or if they induce some change in gradient, forming thresholds (figure 46b).

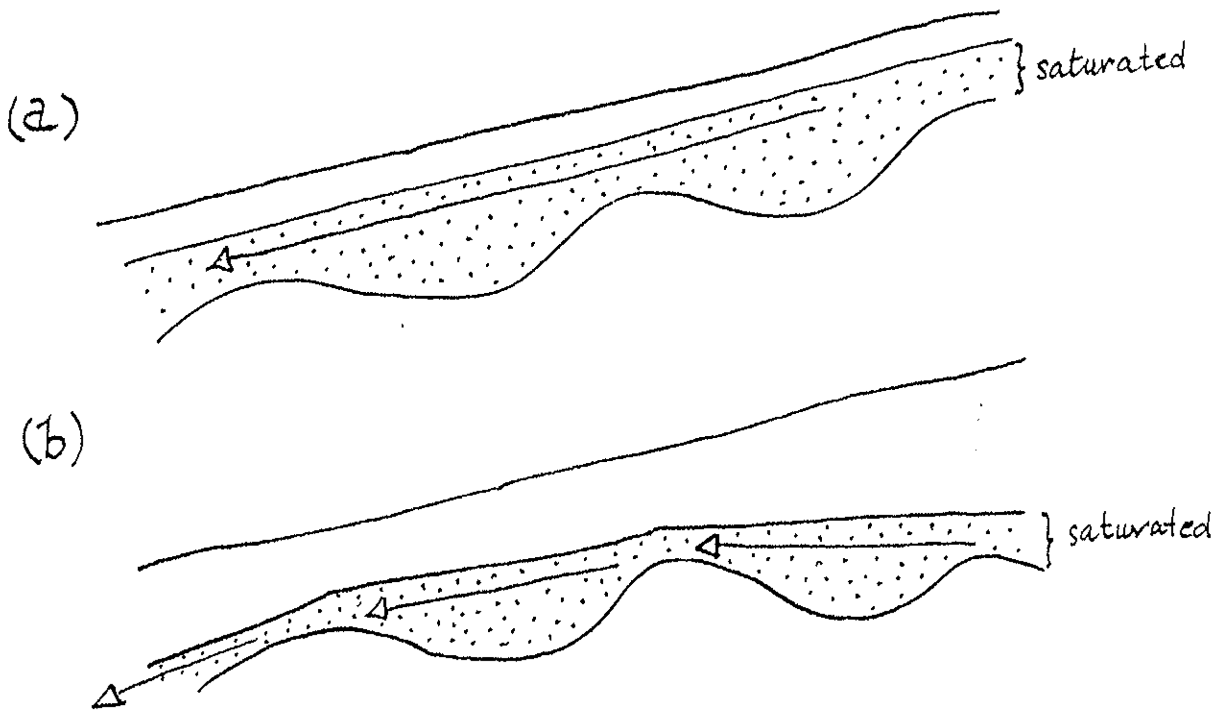


Figure 46

In both cases, but possibly more so in the latter case, lateral flow may induce circulation within the basins. Even the direction of this postulated movement is very much in the realms of speculation. Is it a couner-flow (figure 47a), or does the difference in height across the basin provide sufficient head to flush it in the original direction of flow (figure 47b)?

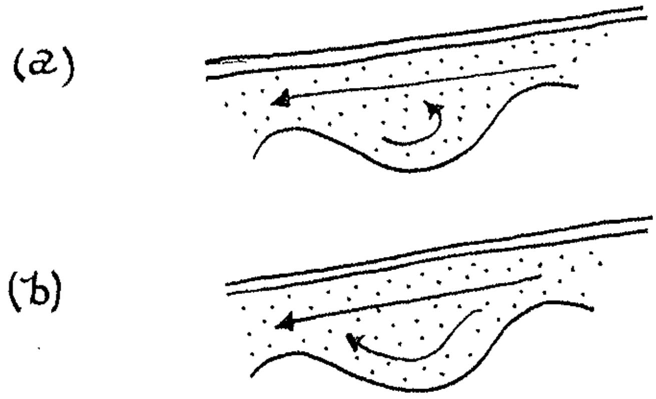


Figure 47

The evidence for deep circulation within such basins, capable of flushing them (without there being an outlet at their base) is very thin. Some indication of this may be gleaned from discussion of periglacial 'suffosion', tropical 'suffosion' and the presently forming karst bauxites of Jamaica. The term 'suffosion' was coined to mean the process whereby, in periglacial areas, masses of highly lubricated mud may move downslope beneath the frozen surface horizons, to erupt as mud 'volcanoes' where there is a break in the frozen surface layers which constrain this material (figure 48) (? subsurface erosion = suffosion ?).

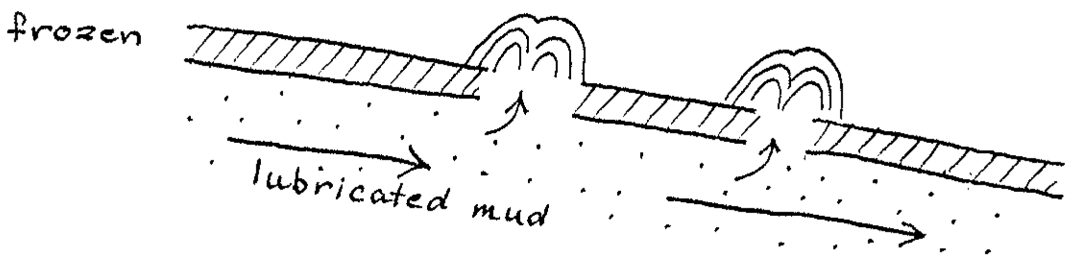


Figure 48

The mud is evidently under pressure from an upslope 'head'. Tricart (1972) extended the term to apply to the tropics. Tropical suffosion he visualised as water moving downslope, under pressure from an upslope 'head' and constrained beneath a surface layer of impermeable laterite, escaping (?under pressure) where the laterite is breached, as in dambos (more or less enclosed hollows in a laterite surface, sometimes with a younger laterite on the floor). Thus, during the wet season, this water may raidly be extruded into the dambo bottom forming ephermeral swamps or even open water surfaces (figure 49).

Figure 49

There appears at first to be some similarity between the seasonal flooding of the dambos and flooding of the bauxite-containing depressions, presently forming in the 'cockpit country' of Jamaica. In this latter case, there is some debate concerning to what extent the depressions are flooded by 'topping up' with relatively fresh water or whether there is upward movement of water within them, induced by the increased 'head' of inflowing water. In the case of the dambos, Tricart certainly seems to imply that it is rather more than 'topping up'. He indicated that Fe- rich water (and possibly clay) is brought up into the dambos (the iron providing the source for the laterite on the dambo floor.) In effect the 'head' of fresh vadose water is believed to force the older Fe-rich phreatic water upwards and this later drains away leaving part, at least, of its original Fe load as precipitated hydroxides. How deep is the effect of the proposed circulation is not known but examples of saline water entering dambos or similar depressions (Kay, pers.com.1984) suggest that the circulation may be to some depth.

In short, there is some indication that it is possible for water in truly enclosed basins to circulate.

In the case of dambos in lateritic terrain, it would be particularly interesting to know the spatial relationship of dambos and enclosed depressions on the basal surface of weathering. If very ancient waters do in fact rise to the surface here we might expect that the confinement of the inflow is in some way exaggerated by the constriction of the groundwater movement (? for example near the downstream lip of an enclosed basin).

3. The third possibility concerning renewal of water in the bottom of depressions is that they may not in fact be completely enclosed, but have an undetected outlet. This seems to be the most likely explanation, particularly with the deeper depressions and in recent correspondence Thomas said "I am pretty sure that there is connectivity between basins and some troughs have outlets" (which even his 100 ft sampling interval failed to identify). The outlet may be very narrow and extremely difficult to locate. There are, for example, enclosed basin, almost entirely exposed as landsurface features in New South Wales and in New Zealand (Thomas 1974). They are deveoped in granitic terrain. Since they are totally enclosed they cannot have been formed by fluvial erosion, which normally links basins across thresholds or via narrow exit valleys. They are outside the glacial zone, so this leaves aeolian action or solutional removal of weathering products as possible mechanisms for excavating them. The former is very unlikely. In agreement with Twidale (1971) who hinted at this, solutional removal through some undetected underground outlet seems to me the most reasonable excavation process. If, in such exposed basins the subsurface drainage outlet remains undetected then it is highly likely that drainage outlets occur concealed below the saprolite in basins on the basal surface of weathering. How small the outlets are is an intriguing question, concerning which Thomas (pers. com. 1984)has this to say "... in Zimbabwe.... were large 'pipes' exiting from solid granite domes, and also entrance holes on the bare rock surface which, though possibly related to sheeting, could not be entirely explained by appeals to this phenomenon. If such features exist below saprolite cover then what ?". I have seen similar 'pipes' on iselbergs in E. Africa, very reminiscent of solutional piping in chalk in England, and it seems likely that these

link with pressure release fractures.

In summary it may be said that:

1. There is a high probability that the deeper of the enclosed basins' have an outlet. Study of the age and water quality of basins which appear to have potential connectivity is more likely to throw some light on this than is search for a postulated outlet, which may be very small.

2. There is some indication that water may circulate within the shallower basins, allowing older waters to reach upper levels at specific sites, but the identification of sites at which it may occur requires further research into their location, particularly in relation to the geometry of the basal surface of weathering and water 'heads'.

The distribution of enclosed basins and their geometry.

There are numerous observations to the effect that weathering is deeper where fissures occur (figure 50a), or that it is more advanced (figure 50b).

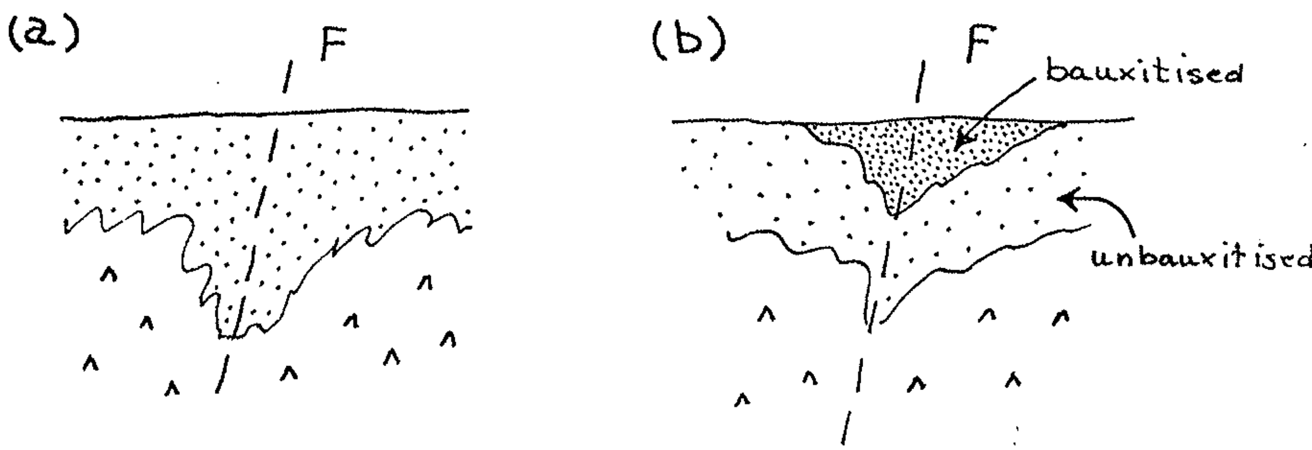


Figure 50

Such observations are usually at specific exposures, which only give us a two-dimensional story. Nevertheless, it seems reasonable to deduce that deeper or more advanced weathering follows the trend of fissures and that basins are most likely to form where fissures are more frequent or where they intersect. For this reason, considerable importance must be attached to Thomas' study of joint trends and enclosed basin geometry, which appears to be unique.

Figure 51 shows the topography and jointing in the area shown in the figure 45. The caption, it is important to note, distinguishes between joint directions 'from observed lineations on outcropping granite' (solid lines) and 'corresponding lineations in mapped weathering troughs' (dotted lines) (present writers emphasis). In the text Thomas says (p91) "a correspondence exists between the orientation of the basins of weathering and the dominant joint directions". This seems to fit well with the widespread observation that deeper weathering is associated with fissures, until we superimpose Thomas' two maps (figure 52), at which point it becomes clear that the basins occur within or between the lineations he mapped.

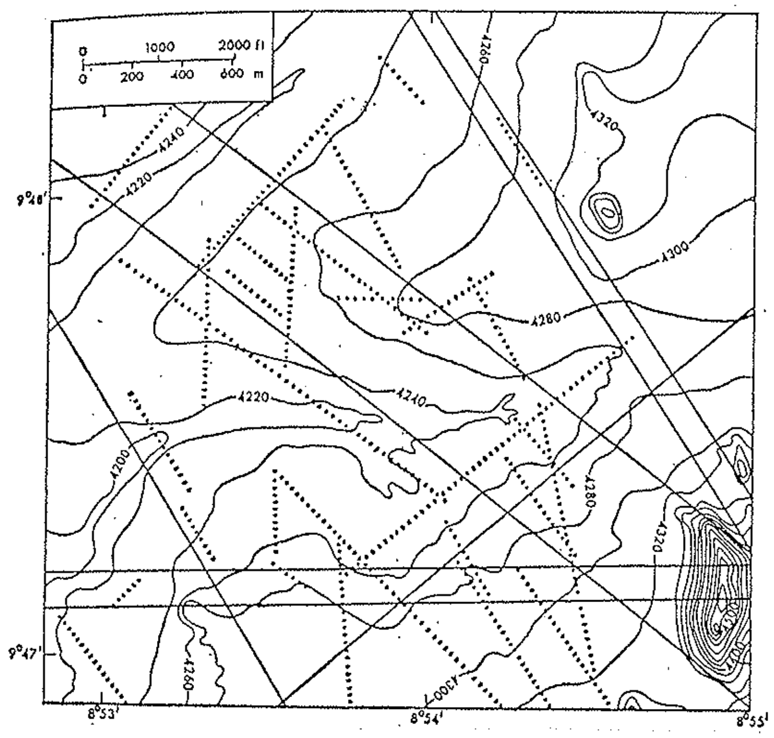


Figure 51

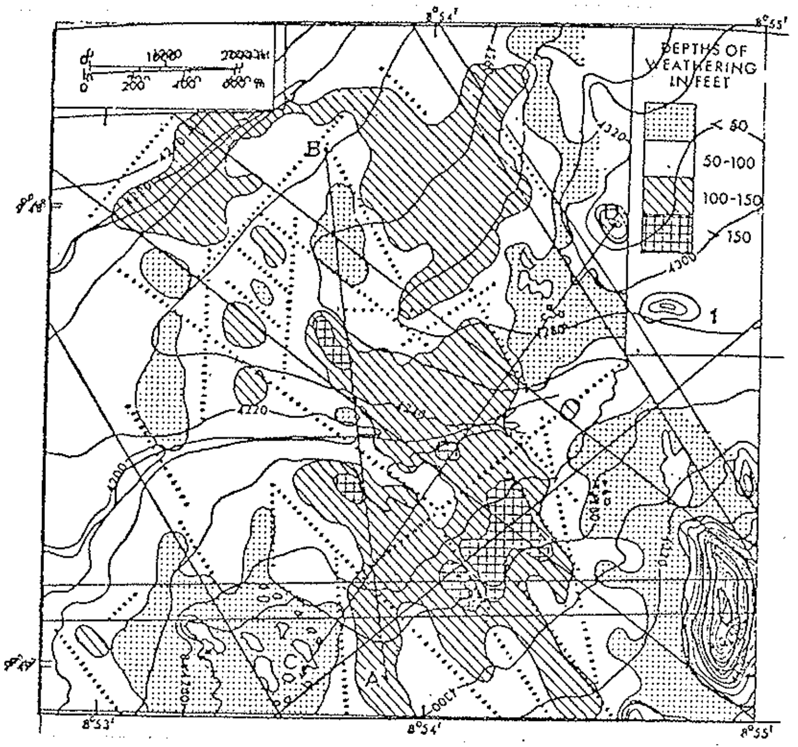
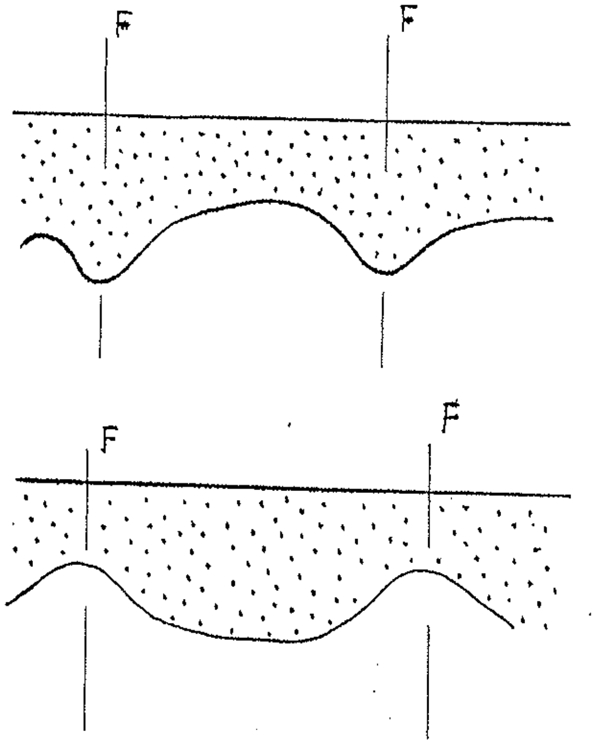


Figure 52

So the relationship is not as appears to be implied (basins orientated along joints), but the reverse (figure 53).



Expected relationship between basins and fissures.

Relationship indicated by superimposition of Thomas' maps.

Figure 53

In the text Thomas indicates that the main lineations were mapped from aerial photographs. The dotted lineations were "in mapped weathering troughs". Pending clarification of the data source for the latter, there is little more to be said by way of attempting explanation of this unexpected relationship. What can be said is that whatever the relationship between joints and basins, jointing will be difficult to use as an exploration tool for locating basins. Obviously, if the only easily located joints are on small, widely separate exposures of fresh rock, long distance extrapolation will turn possibly small angular errors into very large ones, so that intersection points could be very far misplaced. It is difficult to see how joints could be located at all, where there is a complete saprolite cover. One possibility exists. There are several observations to the effect that the vegetation is very sensitive to weathering stage The principle is illustrated in figure 54. The differences in the plant assemblages may

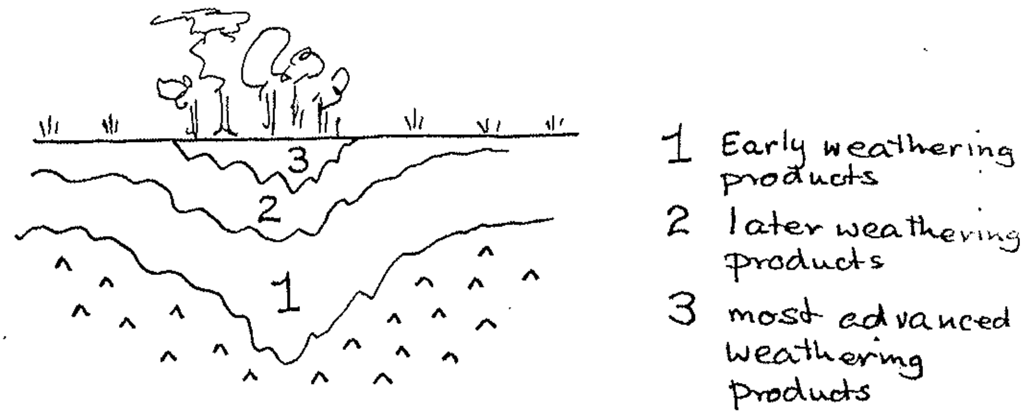


Figure 54

very subtle - the presence or absence of a particular species - and appear to be the result of a particular sensitivity to accumulated toxic materials or the absence of particular trace elements, in some cases. Even slight changes on the clay proportions and associated permeability affect the pattern. Thus there would seem to be scope for a combination of botanical studies, linked to air photo identification of joint trends, to indicate troughs.

There is also evidence that the base of inselbergs are preferred sites for enclosed basins. See, for example, figures 55 and 56.

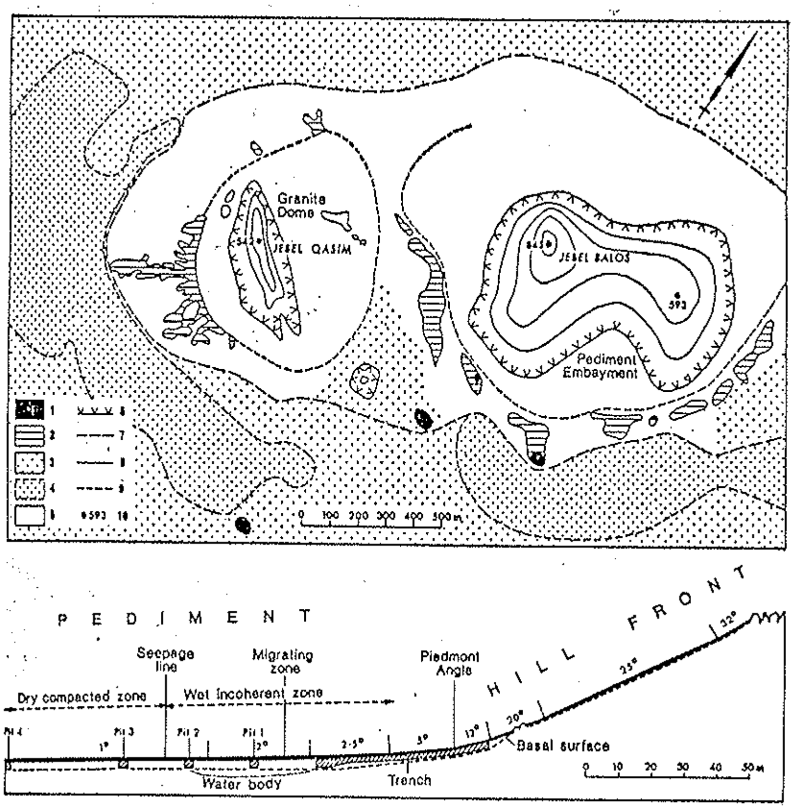
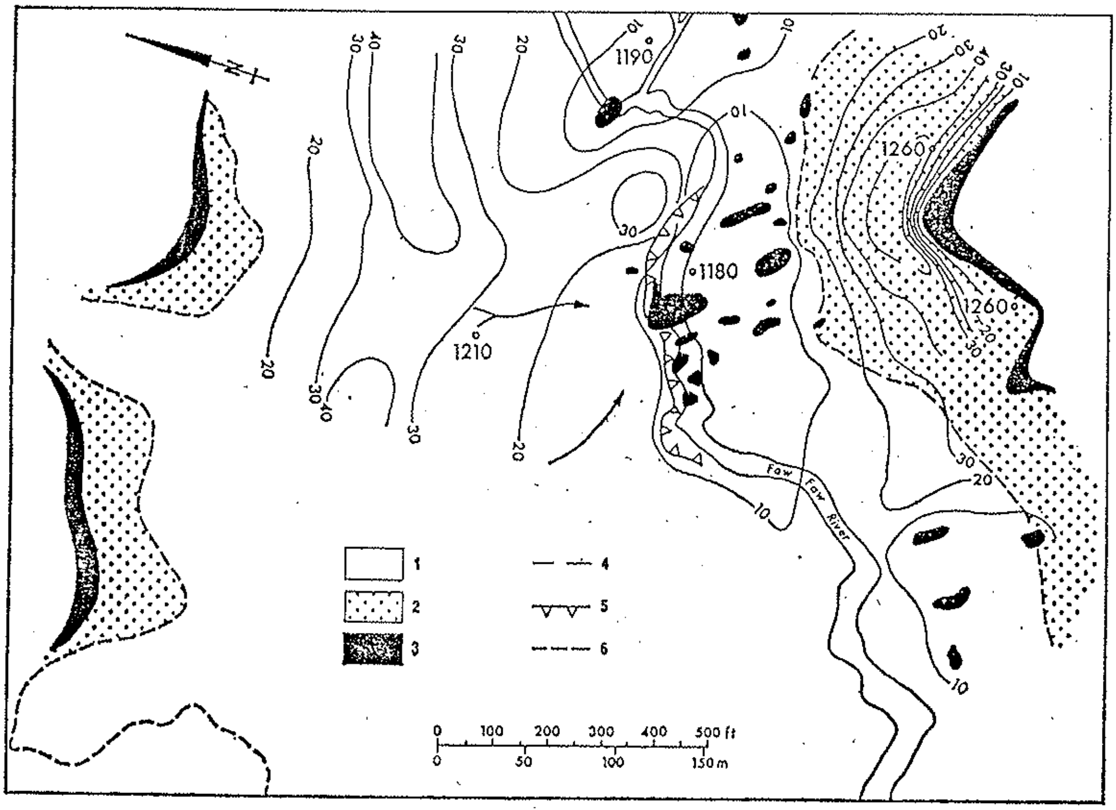


Figure 55

1. Closed depressions
2. Eluviated clay
3. Long grass/thin bush
4. Tall grass/thick bush
5. Short grass/some trees
6. Piedmont angle
7. Sand/clay boundary
8. Form lines
9. Seepage line
10. Heights: in feet a.s.l.

Geomorphic map of Jebel Balos and Jebel Qasim near Balos, Sudan (after Ruxton 1958).



Sub-talus weathering in Precambrian granite near Shaki, Nigeria.

1. Soil covered surfaces; 2. Talus and other boulder-controlled slopes; 3. Outcrops of fresh rock; 4. Contours at 10 feet intervals; 5. Convex break of slope; 6. Concave break of slope around the base of the talus slope.

Figure 56 (Thomas 1974)

There are several factors which may act separately or in conjunction to favour deep weathering at such sites.

1. Water is shed rapidly from fresh rock 'highs', so that peripheral areas enjoy greater concentration of infiltration and this may be made more effective by the coarser texture of surface debris and saprolite here. In such situations it seems reasonable to propose that sufficient 'head' is available for water to circulate in these relatively shallow basins without there being an outlet at their base.

2. In many cases the inselberg occurs where there is a change in rock type and this suggests several possible advantages for deep weathering immediately beyond the junction.

(a) In the case of granite intrusions, the intrusion may have caused structural stresses or fractures in the country rock.

(b) Even in the absence of macroscale fissures, individual crystals may be stressed and therefore have a greater susceptibility to weathering.

(c) The intrusion may have an alteration aureole, or some alteration of specific minerals caused by hydrothermal activity, such as to make adjacent country rocks more susceptible to weathering.

3. Even in cases where there is no change of rock type, a lithological advantage may occur in the form on an intersecting zone of pressure release fractures. These fractures are well known on exposed rock surfaces. There is some evidence that they also occur below saprolite (Thomas 1974). Hence intersection is likely at the abrupt change of slope at the foot of inselbergs and this would clearly facilitate weathering here (figure 57).

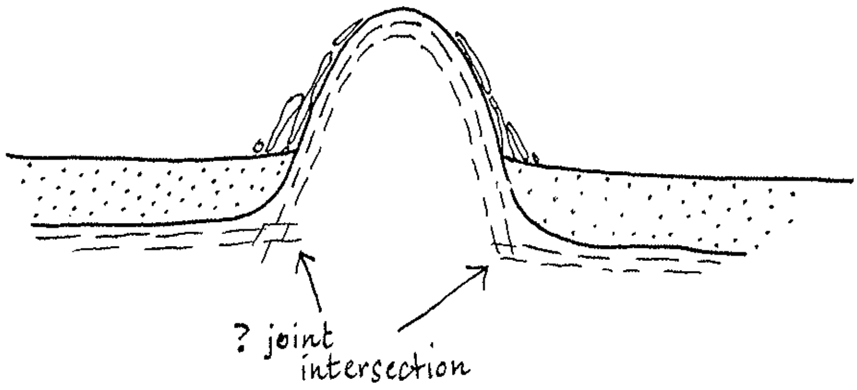


Figure 57

(c.f. the Vaiont disaster -figure 58- pressure release fractures associated with the pre-glacial, V-shaped valley intersected with fractures associated with the U-shaped glacial valley. Landsliding was associated with the zone of intersection.)

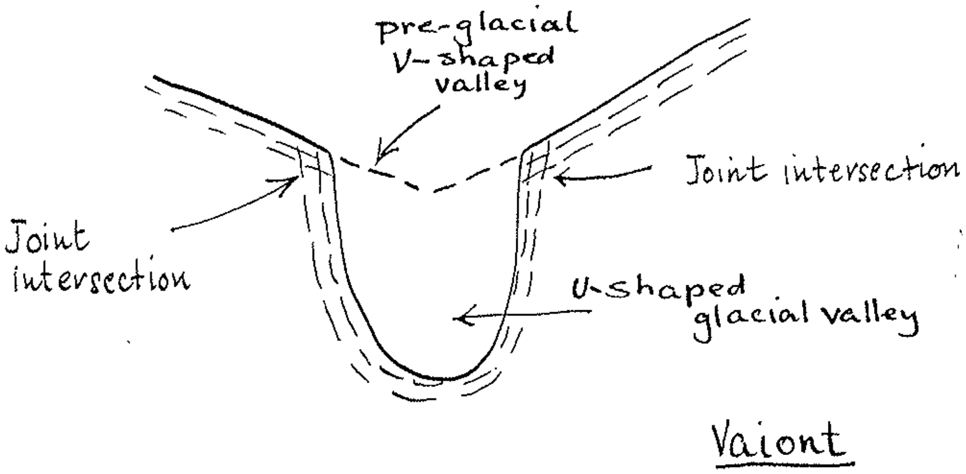


Figure 58

The origin of inselbergs is discussed elsewhere. From this emerges the suggestion that the highest inselbergs form under of conditions of periodic or ongoing uplift and concommittent lowering of the surrounding plains. Where the plains (main landsurface) are more stable the inselbergs are gradually destroyed and an essential part of this destruction process is weathering at the margins which undermines the berg. The development of marginal weathering basins would appear to pertain to this type of destructive situation. That is, it may not be correct to assume that the bigger and better the inselberg, the more likely there are to be peripheral basins. It may well be that the better basins are associated with more degenerate examples of the feature. (Aspects of their distribution are discussed in the section on inselberg genesis).

The function of inselbergs in 'shedding' water, to enhance peripheral weathering, raises the question "Can we expect similar features at the margins of mesas or plateaux capped by impermeable laterite?" Permeability is an essential requirement for the development of laterite by differential leaching. Impermeability is not the norm. In many cases, the obvious impermeability of some laterites can be directly attributed to man's activities. Destruction of the original vegetation cover exposed the laterite to the more extreme conditions of the "atmospheric", as compared with "soil" climate, and induration resulted. Susceptiblity to induration is very variable and the depth to which it operates varies. Both depend on the nature of the laterite, in particular the condition and distribution of the iron in it. In Uganda, for example, during drilling through the vermiform laterite (high level), the water of circulation was lost at a depth of 5 feet, which corresponded with the penetration of induration at this site, dated by associated artefacts as late Acheulian - early Sangoan i.e. 20-40,000 B.P.(Chaplin & McFarlane 1969). If man is responsible for such induration, then time would seem to be rather too short for this to have had much effect on the depth of peripheral weathering. However, this only applies in 'core areas' of persistent forest, areas which have not experienced climatic change. Outside these core areas, climatic change towards temporarily (in geological terms) drier or more seasonal conditions, would have the same effect and the time-scale might well be sufficient to allow the results of 'shedding' to be expressed as facilitated deep weathering. Clearly the dating of induration is the essential point here. There is another geomorphic context in which the attainment of impermeability may be very ancient. It is often the case that although the in situ laterite is permeable, the detritus that results from its reworking or erosion is not. This situation occurs, for example, in Uganda, where acyclic detrital laterites occur at altitudes between cyclic, in situ laterites. The detrital laterites can be recognised by textures, but perhaps more important for the recognition of these impermeable laterites is the "text-book" mesas with which they are associated. The mesas capped by more permeable laterite are strongly deformed by subsidence caused by ongoing, post-incision leaching. In Uganda, the oldest of these detrital laterite mesas is dated between the Buganda Surface (? Gondwana/Jurassic) and Ntenga Surface (?post-Gondwana/ Cretaceous), so time has certainly been available for the effects of water shedding from these surfaces. In any serious search for laterite capped mesas likely to have functioned in this respect, the age and the form in particular could be used as criteria to establish exploration priorities.

Impermeable detrital laterites also occur in foot-slope positions, the detrital material being re-cemented, in some cases, by Fe moving through the ancient profile in solution and seeping out through the detritus (figure 59). These tend to be contemporaneously forming and temporarily ephemeral features in the landscape (sometimes forming small terracettes). As such their potential, in respect of shedding water which might facilitate deep weathering, is limited.

Thus the possible role of laterite-capped mesas or plateaux in shedding water, like the inselbergs, sufficient to develop depressions on the basal surface of weathering, depends very much on geomorphic history, in particular which laterites are permeable and which are not and the date of the development of impermeability.

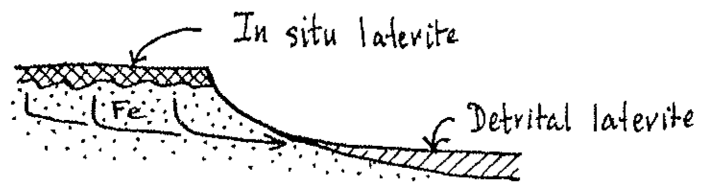


Figure 59

Inselbergs

Inselbergs are not merely the exposed 'highs' of the basal surface of weathering. The relief on the basal surface of weathering is often rather subdued and the bergs are anomalously 'upstanding' (fig 60).

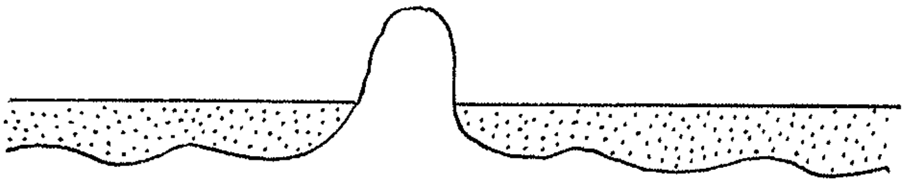


Figure 60

Nevertheless, they appear to originate as exposed 'highs'. Once these highs have surfaced (; the plains have lowered to achieve this), their survival is favoured. They shed water quickly and in the footslope area chemical weathering has the advantage of this concentration of water. Thus, inselbergs are "sharpened up" as they emerge and clearly emergence is associated with the lowering of the surrounding plains (figure 61).

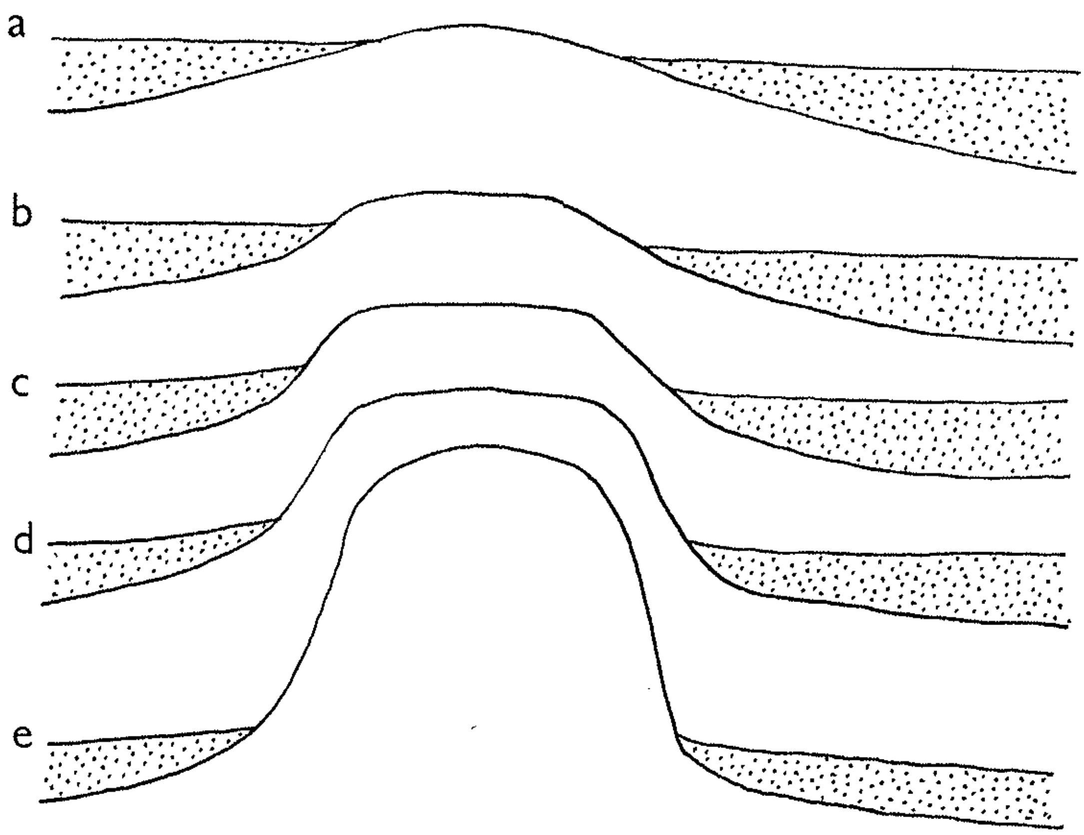


Figure 61

Thus their form can be attributed to two things .... (1) having emerged they are relatively immune from weathering and (2) weathering is most aggressive near the upper limits of the weathering profile and the inselberg increases the aggression by shedding water into this zone at the margin.

One of the key factors in the development or destruction of inselbergs appears to be the rate of lowering of the surrounding plains. For inselbergs to emerge as high features it seems that constant lowering of the plains is necessary. Given a situation where lowering slows down or stops, the inselberg is slowly destroyed. It is undercut by weathering in the upper parts of the profile (figure 62). The joints between pressure release plates become weathered and the shells slide off the berg to join the footslope debris which is weathered and reduced to individual sand grains and clay.

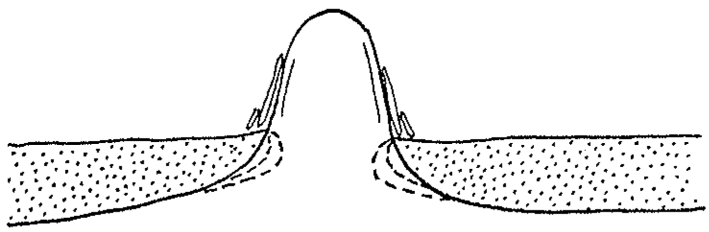
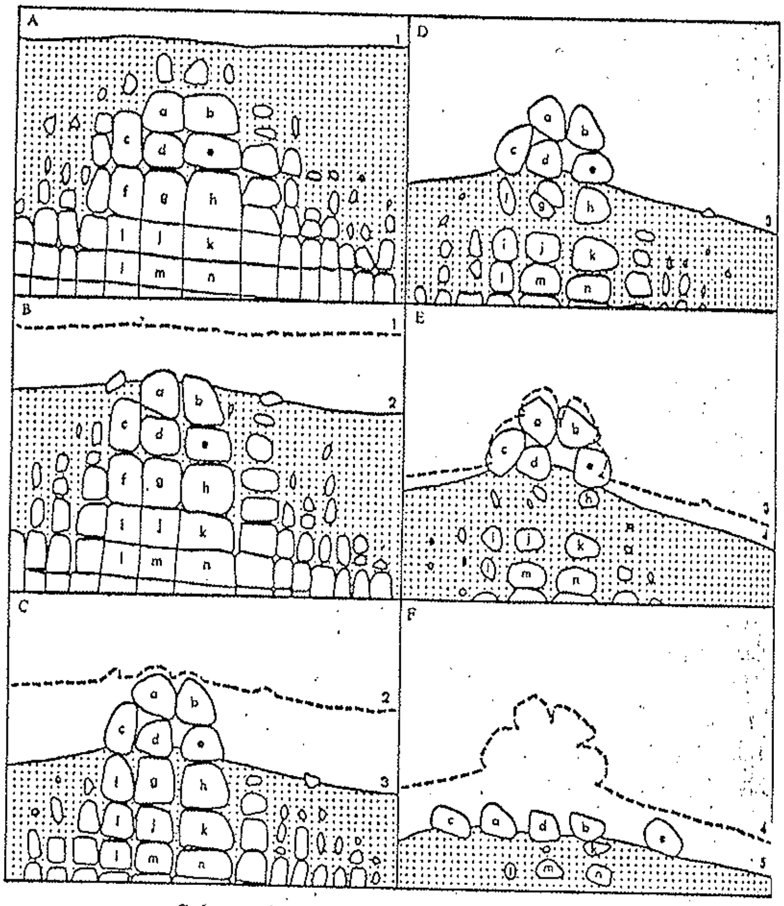


Figure 62

Thomas (1974) has provided a sequence of the stages of destruction of a small tor, which illustrates the essential features. Note that the emergence (A-C) involves significant lowering of the plain, while the destruction involves only very slow movement (Figure 63).



Schematic representation of the development and decay of granite tors (after Linton 1955, Thomas 1965).

A Differentially weathered granite (joint blocks are indicated a–n; B emergence of joint blocks a, b as a result of ground surface lowering from 1 to 2; C tor comprised of blocks a–e exhumed from regolith following further surface lowering from 2 to 3; D foundations of tor become rotted as blocks f–n remain subject to continued groundwater weathering; E tor subsides as ground surface is lowered from 3 to 4; F tor becomes reduced to a group of residual corestones as further lowering of surface and continued groundwater weathering take place (3 to 4 to 5).

Figure 63

Thus we can conceive that near the drainage lines, where surface lowering is slow, degraded forms might be expected to prevail, while further away from these lines, more active surface lowering yields better forms and low relief 'nascent' inselbergs would occur in the higher areas of plain (figure 64).

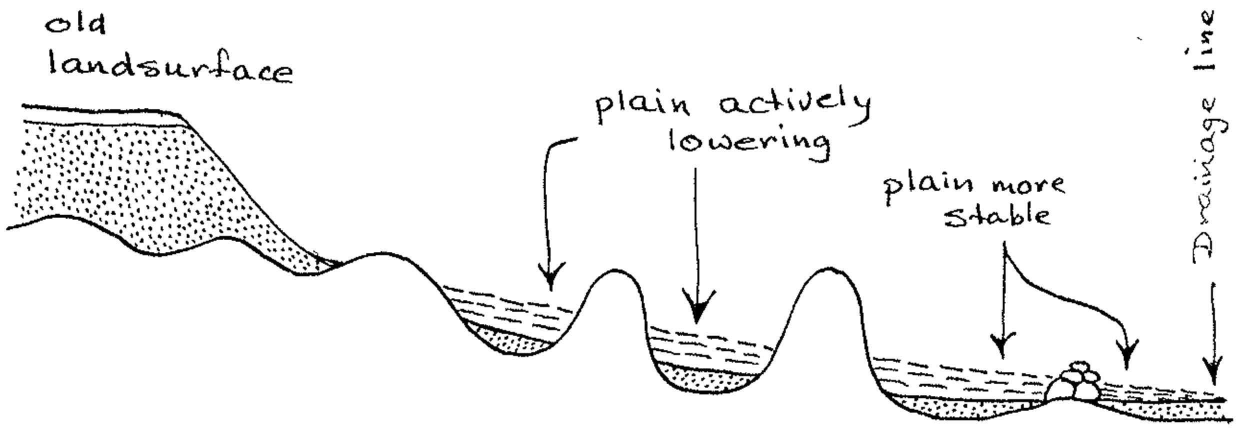


Figure 64

The formation of 'enclosed basins' around inselbergs would appear to be best placed at an early stage of destruction, preceding undercutting by weathering and ultimate degradation. It is difficult to see how such basins could develop in a situation where the plains are actively lowering and the inselberg is emerging as a pronounced feature. It follows that the best basins are likely to develop where the inselberg survives this destruction for the longest time, so that water-shedding continues for a long time. This would require that the inselberg be made of rocks which, in comparison with those underlying the plains, are relatively resistant to weathering so that undercutting and destruction are delayed (figure 65).

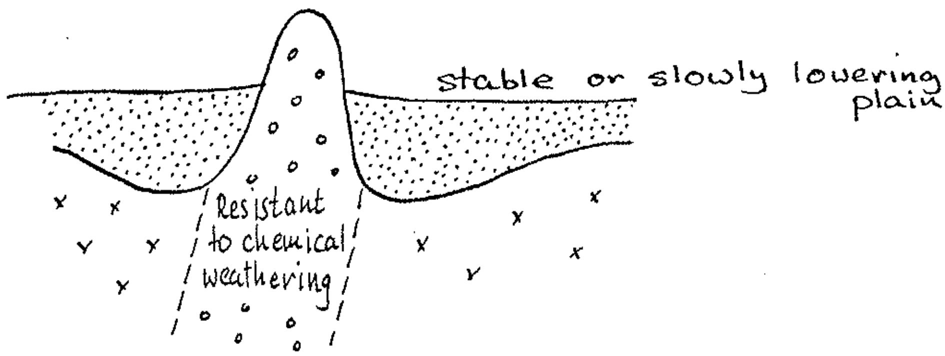


Figure 65

Thus, both lithology and stage of development appear to be relevant to the formation of enclosed basins around inselbergs. In some cases, where the inselberg rock is particularly resistant to weathering, the surrounding surface may also be depressed (figure 66), containing pools of standing water (seasonal usually, but sometimes perennial). The depression results from collapse of the saprolite where weathering is particularly intense.

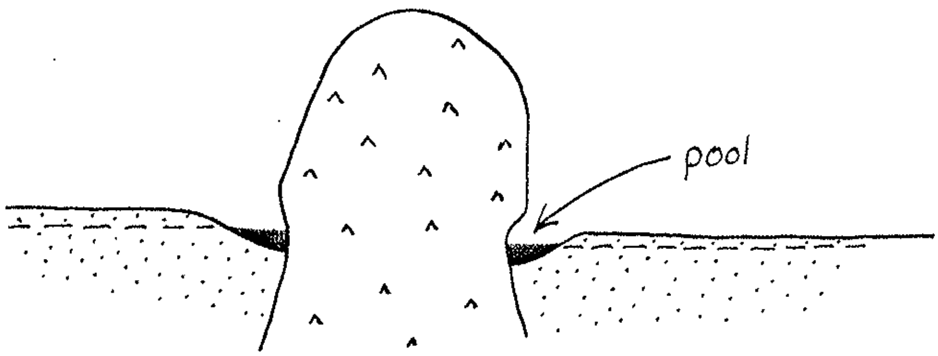


Figure 66

Sometimes inselbergs are flanked by aprons of fresh rock, either exposed or with a thin veneer of unconsolidated material or saprolite. This feature appears to develop where rather arid conditions are associated with inselberg destruction (as compared with the earlier wetter conditions during which the original deeply weathered profile formed and during the emergence of the inselberg). The mechanism of slope retreat, to leave a shallowly weathered pediment, is unclear. Only very slight lowering of the plain would be sufficient to allow emergence of the fresh rock apron (figure 67).

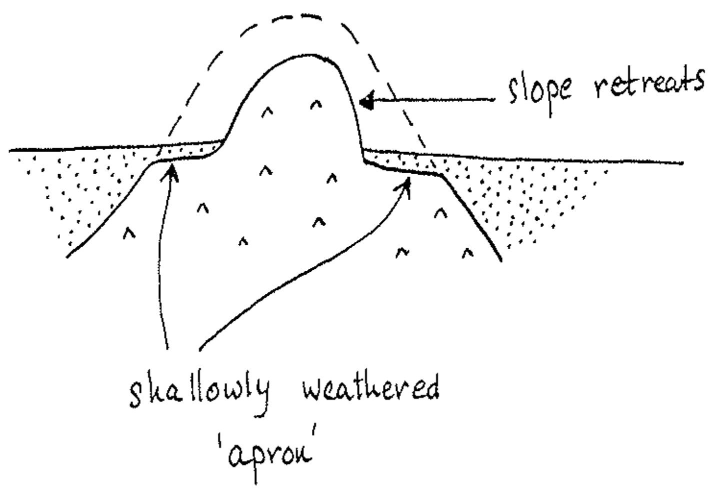


Figure 67

Enclosed depressions on the landsurface

In tropical areas, particularly where weathering crusts have developed, enclosed surface depressions are very common. These features are strongly reminiscent of karst hollows, long known to be caused by solution and collapse in limestone areas. Pseudo-karst depressions in tropical areas vary in form and origin (Twidale & McFarlane, in prep.). In some cases the carapace subsides into areas where preferential solution and weathering of the underlying saprolite has promoted collapse (figure 68).

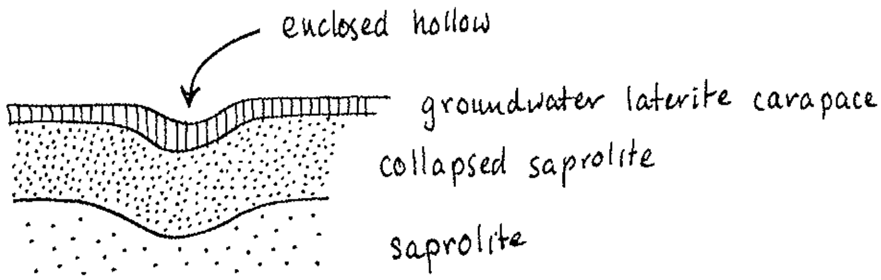


Figure 68

In areas where there is no crust, the unconsolidated surface material moves into collapse sites, flattening the surface, but the rigidity of some lateritic materials prevents such infill and 'evening out' of the surface (figure 69).

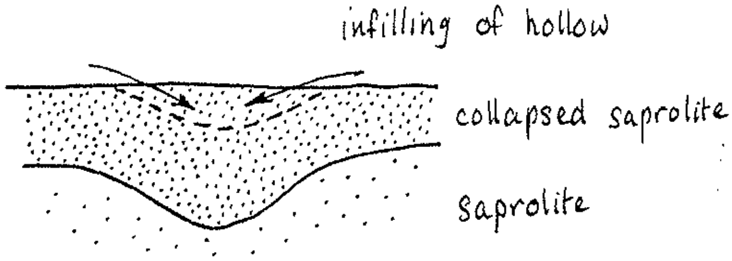


Figure 69

A pre-requisite for collapse of a groundwater laterite is clearly that the water-table has lowered. The necessary differential solution of the underlying saprolite can only be achieved when the profile has been elevated and through-the-profile leaching promoted. This is also true of the more rigid pedogenetic crusts, but in some cases pedogenetic laterite can fill a depression by repeated solution and deposition of the laterite. This results in a laterite of very variable thickness and the infill may be penecontemporaneous with the subsidence of the saprolite (figure 70).

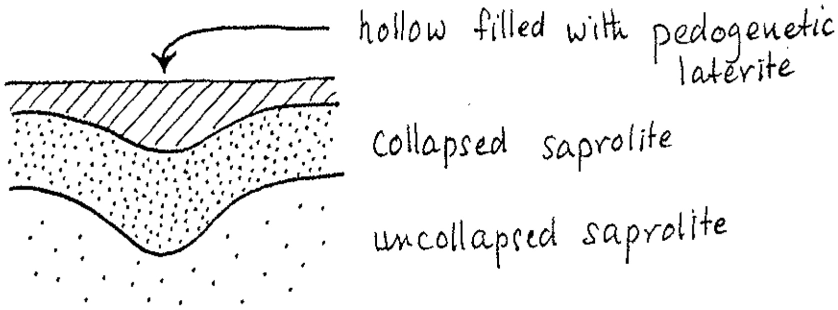


Figure 70

In some cases the formation of a depression, by lateritic carapace subsidence, ensures that these sites continue to develop preferentially, by channelling surface water into the depression (figure 71).

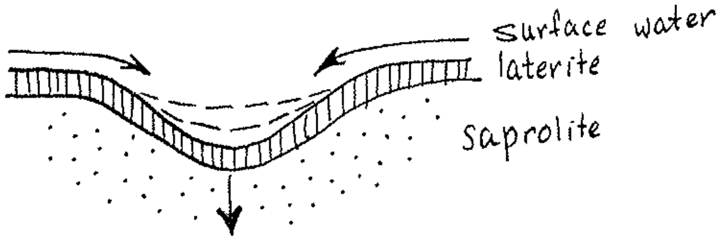


Figure 71

In other cases, the formation of a depression is followed by illuviation of clay and loss of permeability. The depression becomes poorly drained, carrying seasonal swamp or even open water and as a result the forest is replaced by swamp grass (figure 72). In Sulawesi the grassy hollows give the virgin forest a pock-marked appearance on air photos.

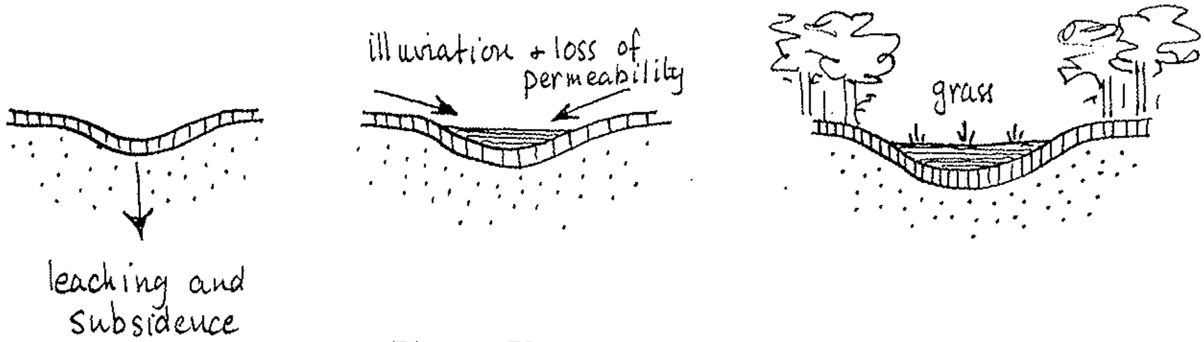


Figure 72

Sometimes the concentration of humic acids or microbial activity in depressions results in the dissolution of the laterite carapace itself. Bissett (1937) excavated one such hollow on an elevated laterite surface in Uganda, to find that the dark soil rested directly on saprolite (figure 73).

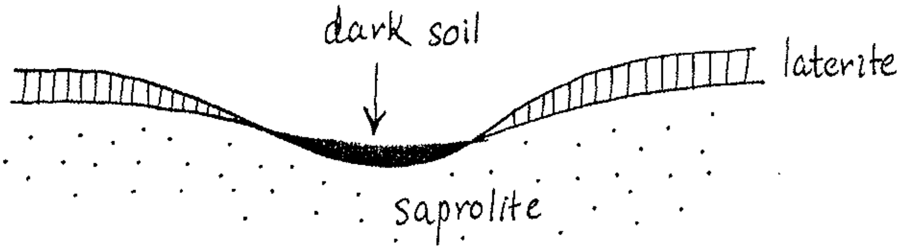


Figure 73

There are also examples of situations where collapse is directly related to site-controlled variations in the permeability of the laterite. For example, at the edges of the 'high level' mesas in south and western Uganda, the carapace is impermeable and thinly grassed (indurated). In the forested central areas, where permeability has been maintained, there is extensive subsidence of the carapace, to give a soup-plate form. So extensive is the subsidence that the summits have been inverted (figure 74).

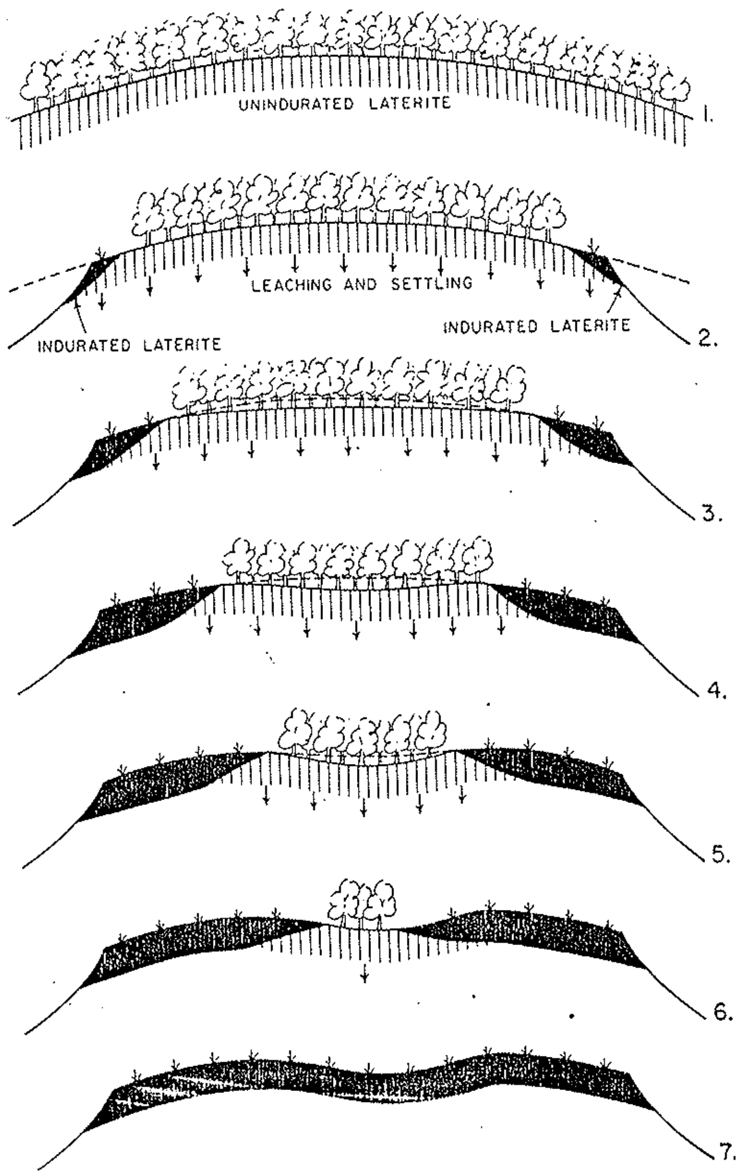


Fig. 21. *Relief inversion — the development of the "soup-plate" form of the Buganda Surface mesas.*
1. A permeable laterite sheet develops under forest cover.
2. Incision and erosion exposes the laterite at the margins of the original interfluve. It becomes indurated and impermeable and the forest vegetation deteriorates. Where permeability is maintained, there is leaching through the carapace and settling of the surface.
3, 4, 5 and 6. Induration of the laterite and vegetation deterioration extend towards the centre of the mesa gradually reducing the area in which settling occurs.
7. Ultimately the entire mesa is deforested and the laterite indurated and impermeable. The central area, subject to the longest period of leaching and settling, now lies relatively lower than the periphery.
(After McFarlane, 1969.)

<u>Figure 74</u>

In some cases the hollows are associated with drainage lines. In Sulawesi, in an area where nickel laterite has developed from ultramafics, the hollows occur within round-headed valley systems. The river courses are stepped in response to repeated rejuvenation (figure 75).

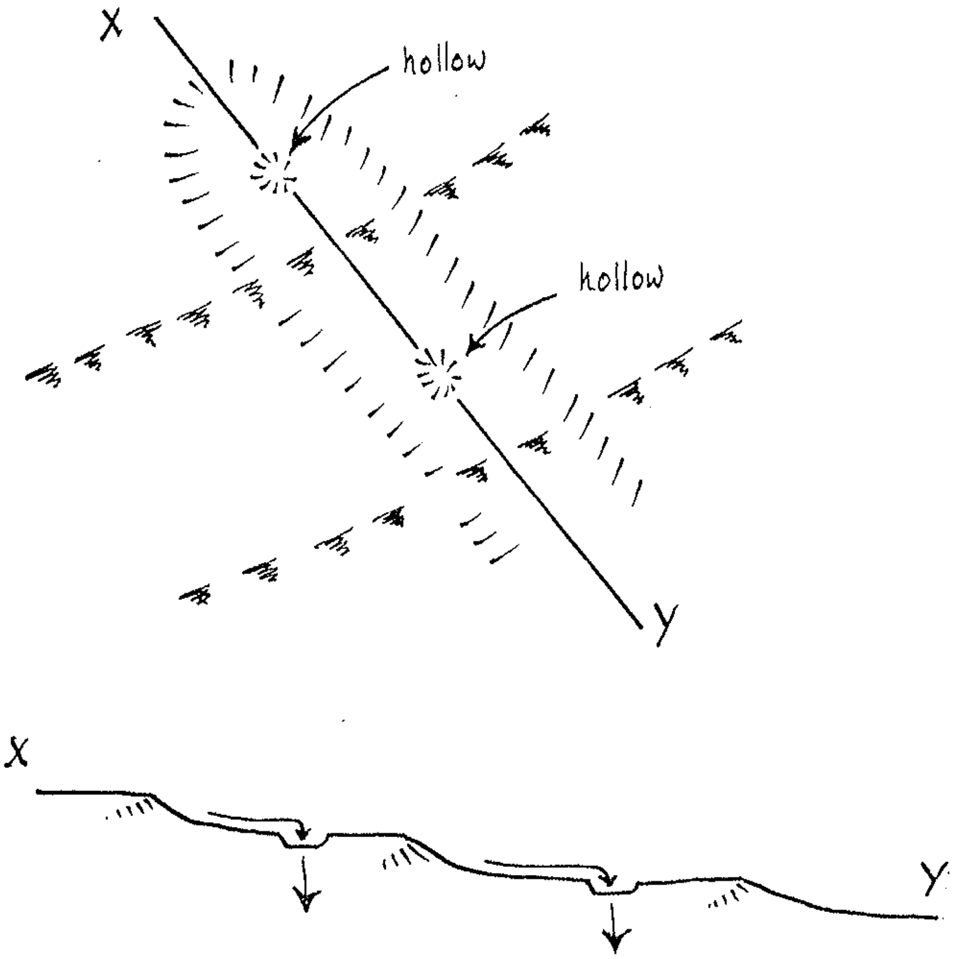


Figure 75

Evidently the water flowing down the valleys has found an exit through the bottom of the elevated valley floors. The question arises "does water, which sinks into the hollow, rejoin the stream lower down the valley?" I am inclined to think that it does not, but drains directly to the groundwater system. Support for this comes from work in New Caledonia (Lajoinie & Vogt 1978) where it is claimed that it is possible to locate the nickel silicate enriched 'lows' on the basal surface of weathering from the palaeodrainage lines on the landsurface, i.e. there is a relationship between surface drainage systems and groundwater drainage (figure 76).

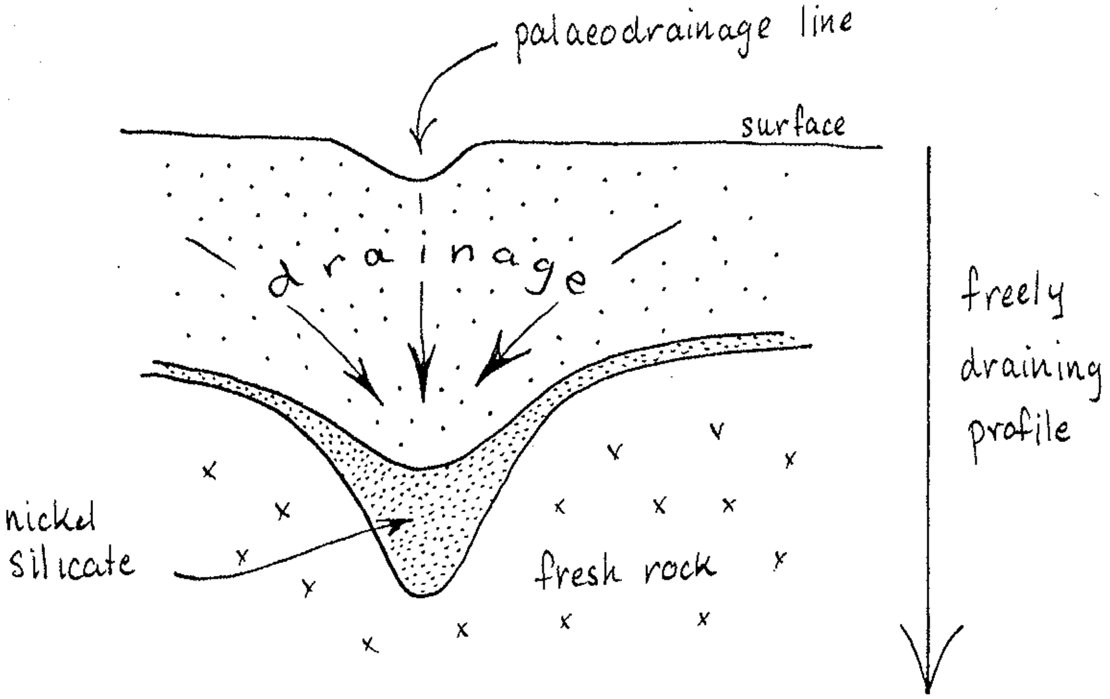


Figure 76

We now arrive at another 'chicken and egg' problem. Do the drainage lines develop as a result of there being a fissure or some such preferred locus for water movement through the profile? Or is the deepening of the weathering profile here the direct result of the existence of the drainage line? In Sulawesi (where the stepped valleys with hollows occur) the rivers are very strongly fault controlled, but we have no information about this from New Caledonia (Company information/classified).

The relationship between drainage lines and hollows (which came first?) and between these and the configuration of the basal surface of weathering have never been systematically analysed, but it is an area of growing interest as geomorphologists are now tending to become more aware of the fact that study of surface features, without knowledge of processes at depth, is inadequate.

Some of these karst subsidence features are very small - yards or a few tens of yards across - but the range of size is large and Lake Sonfon, some two miles long, is suspected to occupy a collapsed area in the Sula Mts., Sierra Leone.

One thing all these depressions appear to have in common is that they formed after the landsurfaces, with which they are associated, were elevated and incised, so that the water-table was lowered and flow of water through the profile was promoted. Thus they join the increasing list of "post-incision modifications" of profiles which originally developed at lower altitude and with a formerly closer relationship with the regional groundwater-table.

Dambos

These depressions, set into an often lateritised low relief surface, have been the centre of much interest. Academic interest stems particularly from the fact that although these features must have something genetic in common, in detail they are very varied. Genetic models proposed from studies of particular dambos differ and the problem is to link these studies in such a way as to identify the common features. Then the specific differences can be recognised as being caused by local influences. Can dambos be 'arranged' in a genetic sequence (early stage of development to late stage) which would account for the differences? Or are the differences fortuitous in that dambos, having formed, may then have different relationships with groundwater of variable content? Or is there a genetic relationship between dambos and the groundwater and basal surface of weathering?

In view of the common occurrence of pseudo-karst subsidence features in lateritic areas it is difficult to avoid the speculation that dambos are initiated as subsidence features. That carries with it the implication that the regional water-table has dropped. The other enclosed hollows are clearly stranded well above the regional groundwater-table, but in the case of dambos it seems that their base is close to the groundwater and so their seasonal flooding has two possible sources. They may be flooded by 'topping up' with surface water or by the rise of the groundwater or both.

Balek and Perry's study (Balek & Perry 1973) of the seasonal inundation indicated rapid response to precipitation and this they believed to be the result of precipitation directly over the dambo, which provides the main part of the water stored in the dambo area. There is a two month delay before the water-table in the woodland between the dambos rises. However, Gear's profile of a dambo (Gear 1968) shows a stone line which is likely to act as a rapid conduit for water falling outside the dambo, as shown in figure 77 (see also section 4.3), so I am not sure that the rapid rise in dambo water argues very well for there being little contribution from water falling elsewhere in the catchment.

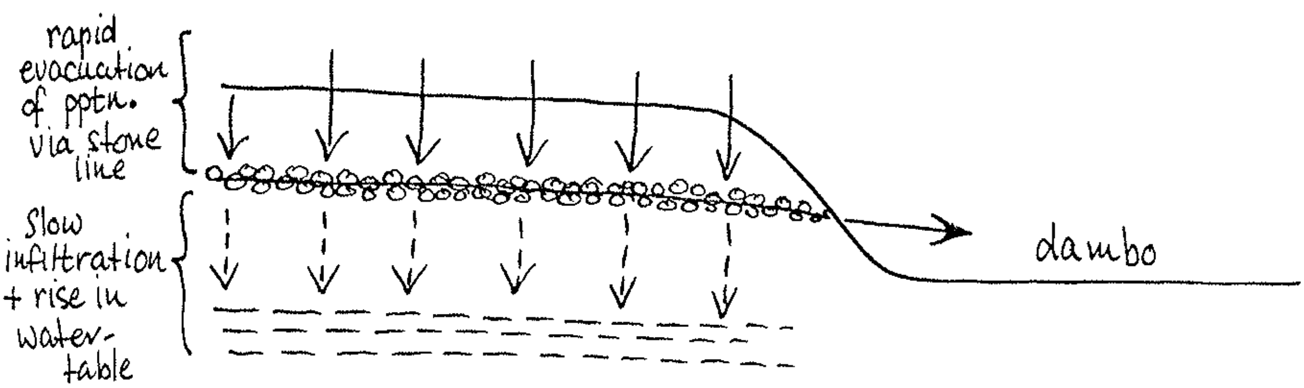


Figure 77

Stone lines are very commonly seen to feed directly from fresh rock 'highs' which protrude above saprolite into the collapsed, migrating mantle, as shown in figure 78.

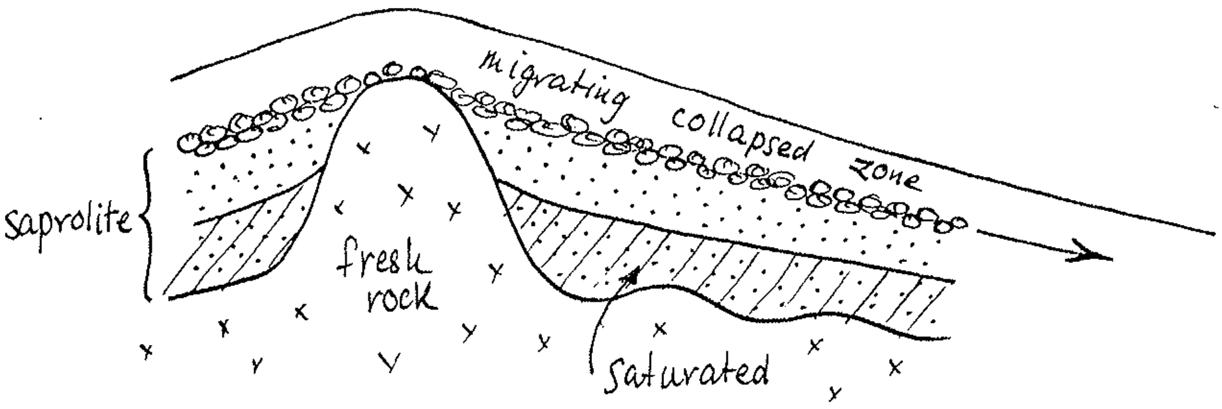


Figure 78

Thus, elements released during the early stages of weathering, normally slowly released at the base of the permanently saturated zone, could be rapidly fed, via the stone line, into the dambos. This is one possible explanation for the occurrence of 'anomalous' water in dambos, e.g. sulphate rich water. In this type of situation the top of the groundwater-tabe would also be expected to have 'additions' of anomalous water, draining more slowly through the profile and topping it up (figure 79).

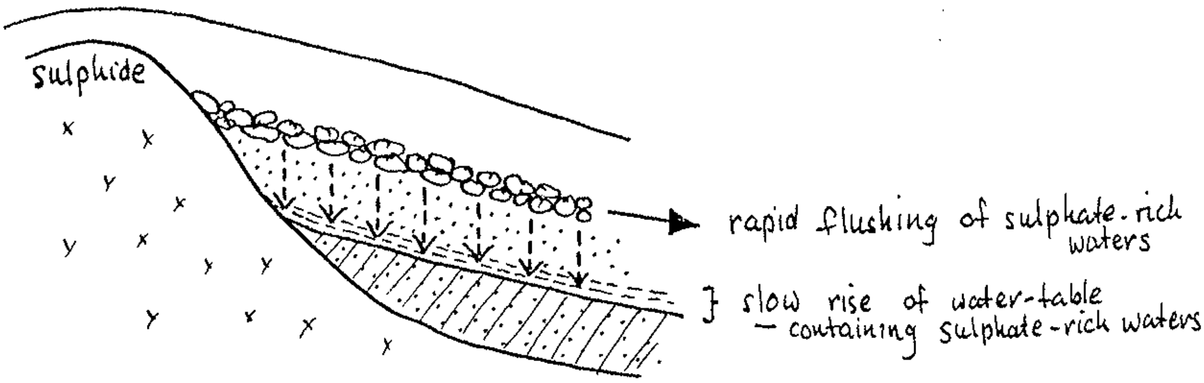


Figure 79

Thus, the presence of a stone line conduit could effect rapid and extensive spread of contaminated water from a very local interfluve source, and it should be recalled that groundwater pisolithic laterites are also stone-lines (section 5.1.5).

In theory, then, if there is a stone-line conduit and if fresh rock penetrates it, 'anomalous' water could reach a dambo not only via the stone-line aquifer, but also via the top of the water-table, if this rises to the level of the dambo floor.

If fresh rock does not penetrate the stone line but protrudes above the general groundwater level, then the anomalous water would only enter via the top of the groundwater-table and the stone-line aquifer would be clean (figure 80).

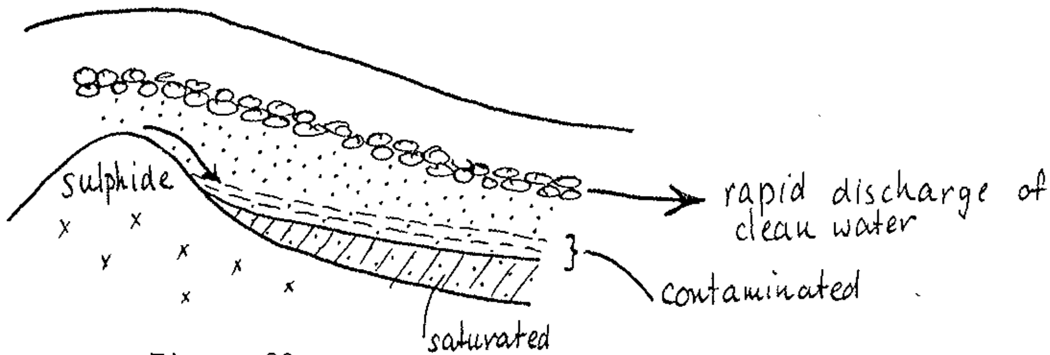


Figure 80

If fresh rock is below the general groundwater level, in the saprolite, it would release elements more slowly into the more deeply circulating body of groundwater (figure 81).

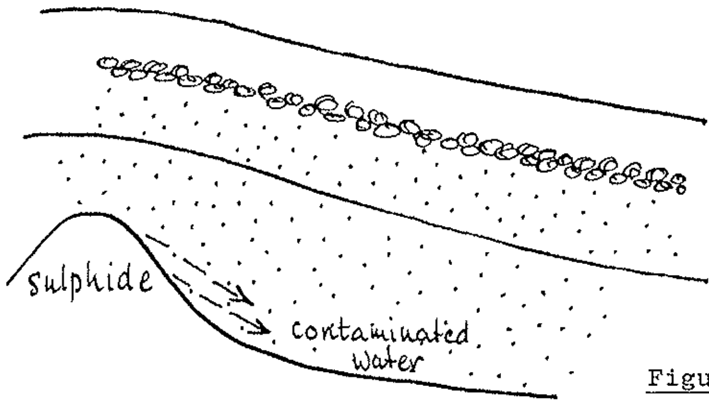


Figure 81

Thus, the configuration of the basal surface of weathering in the catchment, particularly how high the 'highs' reach in the weathering profile, would seem to be a crucial factor in explaining the quality of water reaching the dambos and in theory anomalous water could enter even if the dambo is well above the groundwater. It is not necessary to postulate either that the groundwater rises to the level of the dambo (feeding in anomalous water in its surficial layers) or that groundwater upwells, i.e. that it circulates in such a way as to force water from the base of the saturated zone up towards the surface. However, there seem to be grounds sufficient for postulating an input from the groundwater and that in some cases it comes from the lower parts of the groundwater body. Tricart (1972) believed the evidence to be sufficient to coin the term 'tropical suffosion' to describe a postulated process whereby water enters the dambo under pressure from an upslope head, the water being confined beneath an impermeable laterite 'lid'. He implied that this water is sufficiently under pressure to be capable of eroding and physically transporting clays, for example, into the dambos. The key to the system is the impermeability of the laterite lid, aproning the dambos, which, as indicated elsewhere, implies a change in the environment (eg. climatic change). Given a situation where a change has created a lid and water now moves under pressure (this too being a change) then it seems reasonable to postulate that the deep groundwater circulation system may be affected in such a way as to bring to the surface ancient waters normally restricted to slow movement near the base of the saturated zone. Again, the configuration of the basal surface of weathering would appear to be crucial to any understanding of the circulation of deep groundwater which might enter dambos.

The occurrence of gypsum in dambos where precipitation far exceeds that conducive to surface accumulations of $CaSO_4$, strongly points to distinctly anomalous groundwater conditions. During the wet season the gypsum must dissolve. For it to survive, it must be reprecipitated by contact with groundwater. Although Watson (1983) is not in favour of a "mixing model" (see also section 5.6), in this situation it surely must pertain. For example, the sulphate source could be a 'high' of fresh rock below an interfluve, which is leached during the wet season. The sulphate-rich groundwater could enter the dambo via the stone line, to meet markedly different groundwater welling from depth.

It seems, therefore, that progress in dambo study would best be achieved by examining the spatial distribution of dambos in relation to the configuration of the basal surface of weathering.To continue to study dambos without this, holds promise only of adding to the already long list of intriguing variations without offering much by way of genetic explanation which could hold ingredients common to all of them, ingredients from which it may be possible to extrapolate, so as to provide the means of predicting the nature of the water or waters which feed them.

There is some indication that climatic change may be a common ingredient in dambo genesis. Their occurrence in a climatic belt which was probably formerly wetter and more heavily forested but now experiences a more seasonal regime which only supports dry forest and scrub, is itself suggestive. Induration of the laterite and the development of impermeability supports such a change. Could this have an effect on groundwater circulation ? Much is known about the effect of deforestation on river regimes - rapid flooding followed by minimal flow. Could a change to a markedly seasonal infiltration into unlateritised interfluves yield a rather more pronounced seasonal rise in the water-table at low sites, accentuated by the laterite lid there ? I have at the back of my mind the problem of reconciling collapsed hollows which need elevated profiles and low water-tables with the fact that seasonally, at least, the water-table apparently reaches the dambos. Should we think in terms of elevation and collapse, under forested humid conditions, followed by a more seasoanl regime which increases the water-table oscillation range sufficiently to bring the level up to the dambo again, albeit seasonally ?

Since water 'head' depends on relief, it would seem important to be very precise about the relief, i.e. to know if it is polycyclic and where the dambos are located in relation to identified facets (see also section 3.3.2, cartographic analyses). Are these a very much more subdued version of the Sulawesi valleys and hollows (see section 3.3.5, enclosed depressions on the landsurface)? A very tight geomorphological analysis, in conjunction with an analysis of the basal surface of weathering should throw some light on the relationships between drainage lines, dambos, groundwater circulation and through-the-profile leaching.

This section is a good example of too many theories and not enough facts, but it seems to me that the really important facts concern, at this stage, not so much the dambos themselves, but their spatial relationships with landsurface facets and with the basal surface of weathering. We really need a background of this kind of data before we can successfully place any detail from individual sites in a genetic context likely to offer generalisations from which extrapolation can be made. At the risk of labouring the point, surface process studies at specific sites are of limited value unless we also look below the surface and place both studies in their wider spatial context.

Section 4. The nature of the profiles

4.1 Mineral progressions

4.2 Chemical progressions

4.3 Structural progressions

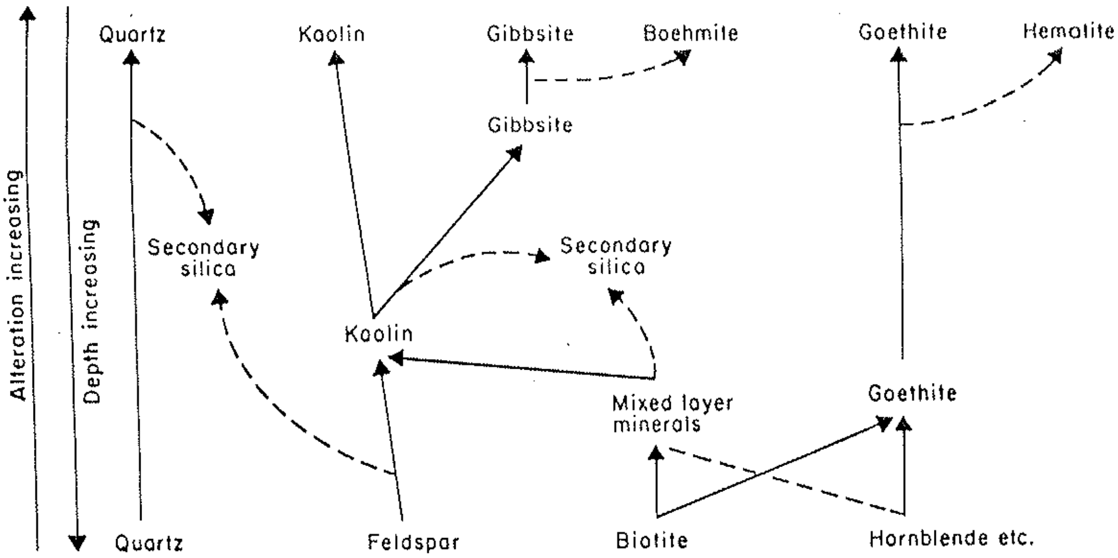
4.3.1 Grain size variations

4.3.2 Voids

4.4 Permeability

4.1. Mineral progressions

Gilkes and others (1973) have published a diagrammatic representation of mineral transformations during lateritic weathering of the Darling Range granites (figure 82). This provides a good summary and also a starting point for discussion of the variations which may occur.



Mineral progressions in a lateritic bauxite developed from granite in south-western Australia (After Gilkes et al., 1973).

Figure 82

Biotite $K(Mg.Fe)_3AlSi_3O_{10}(OH)_2$
In this mineral, the silicon oxygen tetrahedra (the basic unit of silicate minerals, with a silicon atom bonded covalently with four adjacent oxygen atoms) are arranged in sheets. Fe, Mg and K are weakly held in octahedral co-ordination sites between the sheets.

Biotite weathering precedes that of feldspars and hornblends (; the level 'base line' of the diagram is misleading in this respect). The main reason for the special susceptibility of biotite to weathering appears to be its fractured condition in the parent rock, but Eggler and others (1969) referred to post-magmatic oxidation of biotite, which results in a slight expansion and rupturing of surrounding grains, i.e. a system of pathways for moisture access to biotite may exist, which should contribute to early weathering.

The susceptibility to weathering of the individual units within a multi-sheet crystal differ. Thus, biotite weathering proceeds through a very complex process of mixed layer mineral development. The precise response of biotite to weathering appears to vary with climate. Thus, in more arid areas, hydrobiotite, smectite and illite are formed, with interlayer mica-vermiculite, vermiculite and kaolinite forming in more humid areas (Melfi et al.1983). It seems likely that this 'climatic' variation is an expression of variations in the ease with which ions are removed and so we could expect to find the 'dry' sequence at the base of low relief profiles in humid areas, if evacuation of groundwater is slow. In effect, the 'steps' in the progression can be increased or decreased by both climate and freedom of drainage. In humid and very freely draining situations, direct alteration to 1:1 clay minerals occurs. Even within such situations we can see a preference for direct formation of kaolinite, without a preceding halloysite stage, where drainage is freer and leaching more aggressive. Gilkes' diagram also shows alteration of biotite to goethite. This has been disputed, but he has established this by carefully prising apart weathering biotite flakes to reveal layers of goethite crystals sandwiched between them (Gilkes pers. com.1983). Thus, in these mineral progressions we must recognise two types of alteration. In the simpler, the succeeding stage is achieved by rearrangement of elements which survive leaching when the parent mineral breaks down. In other cases, elements are introduced from outside the immediate vicinity, so that the new mineral contains more of a particular element than that originally contained in the destroyed mineral. Hence, goethite can pseudomorph biotite which originally only contained a small fraction of the iron contained in the goethite. Such pseudomorphs provide proof positive of the mobility of such elements as Fe and Al even in profiles in which they accumulate relatively (and are therefore dubbed 'immobile').

<u>Muscovite</u> $KAl_2(AlSi_3O_{10})(OH,F)_2$ is very much more resistant to weathering than is biotite. It is reported to accumulate relatively, like quartz, not only in profiles in semi-arid terrain but also in humid and subhumid, where weathering has proceeded to the extent that there is even some gibbsite formation (Melfi et al.1983).

<u>Feldspars</u> Ca and Na feldspars weather much more readily than the K feldspars and the dissolution of Ca feldspars tends to precede that of Na feldspar. The weathering product varies with leaching aggression. In the expanded sequence, halloysite precedes kaolinite formation, with gibbsite as the end member of the sequence, but where leaching is more aggressive, feldspars alter directly to kaolinite. Under very aggressive conditions, there is direct feldspar to gibbsite transformation.In other cases, the kaolinite stage is by-passed, with halloysite altering directly to gibbsite. In New South Wales, plagioclases have been shown to weather to kaolinite via montmorillonite, while alkali feldspar alters directly to kaolinite or halloysite, without passing through a smectite stage (Craig & Loughnan 1964). Where conditions do not favour the retention of Al in the profile, the kaolinite is entirely 'dissolved'. As indicated elsewhere, such 'congruent' dissolution of kaolinite presents geochemical problems,

but, recently, dissolution and mobilisation of Al were achieved experimentally, using a laterite-indigenous micro-organism (Heydeman et al.1983). An intermediate stage appears to exist - a mineral with hexagonal form very like kaolinite but with only 1/3 the Al of normal kaolinite (McFarlane & Heydeman, in press).

There has been some confusion about the relative positions of kaolinite and gibbsite in the progression, some claiming that kaolins are the endproduct, preceded by gibbsite formation. Thomas (1974) implied that this is the more 'normal' progression, as summarised by Fieldes and Swindale (1954) in figure 83.

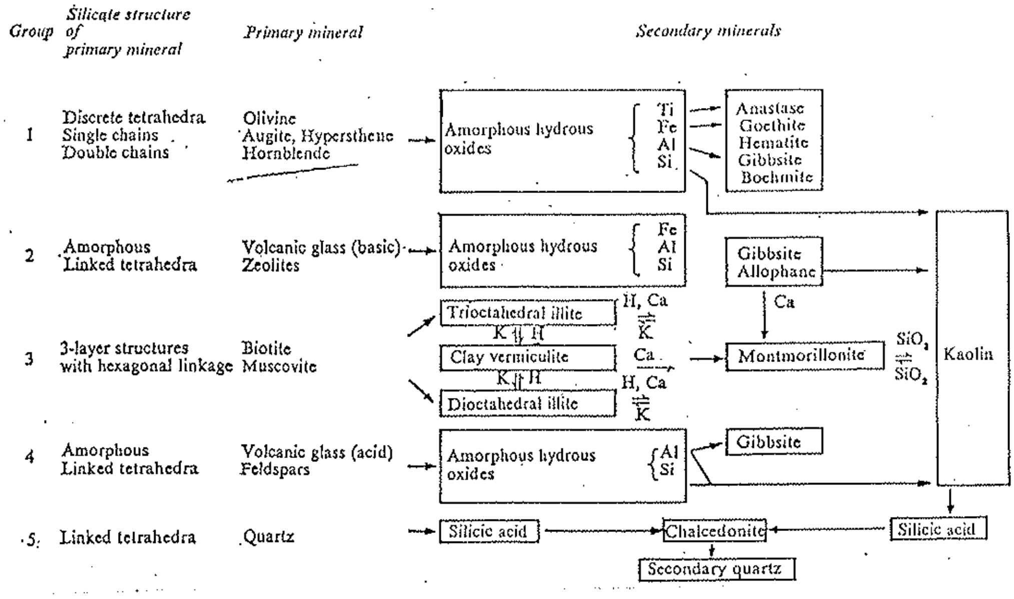


Figure 83

However, it has since become clear that resilicification of gibbsite to form kaolinite only occurs in unusual circumstances, where a Si supply becomes available after the normal endproduct, gibbsite, has been reached. For example, within the Pocos de Caldos caldera, following the formation of a gibbsitised profile, erosional conditions changed in such a way as to add a kaolinite-rich colluvium to the top of the profile. Desilicification of this colluvium provided the Si source for resilicification of the underlying bauxite. All stages of the process are clearly seen, beginning with halloysite formation down fractures in the bauxite and followed by lateral encroachment of halloysite into the bauxite, ultimately leaving bauxite 'core stones' isolated within the kaolinised profile (figure 84).

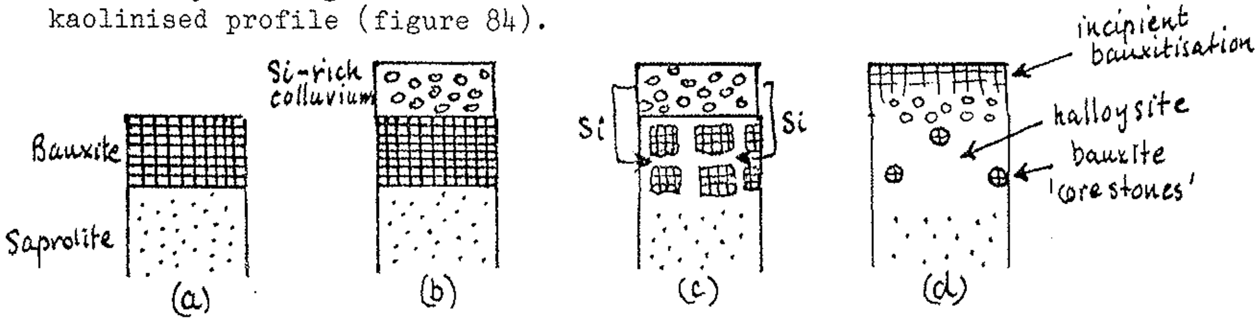


Figure 84

There now seems little doubt that the normal sequence is kaolinite to gibbsite. However, it is equally clear that gibbsite is by no means nobly indifferent to alteration or complete destruction. Alteration to boehmite has been indicated by Gilkes and others (1973). Corundum has also been recognised in the immediate surface horizons of some bauxites and if it is indeed pedogenetic, as its position appears to imply, explaining its formation presents an enormous problem. The transition from gibbsite to norstrandite (chemically similar but with a cubic structure) is also implied by their co-existence in the upper parts of bauxite profiles and the preliminary results of microbial leaching experiments indicate this transformation to have been achieved under laboratory conditions, using several bauxite-indigenous micro-organisms. There is also a variety of evidence to show that gibbsite may be directly 'dissolved' and in certain situations may be completely leached out of the profile, possibly via an intermediate kaolinite stage. In short, although it is probably valid to regard gibbsite as a general endproduct in the successive stages of mineral evolution (as Gilkes indicates), the impregnability that this implies is only relative.

<u>Hornblende</u> joins with biotite in the role of parent mineral for goethite formation. Formation is, in many cases, via an X-ray amorphous condition and a poorly crystalline phase or phases (eg. ferrihydrite), the complexities of which are difficult to unravel. Up-profile improvement in goethite crystallinity is widely observed. The various possible reasons for this are more fully discussed later (5.1.5) and there are strong microbial implications, as also for the goethite to haematite transformation in the higher parts of the profile. Haematite may also be a very early weathering product, co-precipitated with goethite. Al may substitute for Fe in the goethite lattice, up to about 32 mole percent. The reasons for these variations are far from clear. Most of the experimental work on this has concerned precipitaton from mixed solutions or gels and it is unlikely to provide much by way of answer because the assemblages express up-profile transformations in a continually evolving situation, not a single set of geochemical circumstances. Microbial leaching experiments with bauxite-indigenous micro-organisms have achieved a reduction in Al substitution in goethite (partial alumino-goethite to goethite transition), apparently by causing 'dissolution' of goethite and immediate recrystallisation with reduced substitution (; the 'lost' Al appears to go into the leachates, in a form as yet unknown).

The behaviour of iron in tropical weathering profiles is very complex and by no means a simple story of immobility achieved by Eh/pH constraints, as is still widely believed.

<u>Quartz</u> Most geochemistry text-books indicate that quartz is virtually insoluble in the natural weathering situation. This is manifestly untrue for the humid tropics. Near the base of deeply weathered profiles quartz tends to increase as other materials are leached out. There it is generally angular and the larger fragments become 'sugary' as a result of separation

into individual smaller grains. In detail, the grains become extensively fractured (pressure release in miniature?). Dissoluton along these fractures gives a runiform structure and the widening dissolution planes become invaded by secondary minerals, for example goethite, haematite, kaolinite and gibbsite. Following the initial relative increase, the percent of quartz then decreases upwards in many laterite and bauxite profiles. For example, in Western Uganda, a rejuvenated (elevated and vadose) groundwater laterite profile contained <u>in situ</u> pisoliths, which encapsulated the state of weathering of the saprolite at the time they were formed. They were richer in quartz than the inter-pisolith material, which was subjected to ongoing weathering and leaching (figure 85).

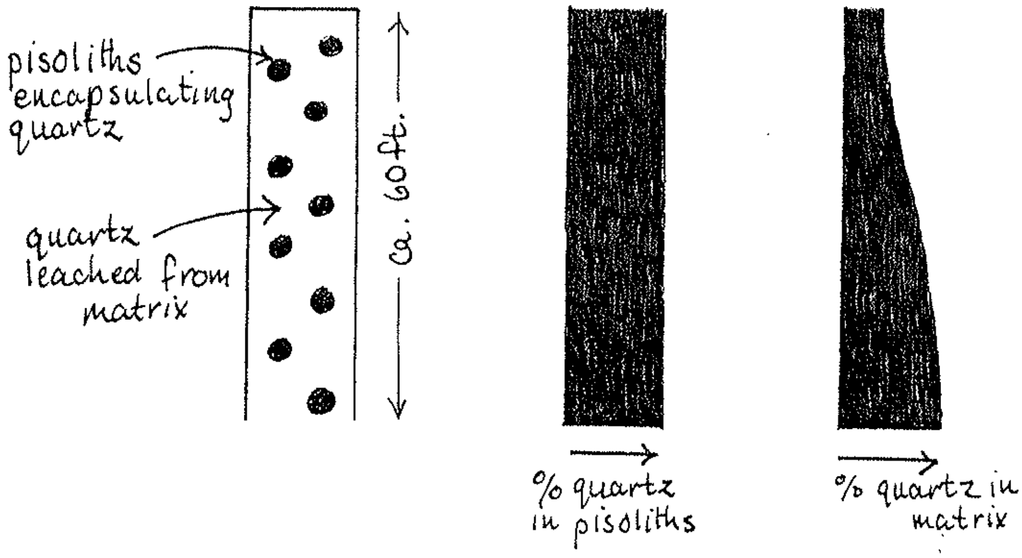


Figure 85

Gilkes and others (1973) clearly demonstrated the progressive up-profile decrease in quartz in the Yalanbee profiles (figure 86) in W. Australia.

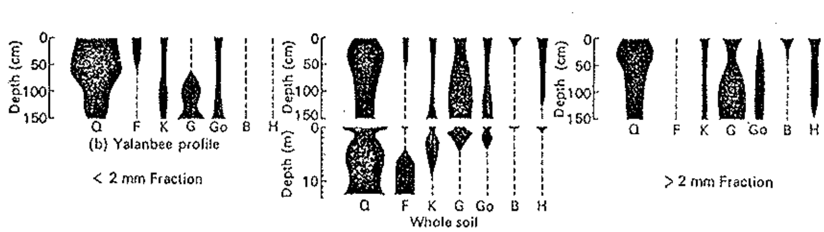


Figure 86

There have also been several studies of thin sections which describe in great detail the stages of dissolution of quartz. The final 'product' is rounded voids where the quartz grains used to be, within a heavily iron-impregnated groundmass. S.E.M. studies clearly show the 'rounding off' and pitting of the surfaces of grains. Dissolution of vein quartz and quartzites is also observed. Neoformation of kaolinite around surviving 'cores' of vein quartz was observed in western Uganda (McFarlane 1969). In Southern Uganda rounded boulders (corestones) of quartzite are incorporated into the laterite of the Ntenga Surface (which cuts across a variety of metasediments) at a level which corresponds to the top of the quartzite 'highs' on the basal surface of weathering (figure 87).

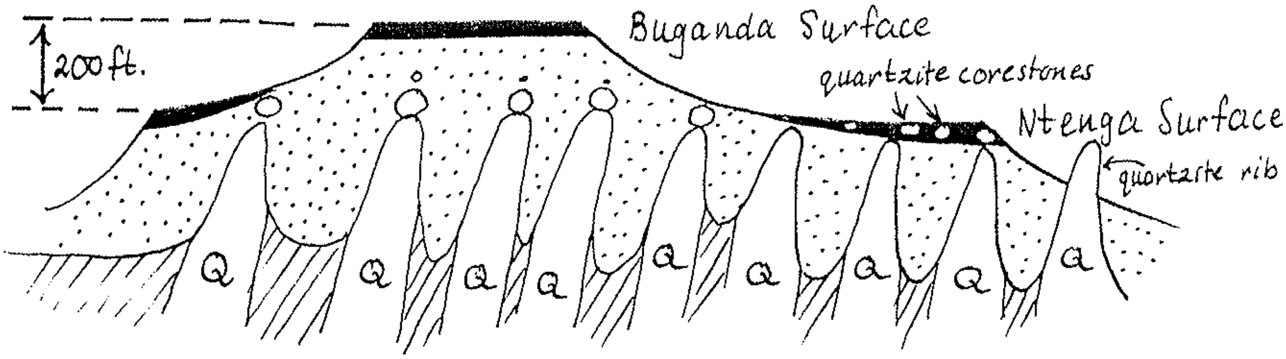


Figure 87

These and similarly rounded quartzite boulders in the Darling Ranges, were taken to indicate deposition under high energy fluviatile conditions simply on the grounds that quartzites could be rounded by no other means since quartz is reputedly virtually insoluble. In small, shallow valleys, set into the elevated, low relief, laterite surfaces, it is impossible to conceive of high energy streams. Rounding by chemical activity is strongly indicated.

There is no doubt whatever that quartz is dissolved and it is a pronounced and seriously unerestimated feature of the profiles at the hotter, wetter, end of the lateritic climatic range. At the drier margins, quartz often remains angular, and quartz veins brecciated, right up into the laterite itself.

It is now well known that microbial activity causes quartz dissolution (Krumbein 1984) and since most surface waters are supersaturated with respect to quartz, complexing is strongly implicated. It is also implicated by the geochemically nonsensical fact that in bauxitised profiles, where both kaolins and quartz are being 'dissolved', beautiful bi-pyramids of neoformed quartz can sometimes be found, eg. at Weipa (Australia) and Galikonda (E.India).

In short, the mineral evolution in tropical profiles points strongly to both limited and protracted mobility of the so-called resistant materials, Fe,Al and Si and reveals a changing scene of mineral evolution which is beyond purely geochemical explanation.

4.2 Chemical progressions

Major elements

Na, Ca, Mg. Where precipitation exceeds evapotranspiration, these elements are readily leached out of the profile, that is, they are lost early in the weathering progression. This is clearly expressed in their distribution in the profile (for example, see figure 88). That does not mean to say that in very mature or ancient weathering profiles they are not to some extent still being released into the groundwaters. As long as the profile is deepening they will be released by the early weathering at the profile base. Nevertheless their release slows down as weathering advances and deepens, particularly below the water-table. It slows down in absolute terms but more particularly in relative terms, because an increasing quantity of the more resistant materials is released into the groundwaters from higher in the profile, where weathering is more aggressive and has reached a more advanced stage.

If mature, deep, profiles, with slow release of Na, Ca and Mg at the base, are rejuvenated by elevation, so that they are once more vadose, then accelerated release of these elements is to be expected (figure 89)

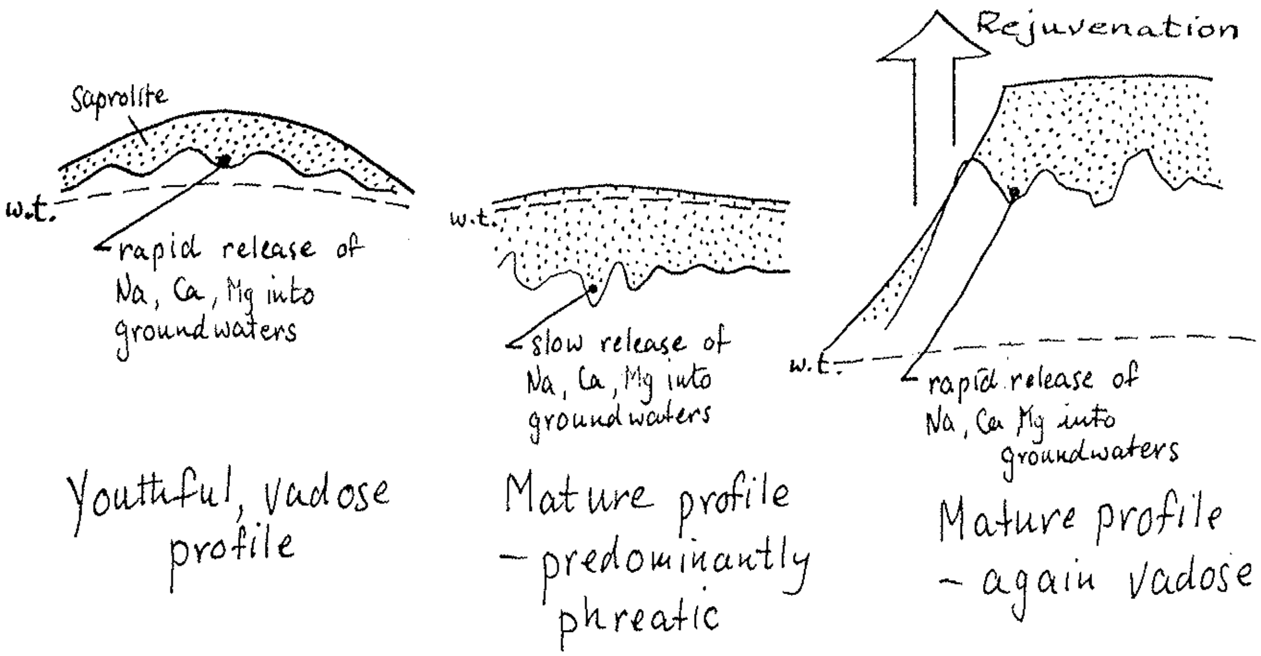


Figure 89

Where we have such a two-cycle situation, climatic change plays an important role in dictating the behaviour of these elements in the younger profiles on the lowlands. Where conditions continue to be wet, they will be washed out of both the higher and the lower profiles. However, where there is climatic change towards drier conditions or a more seasonal

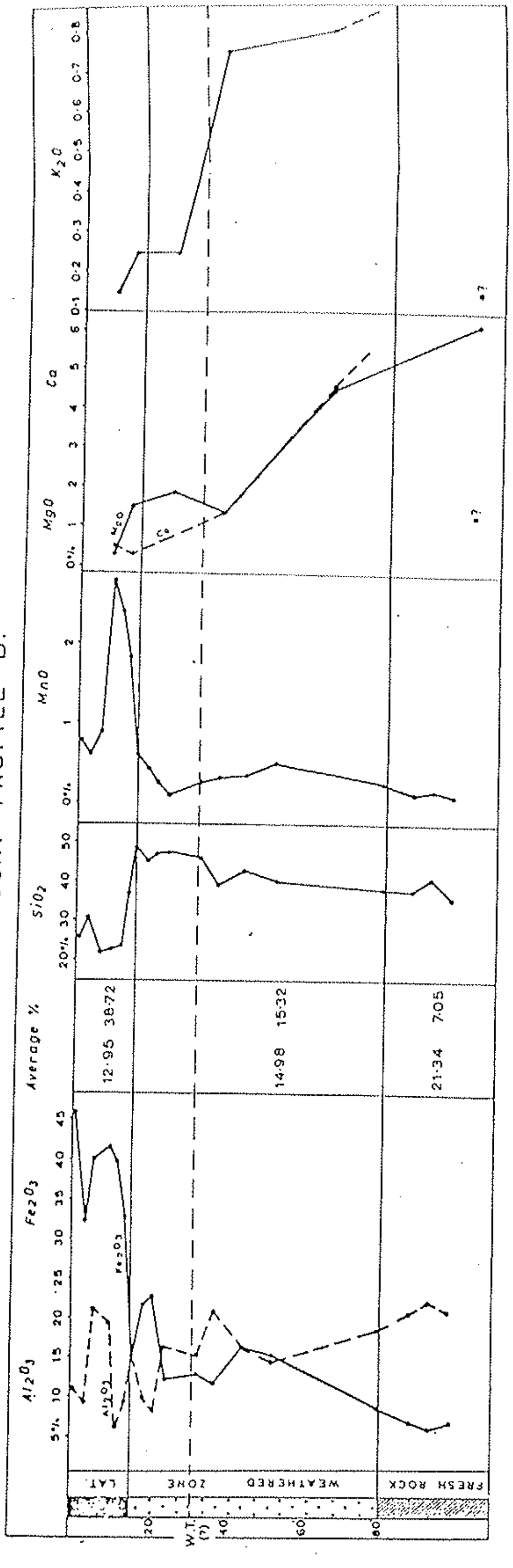

BUSIA PROFILE B.
K_2O
Ca
MgO
MnO
SiO_2
Average %
12·95 38·72
14·98 15·32
21·34 7·05
Fe_2O_3
Al_2O_3
LAT.
WEATHERED ZONE
FRESH ROCK
W.T. (?)

Figure 88

regime, if moisture is still sufficient to penetrate the old profile and leach out Na, Ca and Mg these may be precipitated in the lower profile. The precipitation of calcrete (superficial crusts composed dominantly of calcium carbonate) appears to be limited to areas with less than 400-600mm rainfall per annum. A pre-requisite for this precipitation seems to be that the water-table in the younger profile should be near the surface. This is the case where the landsurface is very flat (figure 90a) or where bed-rock forces the groundwater to the surface (figure 90b). In many cases, calcrete precipitation is restricted to a narrow belt along river courses (figure 90c).

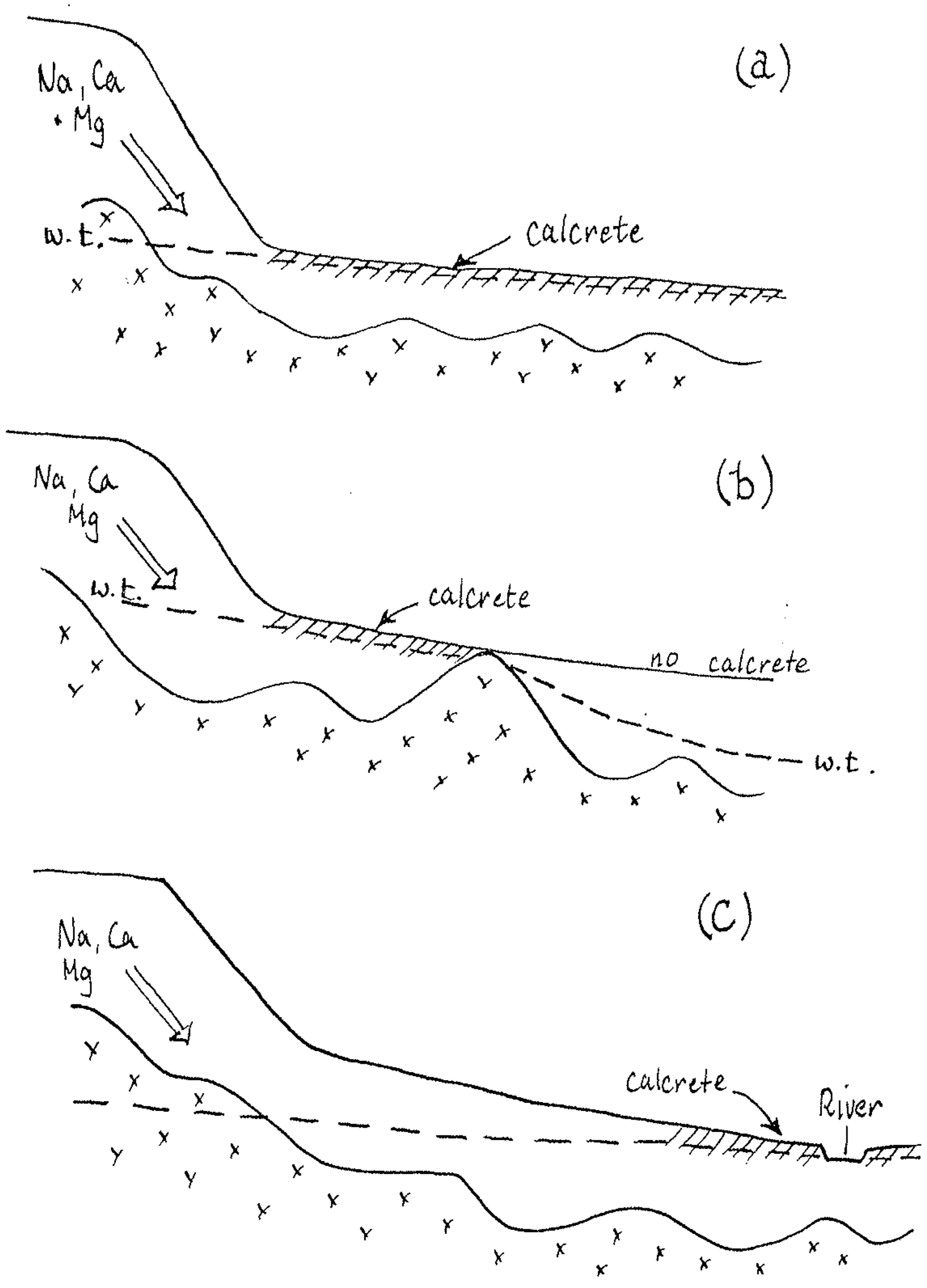


Figure 90

Where the water-table is low in the profile, there is usually no calcrete and therefore no obvious indication that the groundwater is enriched in these elements.

Precipitation of calcrete is discussed more fully in Goudie (1983). It may be caused by evaporation, or by degassing. Loss of CO_2 from the solutions is probably the prime cause of imbalance in equilibrium and this may be effected by turbulence, warming or biotic extraction. Transpiration can, for example, bring about CO_2 loss by decreasing the pressure of pore water (as a result of increase in suction pressure). Micro-organisms are becoming increasingly indicated as agents of precipitation. Calcrete precipitation may also be achieved by the common ion effect - the addition to a saturated solution of one salt of a quantity of a soluble salt that possesses an ion in common with it leads to the precipitation of the first salt.

Precipitation of gypsum (calcium sulphate dihydrate) appears to occur where rainfall is less than 250 mm per annum. Sodium salts tend to be precipitated in seasonal lakes or lagoons.

In short, in a two-cycle situation, where climatic change is towards increasing dryness, if precipitation is sufficient to continue leaching of the older profile it may only be sufficiently aggressive to effect leaching of the most mobile elements Ca, Na and Mg and these will be enriched in the groundwaters of the younger profile and may be precipitated as surficial crusts where favourable conditions prevail.

K Potassium leaching tends to be marginally slower than that of Na, Ca and Mg, almost certainly reflecting the lesser susceptibility to weathering of the K-feldspars. Apart from this rather slower start, the pattern is very similar to that of Na, Ca and Mg. The element is readily lost from the profile, as shown in figure 87, for example.

Si It is the extensive loss of Si which is taken as the hallmark of tropical weathering, in that Si is lost when 2:1 minerals break down to be replaced by 1:1 minerals, and this requires aggressive leaching. Under the most agressive condition there is further loss of Si to yield hydrated oxides of Al.

Si loss begins higher in the profile than loss of Na, Ca, Mg and K, as major losses are essentially linked with first kaolinite formation from 2:1 clay minerals and then kaolinite dissolution or desilicification, (and the latter is above the water-table in cases where the weathering profile extends below it).

Solution of amorphous silica is moderate under the prevailing pH conditions (6-7) as shown in figure 91.
Theoretically, solubility at 25 degrees C is 135 ppm (Krauskopf 1967) and even this raises interesting problems because the Si content of tropical groundwater appears to be too low to 'fit' the massive losses from the profiles (8-16 ppm for vadose and 30-40 ppm for water from deep wells, according to Thomas (1974)). In fact the problem is very much greater because the desilicification was assumed to exclude quartz dissolution, which is widely believed to be insignificant (eg.... "the effects of solution on quartz are probably minimal" (Thomas 1794,p.25), and this is certainly not the case. The disparity between Si losses from the profile and Si content of groundwaters is thus even greater than has been indicated by groundwater analyses.

Si may initially increase in the profile, a relative increase as the more readily leached components are removed. Thereafter, up-profile losses

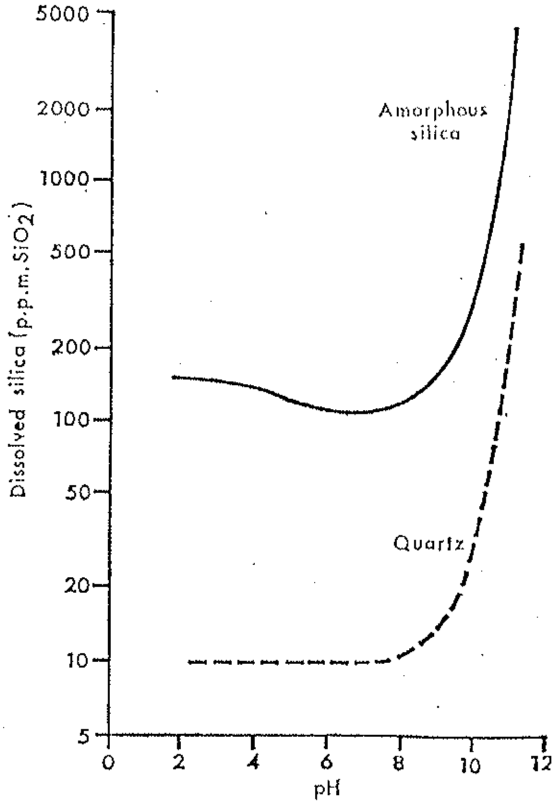


Figure 91

Solubility of silica at 25°C (from Krauskopf 1959)

The solid line shows the variation in solubility of amorphous silica with pH, as determined experimentally. The lower dashed line is the calculated solubility of quartz, based on the approximately known solubility of 10 p.p.m. SiO_2 in neutral and acid conditions.

are progressive, and are linked first with the formation of kaolinite from 2:1 clay minerals and then with the decreasing proportion of kaolinite and quartz in the profile. After the general trend of loss within the profile, Si tends to increase in the immediate surface horizons, and this is often clearly attributable to accumulation of the quartz which survives dissolution. It is a relative accumulation, resultant upon surface lowering as the other materials are removed by leaching (figure 92).

Where Si-enriched horizons occur at depth in such a 'typical' progression, this feature appears to be attributable to a later stage when, under drier conditions, the Si mobilised in the upper part of the profile may be deposited lower within it rather than being entirely flushed out.

A change towards drier conditions also results in a similar two-cycle effect to that described for calcrete; Si leached from older, elevated profiles may be deposited as silcrete in the profile of a younger landsurface.

Silcrete formation has been reviewed by Summerfield (1983) and there are still many unsolved genetic questions.

Apart from the difficulty of reconciling the huge silica losses from the profile with the low Si content of groundwaters, the mechanism for mobilisation is problematic. Kaolinite dissolution, for example, requires leaching of both Al and Si, and yet it is known that certain ions, most noteably Al^{3+}, drastically reduce silica solubility, even in trace amounts (Okamoto et al. 1957). Kaolinite dissolution by true solution appears therefore to be impossible, unless either the Al or both the Si and the Al are complexed. Leaching experiments with a laterite-indigenous

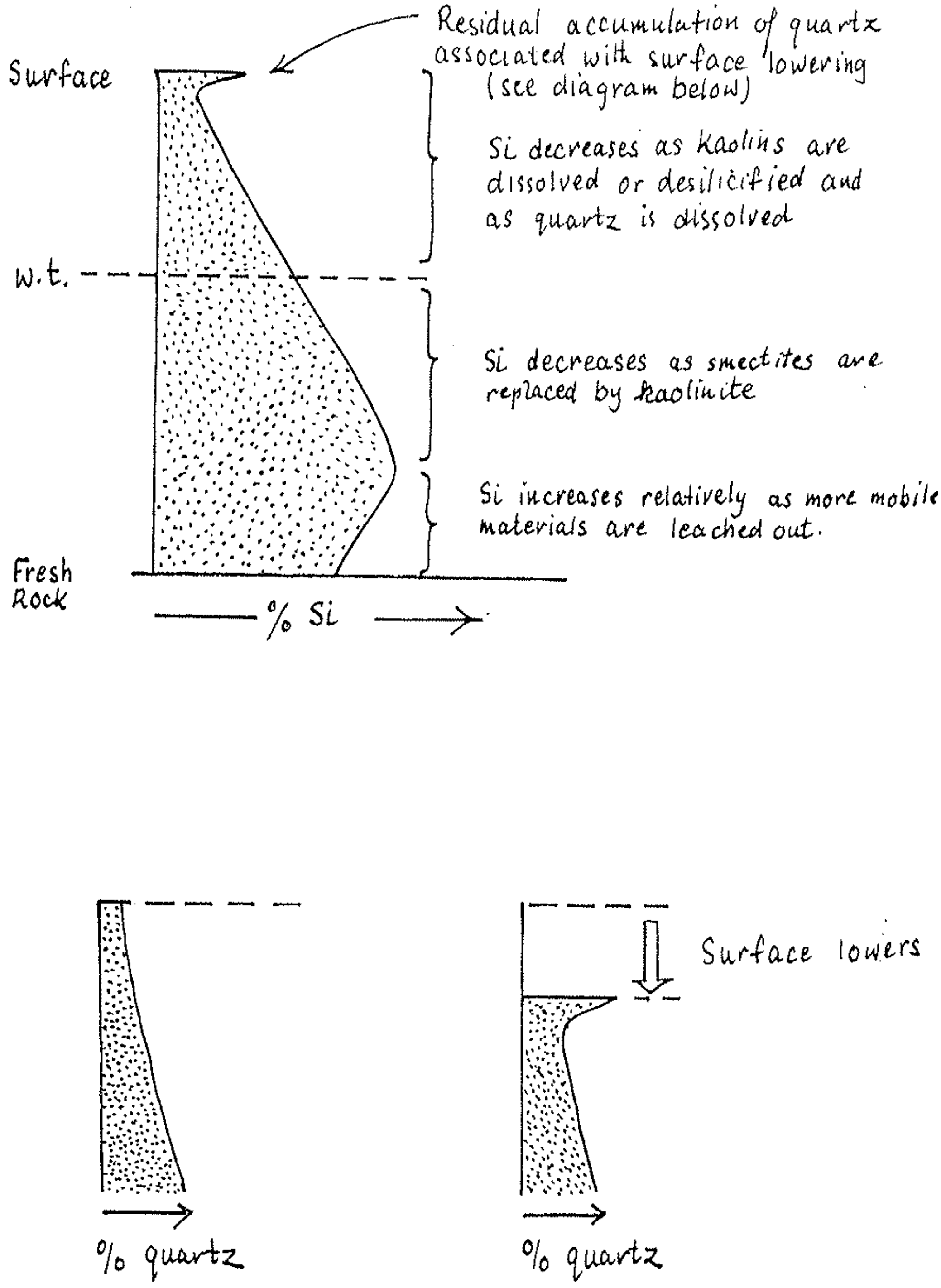
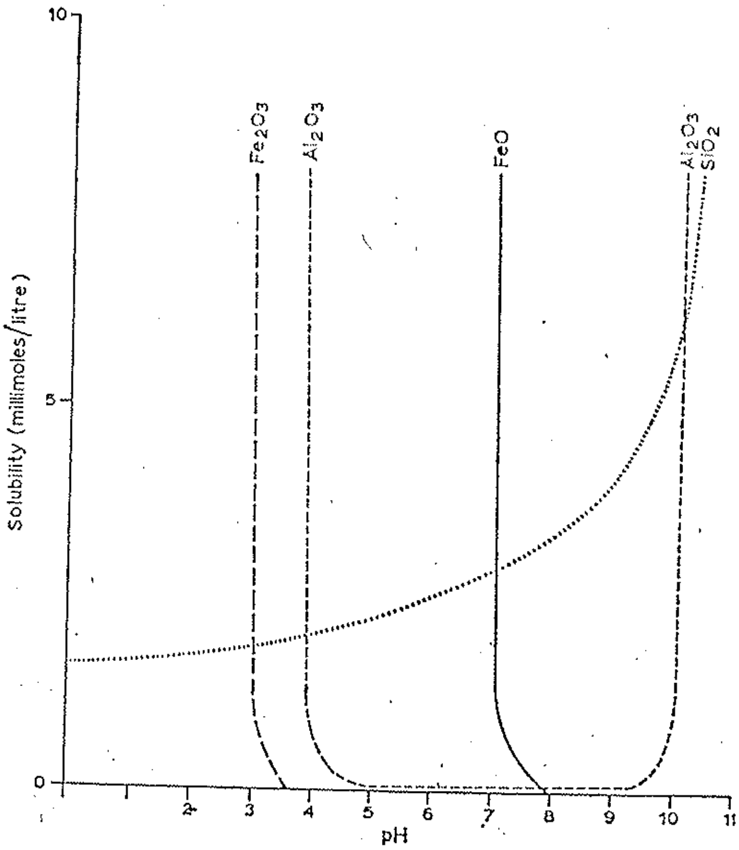

Residual accumulation of quartz associated with surface lowering (see diagram below)
Surface
Si decreases as kaolins are dissolved or desilicified and as quartz is dissolved
w.t.
Si decreases as smectites are replaced by kaolinite
Si increases relatively as more mobile materials are leached out.
Fresh Rock
% Si
Surface lowers
% quartz
% quartz

Figure 92

micro-organism, extracted from a laterite in which it is clear that kaolinite is being destroyed, effected dissolution of kaolinite to leave a solid silica 'frass' and with Al in the leachates, apparently as a complex Heydeman et al. 1983). This provides a mechanism for kaolinite dissolution, but does not contribute to the disparity between loss of Si from the profile and the low concentrations of Si in the groundwaters. Although Summerfield (1983) has stated that "It is now well established that silica exists in natural waters as monosilicic acid (H_4SiO_4) rather than as a colloid" the disparity suggests that Si complexing may have been underestimated. This is also implicit in the failure to date bauxitisation by Si content of groundwaters (Section 5.2) and it is certainly implied by the quartz dissolution from these profiles, since, although the groundwaters are undersaturated with respect of amorphous silica, they are supersaturated with respect of quartz. Microbial dissolution of Si is now well established and, in total, the balance of evidence is in favour of the existence of Si in the groundwaters in a microbially complexed form.

Fe and Al

These are generally regarded as stable elements in tropical weathering profiles where precipitation exceeds evaporation. Decrease in Si/Al or Si/Al+Fe ratios were at one time used in attempts to define lateritisation. These elements are generally more resistant to leaching than the bases and also Si. When the 2:1 clay minerals are replaced by 1:1, Si is lost and the Fe is usually retained (amorphous, oxides and hydroxides), the Al being retained in combined form (kaolinite). Both therefore increase relatively at this stage of the weathering progression. Thereafter, lateritic profiles fall into two groups: those in which Fe increases up-profile and those in which Al increases. It is very much a case of either/or, although the literature tends to imply 'both'. It is a common observation that Fe and Al behave antipathetically in the profile. In horizons where Al increases, Fe decreases and vice versa. So two situations exist. In the one, Si and Al are leached out and Fe retained and in the other Si and Fe are leached out and Al retained. Explanation of this has presented enormous problems since the process of accumulation has long been regarded as essentially differential, pH-controlled leaching. Figure 93 shows variations in solubility of iron and aluminium oxides and silica with pH. Lateritic iron is ferric and at pH 6-7 both this iron and aluminium are virtually insoluble. Norton (1974) attempted to explain relative accumulation of either Fe or Al in terms of pH, mineral stabilities and variable concentrations but ultimately conceded that the mineral assemblages found to occur in laterites cannot be explained in these terms. He suggested metastable associations as an explanation. Study of textural evolution and associated mineral assemblages certainly points to a condition far from stable (see section 5). Textural components and their mineral assemblages which form in a given horizon survive as relics in higher horizons where different assemblages are stable. So there are elements of truth in Norton's explanation, but this is only part of the story. The fundamental misconception appears to be that the system is essentially Eh/pH-controlled differential leaching. The most damning evidence to the effect that this is not so comes from laboratory studies by ALCOA, who, for years, have been exploring the possibility of extracting Al from kaolinite using pH. This line of approach has finally been abandoned. There is invariably some Fe associated with kaolinite deposits and whether high or low pH is used "you are always stuck with the iron" (ALCOA, pers.

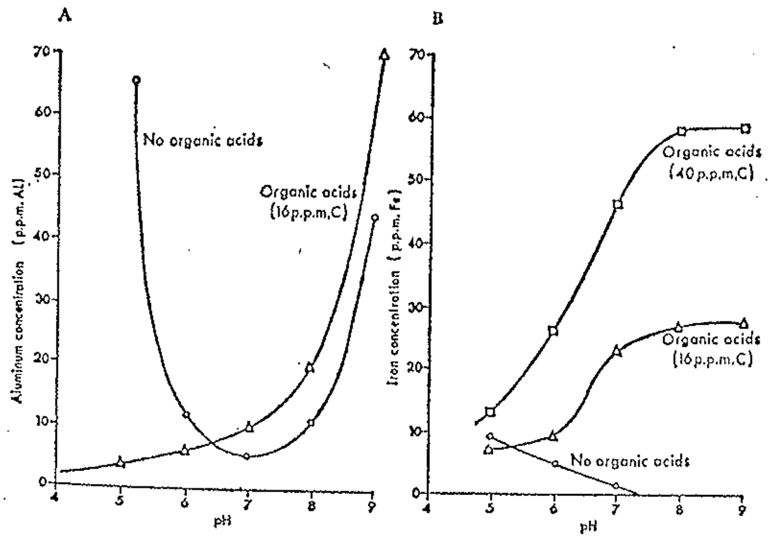


Variations in solubility of iron and aluminium oxides and silica with pH.

Figure 93

com. anon.). In effect, if pH conditions are conducive to leaching of Al from kaolinite, Fe is also leached out. If Si is leached out, then Fe remains with the Al. Yet the separation of Si and Fe from Al and also Si and Al from Fe are achieved in nature in the lateritisation processes.

One suggested mechanism is complexing by organic (humic) acids. The effects of this are shown in figure 94.



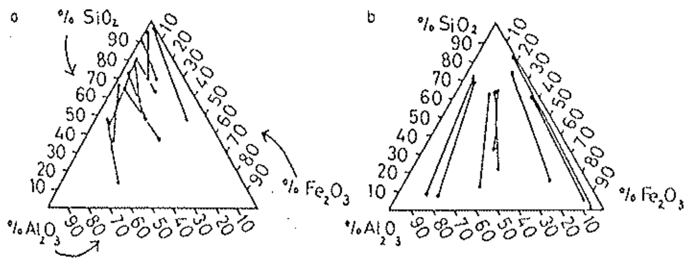
Solubility of aluminium and ferric iron as a function of pH in the presence and absence of organic acids (from Ong, Swanson and Bisque 1970).

A. Solubility of aluminium as a function of pH in the presence and absence of organic acids; B. Solubility of ferric iron as a function of pH in the presence and absence of organic acids.

Figure 94

This explanation is almost totally insulated from the realities of the situation. The survival of tropical rainforests on laterite profiles, almost entirely impoverished of plant nutrients, depends on extraordinarily efficient nutrient recycling. Organic acid movement down through the profile cannot play a significant role in this element differentiation question.

Schellman (1977) offered a contribution to this question by his identification of different weathering trends over different rock types (this implying a physico-chemical control, unspecified). He used ternary diagrams to plot the changing concentrations of Si, Al and Fe in the weathering profiles over quartz-rich and quartz-poor or free rocks (figure 95).



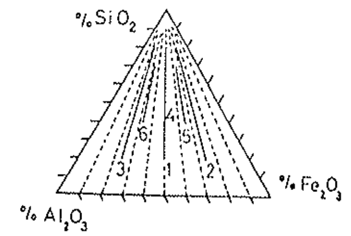
a. Weathering trends over quartz-rich rocks.

b. Weathering trends over quartz-free rocks

Figure 95

On the diagram for quartz-rich rocks he pointed out that the trend is away from the SiO_2 side of the triangle, this indicating preferential Fe enrichment, not Al enrichment. For the quartz-free rocks the trend is away from the SiO_2 apex. The first of these trend diagrams appears to provide support for the long-held belief that quartz-rich rocks are unfavourable for bauxitisation, a view expressed by Schellmann (1977) in his paper which provides guidelines for bauxite exploration. However, the significance of these trends is more than doubtful. In part they are artefacts of the cartographic technique. A high proportion of SiO_2 in the parent rocks inevitably produces a trend from the apex. Rocks rich in quartz usually have Al_2O_3 in excess of Fe_2O_3 and are therefore placed along the SiO_2 side of the triangle. They are therefore predisposed to weathering trends away from this side. Significant weathering trends, as far as Fe and Al richness of the product is concerned, are those which swing to the left or right of the equal gain trends, that is in the direction of preferential Al or Fe gains. Equal gain trends, radiating from the apex, are shown in figure 96a (also the values for the construction). Re-examination of the trends (Schellman's and other published trends) shows (figure 96b) that quartz-richness or poverty do not affect them.

(a)



	SiO_2	Fe_2O_3	Al_2O_3	Enrichment
1	80%	10	10	
	20	40	40	x 4
2	80	15	5	
	20	60	20	x 4
3	80	5	15	
	20	20	60	x 4
4	70	15	15	
	40	30	30	x 2
5	70	20	10	
	40	40	20	x 2
6	70	10	20	
	40	20	40	x 2

(b)

Preferential enrichment of Al_2O_3 or Fe_2O_3 in laterites developed from Al-rich, Fe-rich, quartz-rich and quartz-free parent rocks

Parent rock	$Al_2O_3 > Fe_2O_3$		$Fe_2O_3 > Al_2O_3$		$Fe_2O_3 = Al_2O_3$	
	No. of samples	% of total number	No. of samples	% of total number	No. of samples	% of total number
$Al_2O_3 < Fe_2O_3$ (18 samples)	1	5.6	14	77.8	3	16.7
$Fe_2O_3 > Al_2O_3$ (eight samples)	3	37.5	2	25.0	3	37.5
Quartz-rich (19 samples)	3	15.8	12	63.0	4	21.0
Quartz-free (eight samples)	1	12.5	5	62.0	2	25.0

Figure 96

Both rock groups yield a similar proportion of Al and Fe-enriched products, with a preference in both cases for Fe enrichment. Rocks with an initially greater Al than Fe content favour relative gain of Fe than Al. Indeed, since quartz-rich rocks are relatively rich in Al, Schellmann's quartz-rich trend appears to express this rather than, as he suggested, a trend related to quartz-richness.

In short, weathering trends towards preferential Al or Fe enrichment do no correspond with quartz poverty or richness, respectively, of the parent rocks. Fe-enriched endproducts can occur on any rock type as can Al enriched endproducts (McFarlane 1983a).

This conclusion raises the objection "But most of the world's known bauxite occurrences are on quartz-poor and Al-rich rocks". Guidelines for bauxite exploration stress that quartz-poor, Al-rich rocks are preferred parent materials and this seems eminently logical since bauxitisation involves Si leaching and Al accumulation. Obviously the less you have of the former and the more of the latter, to start with, the better. If bauxite exploration is directed to such parent rocks, sometimes it is found and sometimes it is not, but at the end of the day it is always possible to say that all the known occurrences are over these rocks. When, relatively recently, bauxite exploration stopped ignoring quartz-rich rocks the story changed. The world's largest single bauxite deposit at Weipa is developed from a quartz and kaolinite sediment. ALCOA's Darling Range deposit is developed from granite. Rich deposits have developed from khondalites in E. India. Bauxite has also been found on granites in Venezuela and Brazil. If, as may still be the case, more bauxite is known to overlie quartz-poor and Al-rich rocks, we should seriously consider that this may express a bias in exploration (McFarlane 1984).

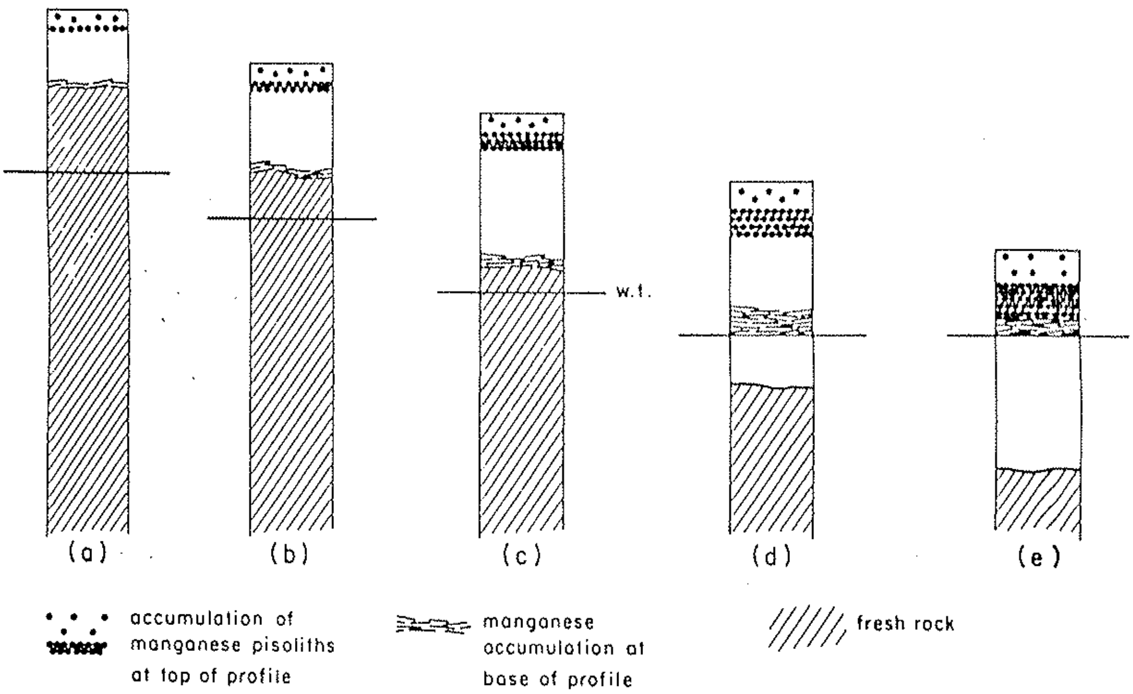
What generalisations can validly be offered concerning trends towards either preferential Al or Fe enrichment? Fe enrichment is common and Al enrichment uncommon. We should therefore look for factors exclusive to the latter. There is clear evidence that Al enrichment is associated with particularly aggressive leaching. Its development appears, for example, to be favoured where the lateritic protore has a structure which is particularly permeable, or where saprolite retains good permeability by resistance to collapse. It is better developed where rocks are faulted and fissured, etc. There is little doubt that aggressive leaching is needed (eg. Bardossy 1983) and in many cases it is demonstrably a more advanced stage of leaching than is that represented by crusts rich in Fe and kaolinite. In other words, following a leaching situation which favours formation of the Fe-rich, kaolinitic horizons, conditions change to more aggressive, so that Fe is leached out and kaolinite desilicified, leaving Al to accumulate. This change has now been linked to rejuvenation and elevation of low level lateritic protores (further discussion in section 5) , so that bauxitised plateaux may be regarded as the leached bones of former Fe-rich crusts formed as a residuum on the lowlands. Like pallid zone formation, bauxitisation appears in most cases to be a post-incision modification of the profile (McFarlane 1983b).

We can with confidence, I think, link Al enrichment with particularly aggressive leaching. That still leaves unanswered the question of how the differential leaching is achieved. In order to further examine the thesis that aggressive leaching is favourable, an analysis of the temporal distribution of bauxitisation was made and this points strongly to what I believe to be the essential underlying facotr. If particularly aggressive leaching is favourable, we should be able to detect this, expressed as a greater quantity of bauxite formed during particularly favourable climatic regimes in the geological history, eg. during the Eocene. Such an analysis had already been made and it appeared to indicate greater bauxite production during hot wet periods than during cool and dry periods (Bardossy 1979). Unfortunately, this analysis did not use an equal class interval.If we re-analyse the data, to consider production per million years within each geological period it emerges that the overall pattern was towards a progressive increase in the rate of bauxitisation to the present time, despite general global cooling and increasing aridity since the Oligocene. Within that overall trend, variations attributable to particularly favourable (hot and wet) periods also occurred. The trend towards increasing rates of bauxitisation is, moreover, very much greater than even this re-analysis indicates, because bauxites were dated by the age of the surface on which they occur, eg. if it lies on an Eocene surface it is Eocene etc. Since it is now quite clear that much of the world's bauxitisation is post-incision, it is very much younger and in many cases is quite clearly presently forming on very ancient landsurfaces. For example, in some cases there is direct gibbsitisation of feldspars at the base of the profile. The Galikonda bauxite (E. Coast, India) on a possibly

Cretaceous landsurface, which survives as a plateau, provides one example. Given that situation, we have a clear choice: either the gibbsitisation of the feldspars at the base of the profile is contemporaneous or it is 'fossil', this latter implying that there is no leaching whatsoever today. In a monsoon climate this is impossible. Therefore the gibbsitisation is contemporaneous and to date the deposit as Cretaceous bacause the landsurface is Cretaceous is incorrect. If we take this re-dating of bauxitisation into consideration, this makes the increase to the present time very spectacular indeed. It is certainly not climatically controlled and we must ask the question "what has increased to the present time?" A biological factor is clearly implicated and the fact that the waters issuing from the base of bauxite profiles are sometimes strongly carbonated and that exploration pits sometimes fill with CO_2 to the extent that it constitutes a hazard to the excavators indicate a microbial role. These crucial observations are rarely published, occurring in very old publications pertaining to the days when "common" observation was more acceptable and data was not valued in terms of the cost of the equipment used to acquire it. If microbial complexing is involved, then the constraints on differential leaching, which pH and Eh conditions impose, can be by-passed. I see no logical alternative at present and it may be relevant that on abandoning their experiments with pH controlled leaching of kaolinite, ALCOA have recently explored microbial leaching and now have an Al extraction process 'at an advanced stage of development' (pers com, anon.).

Mn Manganese behaves like iron; it tends to be retained in the profile and therefore to accumulate relatively in the horizons where Fe accumulates. Prior to the release and accumulation of Fe, Mn is lost so that the onset of accumulation involves already partially depleted saprolite. It is rather more mobile than iron, so that although part remains in the upper soil horizons (in which the iron-rich pisoliths act as foci for precipitation) part is leached down the profile. The base of the profile appears to be a major locus of precipitation and when the basal surface of weathering lowers below the water-table, precipitation appears to occur within the zone of oscillation. Possibly manganese enters the groundwaters and is oxidised within this zone when the water-table lowers, leaving a precipitate which survives re-immersion when the water-table rises once again. During profile development, these two loci of maganese concentration apparently merge, as indicated in figure 97.
There are many outstanding genetic problems surrounding the behaviour of manganese in the weathering profile. Chukhrov is examining the role of micro-organisms (pers. com. 1982), but results are not yet available. It is clear, however, that the manganese retained in the profile is only part of the original total in the rock consumed to provide the residuum; considerable quantities must be deduced to have entered the groundwaters, in a form as yet unknown.

To summarise, as tropical weathering proceeds it becomes progresively more difficult to explain the behaviour of major elements in terms of pH-controlled leaching. There seem to be no problems with Na, Ca, Mg and K, the most soluble of the major elements. Leaching of amorphous Si can be reasonably explained in terms of the prevailing pH conditions, but this only goes a small way to explaining total Si losses from the profiles.



Tentative schematic representation of familial progression of manganiferous laterite.
(a) Some manganese moves into ferruginous pisoliths. Some moves downprofile to be precipitated near the basal surface of weathering.
(b), (c) Manganese accumulates at these two loci, as the profile deepens and moves downwards, encroaching on more fresh rock.
(d) When the basal surface of weathering moves below the groundwater-table, the lower locus of precipitation is the base of the vadoze zone.
(e) With continued land surface reduction the vadoze zone is 'squeezed out' and the two loci coalesce.

Figure 97

Thus, the extreme desilicification which characterises lateritic profiles appears to depend to a considerable extent on microbial complexing, as does explanation of the behaviour of Fe and Al. This carries with it the implication that groundwater analyses for materials 'in solution' may very seriously under-represent the concentrations of the so-called resistant elements, Si, Fe and Al.

To consider the behaviour of elements in a tropical weathering profile in terms of two things, what has been leached out and what has been retained, is misleading. It inadvertently implies that materials are either nobly indifferent to leaching or that they succumb. This is not the case. The development of lateritic horizon differentiation depends on the relative durations of mobilities. Protracted mobility allows a material to be leached out of the profile. That is widely appreciated. What is less well appreciated is the fact that the Fe and Al, for example, which resist leaching and therefore accumulate, are also mobilised but their mobility is more limited. Al-rich residua show clear signs of short-term repeated 'solution' and deposition and this is also true of Fe-rich horizons, particularly those of the pedogenetic class of laterites. Indeed, this repeated solution and deposition is an essential cumulative mechanism (see section 5). Relatively recently it has become appreciated that even where such residual crusts are very well developed the mobility of the enriched elements is much greater than was formerly suspected and the accumulation is only partial. Considerable quantities of the accumulated elements, particularly Fe, are mobile to the extent that they too are leached out of the profiles and into the groundwaters. Details are provided elsewhere (section 5). Here it should only be noted that an Fe-rich surficial crust does not indicate that groundwaters can be expected to be relatively free from Fe on the assumption that the crust indicates total resistance to leaching.

Trace and ultra-trace elements

Pickering (1983) has recently reviewed the conditions under which trace elements are retained in or leached from soils - the variability of element behaviour and the variable retention capacities of various clays and Fe species. The review is almost entirely concerned with single elements, separate clays, a range of pH conditions etc, and a very complex situation is revealed. It is virtually impossible to use this experimental work to predict the behaviour of trace and ultra-trace elements in tropical weathering profiles because there the mixtures of materials lead to even more complex 'competition' situations. Moreover, the mixtures are in a constant state of evolution and we simply do not know enough about the nature of the materials involved. The X-ray amorphous components are, it is generally agreed, the most important and we are still only at an early stage in examining them. We are only beginning to explore the intermediate stages of kaolinite dissolution. We know virtually nothing about 'solid state solutions' of Fe, the X-ray amorphous "stuff that plugs the holes" (to borrow La Brecque's clear description of it) and it is only recently that ferrihydrite has been recognised as a mineral, poorly expressed on XRD traces, even at high concentration. Synthetic ferrihydrite has itself recently been indicated to be a mixture of two materials with different solubilities (Hughes, pers. com 1984). To these problems we can add a similar one concerning the soil solutions. The water most readily examined (most accessible) is probably the least important, in that it is the least active. Water with the most intimate and longer lived relationship with soil or mineral surfaces is more important and rather inaccessible for study. When we measure the pH of the soil water we should ask the question "do we really know what we are measuring?" (Holtzhey, USDA, pers com. 1982). Similarly for the 'equilibrium conditions' of solutions - "what solutions?".

In short, there is an enormous, possibly unbridgeable, gulf between trace element behaviour predictions based on laboratory work and understanding, let alone predictions, of behaviour in tropical weathering profiles.

Published accounts of trace element distributions in weathering profiles have been relatively few, in comparison with the economically more interesting major elements. The situation is now changing for two reasons. First, the production of Ni from nickel laterite is facing economic problems such that the co-extraction of "sweeteners", for example Co, may tip the balance in favour of continued viability. It is known that this laterite also "scavanges" other metallic elements of economic interest, for example palladium and their concentration and distribution are now beginning to be researched systematically (by Morris, at Brunel). A second reason for growing concern with trace elements in deeply weathered profiles is for geochemical prospecting, in order to locate base metal concentrations in the fresh rock below the saprolite. This depends on the identification of "pathfinders", elements or minerals of no concern in themselves, but typically found in association with the economic minerals and, unlike these, with ability to survive in the weathered profiles. Elsevier have recently contracted Dr C R M Butt, Division of Mineralogy, CSIRO, Western Australia, to edit a review on this subject. It is still at an early draft stage, but will evidently take the form of a START report, in that having indicated what little is known, it identifies key research objectives, to examine the hypotheses indicated by our available knowledge.

Information about trace element behaviour in the early stages of weathering, especially at the base of deep profiles, is particularly noteable for its sparcity, largely because pedologists regard saprolite as 'parent material' for soils and do not extend their analyses to include it (Minarik et al. 1983). The distribution of a restricted number of micro-elements has been examined in the weathering profiles (Blaxland 1974, Nesbitt 1979, 1980, Bojko et al. 1981, Mosser 1979). Minarik and others (1983) have described a more extensive range of chemical changes of a Bohemian granite during its weathering. In this case the profile is 3m deep. It seems reasonable to extrapolate from such shallow profiles. The study appears to represent a microcosm of patterns which we might expect to find at the base of deep profiles in the tropics, for there is little reason to suppose that the early stages of weathering are significantly different - it is in the acceleration of the processes and their advancement, that tropical chemical weathering differs essentially from temperate. The parent material in Minarik's study is a biotite granite. Modal analysis of fresh granite is shown in table 4.

MODAL ANALYSES OF FRESH GRANITES

	Thin section 1	Thin section 2	Thin section 3	Average
Quartz	22,3	27,7	26,0	25,3
Orthoclase	41,1	37,0	34,7	37,6
Microcline	5,3	6,5	8,7	6,8
Plagioclase	23,8	20,0	22,4	22,1
Biotite	7,4	8,7	8,1	8,1
Muscovite	0,1	0,1	0,1	0,1
Accessories	–	–	–	–
Plagioclase basicity	An_{15}	An_{18}	An_{13}	$An_{15,3}$

Table 4

Sample descriptions from the profile are shown in table 5.

SAMPLE DESCRIPTIONS

Sample number	Depth /m/	Remarks
1	3,00	Fresh compact rock. Quartz and feldspars unaltered, biotite slightly chloritized.
2	1,60	Structure massive with some cracks and cleavage in profile. Parent material is partly decomposed. Dioctahedral chlorite and minerals of mixed-layer 1M structure prevail in the clay fraction. A minor amount of illite and smectite.
3	0,80	Columnar and prismatic breaking into blocks. Minimal content of quartz. The accumulation of the clays by leaching from upper horizon.
4	0,30	Rock is very friable, with granular structure. Primary minerals excluding quartz are transformed. Smectites are the dominant phase in the clay fraction.
5	0,15	Yellowish to brownish silty clay with sand particles and the debris of rock fragments. Montmorillonite and chlorite are the most abundant minerals in the clay fraction, illite and minerals of mixed-layer structure are also presented. Taken very near the surface layer of humus.

Table 5

The relative changes of the concentration of minor and trace elements during the weathering of the granite are shown in figure 98 (;the numbers refer to the samples in table 5).

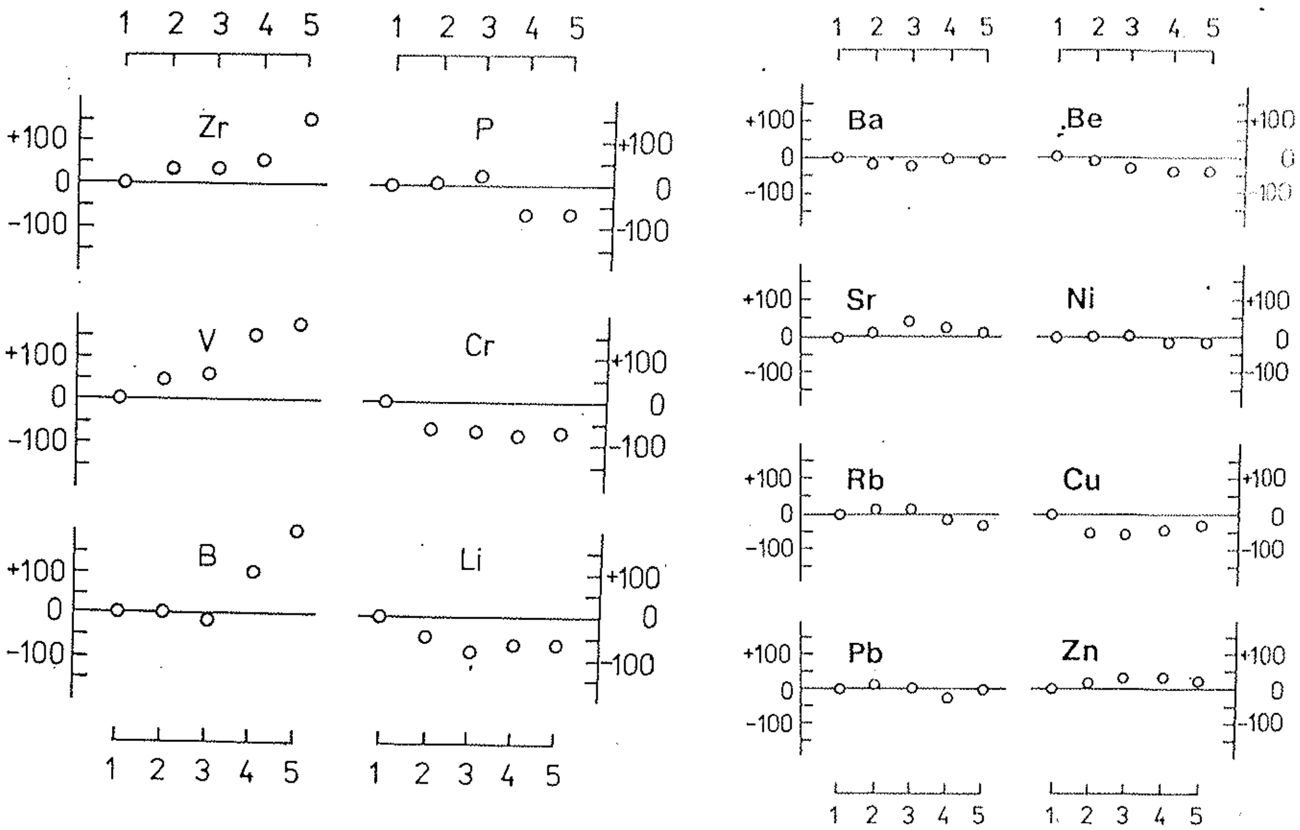


Figure 98

Phosphorous initially increases as other elements are leached out. Loss in the upper part of the profile may indicate apatite dissolution and part of the increase at the base of the profile may represent adsorption, by clays, of P which moved down-profile in solution.
Manganese, calcium (major oxide, not illustrated) and copper decrease rapidly during early weathering (? associated with plagioclase feldspar dissolution). Thereafter they remain constant. Since other materials are leached out (see major elements), such constant levels of concentration do not indicate that the material is entirely retained (if it were, it would increase relatively). It indicates that some is retained and fixation by cation exchange on the clays seems the most likely explanation.
Zirconium, like titanium (major oxide, not shown) and vanadium occur mostly as accessory minerals, highly resistant to weathering, hence there is a constant up-profile relative increase as other materials are leached out. Ti, associated with biotite, would be expected to be retained by smectites on its release.

Lithium and Beryllium, mobile and easily leached, decrease up-profile. Boron, occurring primarily in tourmaline, which is very resistant, accumulates in surface horizons. Its constancy in the early weathering stages, suggests that it is also hosted by a more easily weathered mineral and some is lost in solution.
Chromium is lost rapidly in the early stages. Its host is not known but evidently it is not chromite as this is rather resistant in the early stages of leaching. Since the concentration steadies in the later stages of leaching, fixation, probably on illite, seems likely.
Nickel remains constant in the profile, not, as the authors believe, because it is 'passive' - some leaching is necessary to prevent concentration.
Zinc concentration is very low but there is some indication of retention in association with clay minerals.
Lead occurs in plutonic rocks chiefly as a replacement for K in feldspars. Since the Pb content in the upper horizons is comparable to the original rather high content of the parent rocks, some loss by leaching must have occurred.
Rubidium occurs mostly in the biotite rather than the K feldspars of granites. In this profile it increases in the early stages of weathering, despite the tendency for biotites to weather earlier than K-feldspars. This appears to indicate retention by cation exchange on clay minerals. It decreases in the upper part of the profile, so it is evidently mobile to a considerable extent.
Barium is probably hosted by biotite and K-feldspars. Initially the content decreases; presumably part is lost by leaching. Since the concentration in the later stages of weathering is comparable to that in the original rock, retention must be deduced and the authors suggest precipitation as $BaSO_4$.
Strontium values are erratic in this profile and no conclusions could be reached.

Table 6 shows the data on which the previous generalisations were based (some of them by the present writer and not the original authors).

CHEMICAL ANALYSES OF GRANITE AND PRODUCTS OF WEATHERING (MAJOR OXIDES, IN MASS %, MICROELEMENTS IN μg/g).

Table 6

Component	Sample number					
	*	1	2	3	4	5
SiO_2	70,62	70,02	68,45	69,22	73,00	68,42
TiO_2	0,29	0,33	0,41	0,45	0,81	1,02
Al_2O_3	14,80	15,09	17,70	16,92	13,86	11,35
Fe_2O_3	0,57	0,72	1,73	2,28	2,40	2,24**
FeO	1,28	1,27	0,53	0,20	<0,10	—
MnO	0,04	0,02	0,01	0,01	0,01	0,02
MgO	1,08	1,11	0,73	0,68	0,40	0,33
CaO	1,36	0,90	0,62	0,29	0,30	0,40
Na_2O	3,92	3,74	3,22	3,20	2,10	1,73
K_2O	5,09	4,99	4,33	438	3,86	3,20
P_2O_5	0,24	0,20	0,21	0,26	0,07	0,07
CO_2	—	0,04	—	0,02	—	—
H_2O^+	0,41	0,79	1,31	1,37	2,70	11,04***
H_2O^-	0,23	0,27	0,55	0,61	0,48	—
Total	99,93	99,70	99,86	99,91	99,99	99,82
Li		75	33	16	28	30
Be		13	12	9	8	8
B		10	10	8	20	30
Zr		210	280	275	310	520
Ba		725	600	550	700	700
Sr		475	530	726	610	560
Rb		278	325	323	228	200
Cr		140	53	53	44	50
V		18	27	29	46	50
Ni		22	23	24	20	21
Cu		9	4	4	5	7
Pb		70	80	73	55	75
Zn		50	60	68	70	65

* aritm. mean of 28 samples;
** total Fe as Fe_2O_3;
*** loss on ignition (1000°C)

In the more advanced, typically lateritic stages of weathering, trace element behaviour is very variable indeed. Leaching is sometimes so extra-ordinarily aggressive that nothing seems to be nobly indifferent to it, not even, for example, chromite. So-called 'resistant index' minerals or elements have been shown to be leached out and mass balance studies can only produce a minimum leaching estimate, based on the most resistant materials.

Although profiles with more advanced weathering show great variety, at this stage some tentative patterns are, however, beginning to emerge.

1. There is some indication that laterites developed from basic rocks have a better capacity for trace element retention. The basal surface of weathering is often sharp and in the case of vadose profiles the transition from fresh rock to highly weathered material is often very rapid. This means that secondary Fe minerals, poorly crystalline, are available early, at the bottom of the profile, and relatively mobile elements may be prevented, by adsorption, from being leached out. In contrast, acid rocks with their wider range of mineral weatherablity (and also lower Fe content), tend to have a less rapid progression so that loss of the more mobile trace elements is facilitated.

2. Groundwater and pedogenetic laterites behave very differently in terms of trace element retention. In the case of groundwater laterite, characterised by kaolinite, quartz and Fe in a well crystallised form (predominantly goethite and haematite), retention capacity appears to be generally rather poor, in that trace elements within weatherable minerals (as opposed to the resistant 'heavies') are easily lost. For example, an element may be released and immediately retained by smectites, by adsorption or replacement in the lattice. When weathering proceeds to the kaolinite stage the situation changes. Kaolinite functions rather more poorly as a 'scavenger', so that, when it forms, the element may be lost providing that there is no other mineral formed at this time which can take over the role of retainer. In the case of groundwater laterite, apart from some encapsulation within the Fe segregations (pisoliths) the bulk of the mobile trace elements appear to be lost because the crystallinity of the Fe minerals (formed as a result of smectite breakdown) is good. In the case of pedogenetic laterites (nickel laterite falls in this class) a large part of the Fe is very poorly crystalline or amorphous. This is well seen by D.T.A. - geothite peaks are very broad and there are large low temperature endotherms apparently attributable to a 'solid state solution' form (figure 99). Thus, the chances are good that trace elements released by smectite weathering may be retained by this 'blotting paper Fe'.

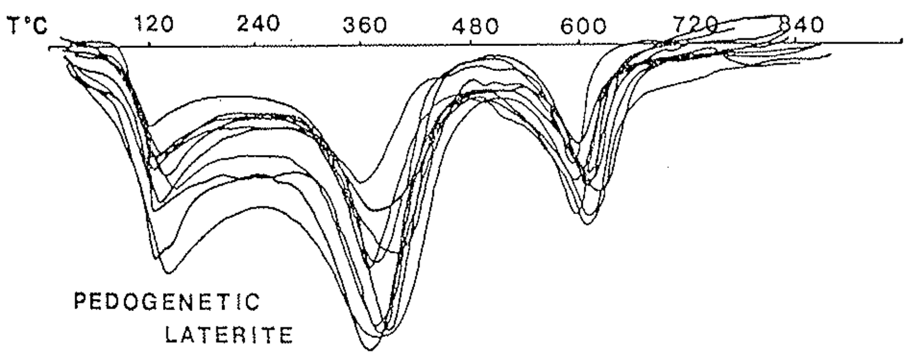


Figure 99

3. In the pedogenetic laterite profiles the crystallinity of the Fe improves up-profile (reasons discussed elsewhere -section 5). Thus, as the profile deepens and as material is leached out, Fe minerals which are formed lower in the profile find themselves placed progressively higher in it, (without moving up.) Improved crystallinity (in fact almost certainly dissolution and immediate recrystallisation in a better form) results in release of associated elements into the vadose water. Unless there is 'recapture' at the base of the profile the elements may be lost into the groundwater. The ability of such laterites to retain trace elements depends on the stage of development. Thus, while the profile is wholly vadose, materials which are released higher in the profile may be recaptured near the base. When, however, the basal surface of weathering lowers below the permanent groundwater-table, the released elements may escape recapture, being lost into the groundwater. It is for this reason that the vadoze Ni-laterite profiles have a secondary (and richer) concentration at the base of the profile, while 'valley bottom' profiles, with the water-table close to the surface, do not.

4. These variable patterns of retention and loss from groundwater and pedogenetic profiles allow some understanding of the temporal supply of trace elements into the groundwater. In the case of groundwater laterite these would be expected to be released relatively early in the leaching history (i.e. when smectites break down) which may encompas millions if not tens of millions of years. Thus, if groundwater removal rates are such that the oldest water is only a few thousand or even tens of thousands of years old, it should be relatively free from them. With pedogenetic laterite, release is ongoing throughout the leaching history with selective retention at the base of the profile while it is above the groundwater-table and more extensive movement of trace elements into the groundwater when the basal surface of weathering is below the water-table. Relatively young groundwater should therefore contain those elements, particularly at the more mature stage when the groundwater is near the surface. Thus, field reconnaisance for groundwater supplies in the lower parts of weathered profiles could reasonably be expected to derive some benefit from understanding of which genetic class of laterites is present and which stage of development it has reached.

4.3 Structural progressions

As indicated elsewhere, weathering of bedrock may be sufficiently gradual to make the basal surface of weathering difficult to define. At the other extreme, it may be so rapid that the profile between bedrock and gibbsitic horizons (extremely advanced weathering) may be microscopic or in some cases submicroscopic. A 'typical' profile can be divided into four structural/textural components, as shown in figure 100.

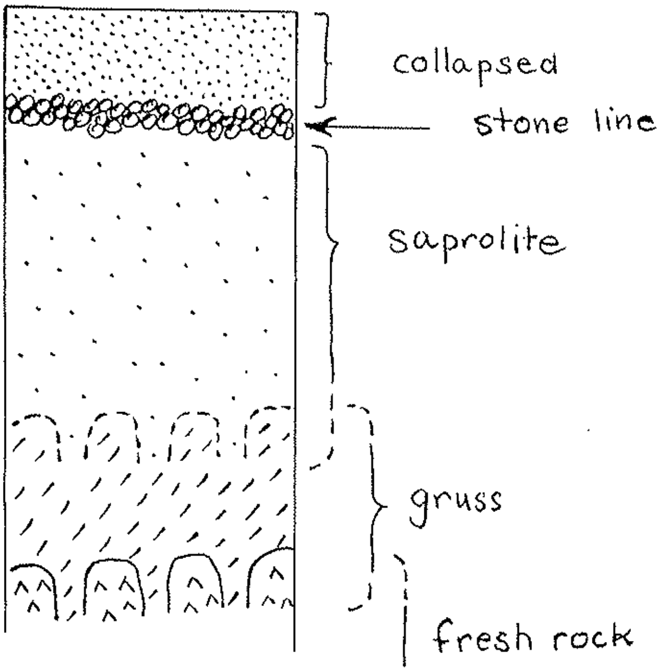


Figure 100

At the base of the profile is the gruss horizon. In texture and structure this is very like the fresh rock, except that it breaks easily because it is 'webbed' with weathered minerals. A very large proportion of the rock still comprises original primary minerals but secondary minerals also occur as replacements for the most easily weathered primary mineral components. The gruss 'horizon' may extend down fractures into the zone of predominantly fresh rock.

Above this lies the saprolite horizon. This is more highly weathered but still retains the textures and structures of the original rock. In the case of granitic rocks the structure retention is essentially attributable to the quartz which survives dissolution and prevents collapse. Between the supportive quartz grains the matrix is kaolinised and voids are often well developed. Iron occurs dispersed through the saprolite, imparting various shades of yellow and pink, depending on its condition. The pink shades usually occur where goethite and even haematite 'blobs' adhere to the kaolin faces (Schmidt-Lorenz, pers. com.1979). Yellow colours are associated with more 'limonitic' iron, again 'dispersed' on the clay surfaces. The transition from gruss to saprolite is usually gradual and progressive void development is associated with mineral progression towards complete kaolinisation. It seems very likely that there is a direct relationship between mineral assemblage and void development but this has never been systematically examined. Aleva (pers. com.1984) has indicated that seismic methods usually indicate the base of the dry part of the saprolite profile, i.e. the top of the water-table, and also the weathering front (; this is in granite areas). He confirms that the failure of seismic methods to consistently succeed in locating the basal surface of weathering is the result of our inadequate understanding of how different rocks weather during these early stages of weathering. In some cases, within the saprolite zone there is a gradual up-profile transition from a grain-supported texture (with angular quartz providing the supportive skeleton) to a matrix supported texture (with quartz grains rather more rounded and separated within a clay groundmass), as shown in figure 101.

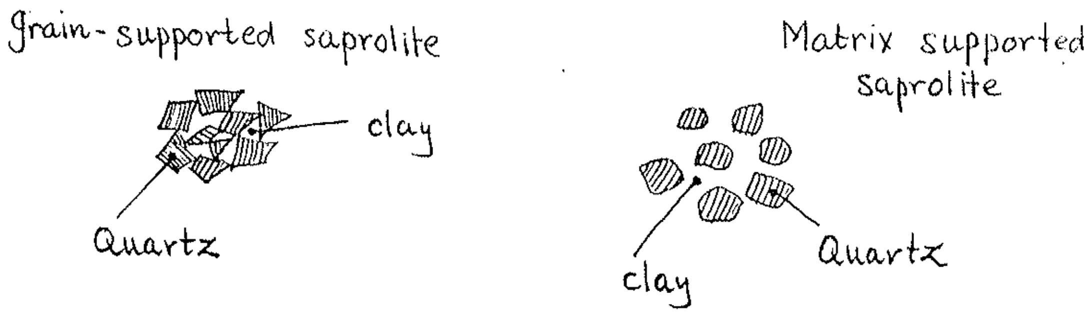


Figure 101

This is without loss of the general 'relict' rock structures, i.e. no collapse. Evidently quartz dissolution is accompanied by neomineralisation of kaolinite, the Al source presumably being dissolution of kaolinite higher in the profile. In such cases up-profile transition to material which has collapsed, and no longer retains relict rock structures, is rather gradual and difficult to place. In the majority of cases, however, there is a fairly clear distinction between saprolite (uncollapsed) and the overlying mantle of collapsed material. In effect what has happened is that when the texture-supportive mineral, quartz in the case of granite, itself undergoes solution, this disrupts the 'skeleton' so that the saprolite subsides and original rock structures and textures are lost. The collapsed material has a higher specific gravity and voids are smaller. The transition to this zone is well seen, in many cases, where vein quartz or cassiterite occurs. The veins collapse and form pronounced 'stone lines', as shown in figure 102.

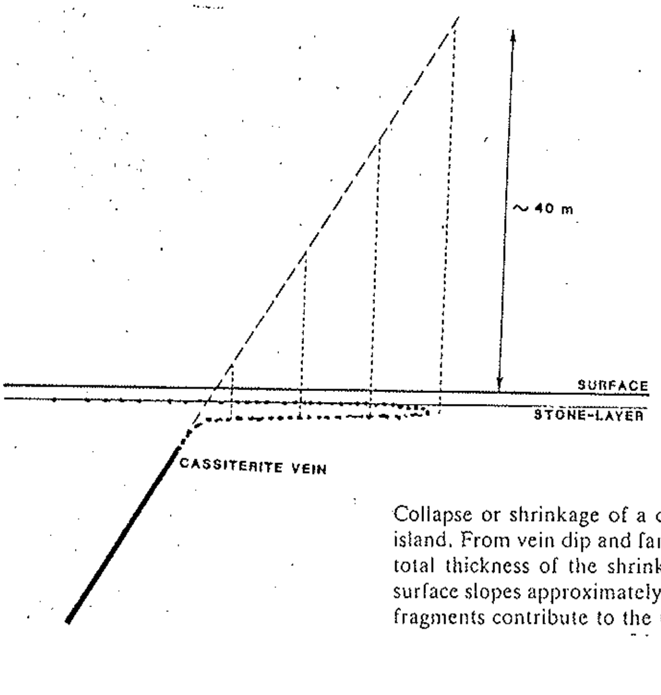


Figure 102

Collapse or shrinkage of a cassiterite vein as observed in Belitung island. From vein dip and farthest upslope cassiterite occurrence the total thickness of the shrinkage zone is estimated at ~40 m. The surface slopes approximately 2 degrees. The downslope moving vein fragments contribute to the ubiquitous stone-layer.

The origin of stone lines provides an endless source of academic dispute. Many geomorphologists see these as evidence of a former dry period - they are believed to be, in effect, lag gravels on a landsurface where sheet-wash removed the fines. Their occurrence below a soil cover is taken as indicating re-burial under more humid conditions. Some stone lines may be formed in this way but as a general explanation this proposed origin is almost certainly wrong. Stone lines are common in the forested 'core' areas and are always at the base of the collapsed zone which is often highly irregular, its configuration expressing the variable extent of collapse. Stone lines vary in thickness - vein quartz commonly yields lines of one metre thickness. The residual sheets of packed pisolithic groundwater laterite, commonly many metres and sometimes tens of metres thick, are in essence very well developed stone lines (see section 5), the heavy bodies which occur at the base of a slowly migrating collapsed horizon. Aleva has likened the migration to slow mud flow or creep, and has described a collapsed zone where surface slopes are 2 degrees or less and where the spread of stone line cassiterite from veins clearly indicates downslope migration of the collapsed mantle. He visualises that this material is eventually transported to the streams and evacuated from the area, but the reduction of a 40m column of saprolite to yield so thin a mantle points strongly to an important role for chemical or biochemical removal of this material and the generally low sediment content of streams in humid tropical areas, where these features occur, supports the suggestion that Aleva may have underestimated chemical removal. In any case, only the top part of the mantle he illustrated is migrating. The lower part has simply collapsed and compacted (figure 103).

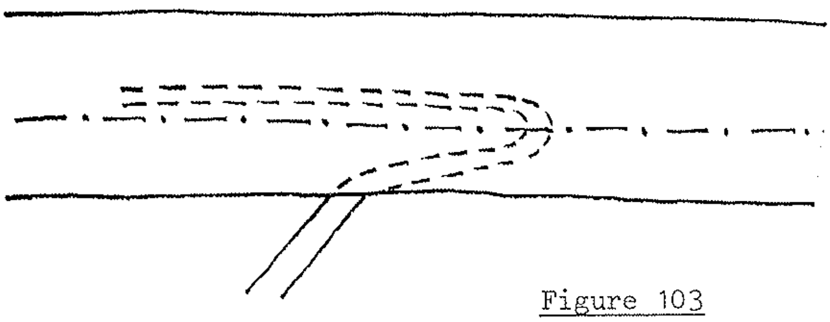


Figure 103

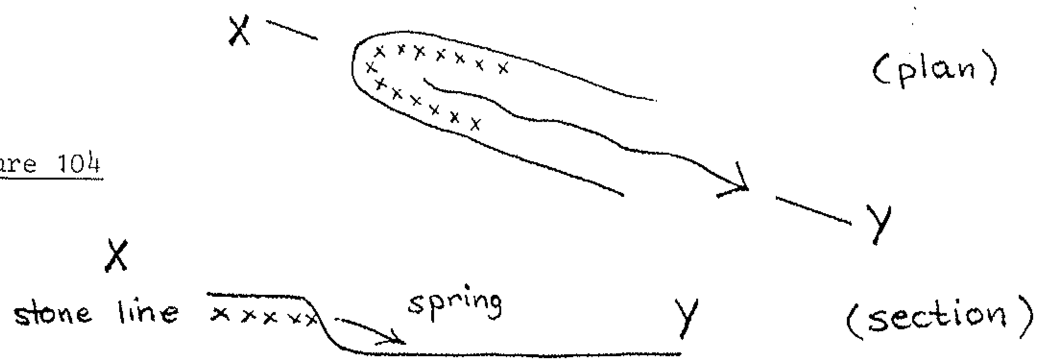
It seems therefore that this very slowly moving mantle is largely reduced by chemical activity and in the case of the pisolithic stone lines the evidence for this is strong (see section 5). Hermelin and others (1983) compared saprolites with mud flows derived from them, in Columbia, and I think their textural data are probably broadly relevant to saprolite and collapsed material in general (table 7). They made the point that mineralogically there is no essential difference between the flows and the saprolite. This is to be expected with a mud flow but may not be the general case where profiles are in a very low relief situation and chemical dissolution is responsible for the collapse.

Lithological Unit	Surface Formation	Saproliths						Mudflow Deposits					
	Sample number		05	06	07		12		02	03	08	09	10
Amphibolite	Specific gravity		2.66	2.65	2.88		2.65		2.77	2.86	2.77	2.75	2.66
	Dry density		1.19	1.17	1.30		1.17		1.39	1.47	1.70	1.47	1.52
	Void ratio •		1.23	1.26	1.22		1.26		0.99	0.95	0.62	0.87	0.75
	Plastic limit		33.1	26.4	35.7		26.2		38.6	41.8	35.7	44.3	46.0
	Liquid limit		48.1	37.2	42.6		37.3		53.2	52.6	42.6	55.5	62.1
	Plasticity Index		15.0	10.8	6.9		11.1		14.6	10.8	6.9	11.2	16.1
	Fe content (1)		—	3	11		4		—	—	—	—	—
	Sample number	13	15	16	17	19	22	18	21	23	24	25	26
Spilite	Specific gravity	2,68	2.67	2,75	2.69	2.66	2.64	2.64	2.73	2.80	2.75	2.76	2.74
	Dry density	1.20	1.10	1.02	1.13	1.46	1.17	1.32	1.38	1.38	1.48	1.40	1.43
	Void ratio •	1.23	1.42	1.69	1.38	0.82	1.26	1.00	0.98	1.02	0.86	0.97	0.92
	Plastic limit	40.3	29.4	44.7	46.8	33.8	32.2	32.0	39.5	39.0	36.4	34.5	40.8
	Liquid limit	57.2	37.7	60.8	68.4	45.8	35.8	41.1	57.6	51.0	52.6	43.1	58.8
	Plasticity Index	16.9	8.3	16.1	21.6	12.0	3.6	9.1	18.1	12.0	16.2	8.6	18.0
	Fe content (1)	—	8	17	—	—	—	—	—	—	—	—	—
	Sample number	27	28	29	30	31	32	33	34	35	36	37	38
Diorite	Specific gravity	2.72	2.67	2.72	2.82	2.71	2.64	2.68	2.71	2.69	2.69	2.67	2.67
	Dry density	1.13	1.22	1.24	1.19	1.27	1.31	1.50	1.35	1.29	1.32	1.44	1.28
	Void ratio •	1.40	1.18	1.19	1.37	1.13	1.02	0.79	1.00	1.09	1.04	0.85	1.07
	Plastic limit	42.0	31.1	29.6	43.3	41.2	32.3	30.9	42.1	33.5	31.1	35.7	40.2
	Liquid limit	53.4	40.8	41.0	55.1	51.5	54.0	45.8	53.2	47.3	44.2	48.0	49.1
	Plasticity Index	11.4	9.7	11.4	11.8	10.3	21.7	14.9	11.1	13.8	13.1	12.3	8.9
	Fe content (1)	12	5	—	—	10	11	—	—	—	—	—	—

Table 7

During exploration for tin placers (cassiterite stone lines) Billiton International found that resistivity was effective in locating the boundary between collapsed and uncollapsed saprolite because the collapsed material, with reduced void size, retains water much better than the well structured underlying saprolite, which can drain out more freely ("a wet sponge with small holes sitting on top of a dry sponge with large holes"). Aleva (1983) also observed that the stone line or layer, commonly 1m. thick, is the main groundwater conduit and springs often occur at this level in places where retreating fluvial erosion produces steep, amphitheatre-type cuts in the saprolite layer (figure 104).

Figure 104



These structural/textural progressions in deeply weathered profiles are common where there are no lateritic or bauxitic surficial crusts. In the case of pedogenetic crusts (section 5) a collapsed zone may be entirely absent because as the quartz is dissolved, and loses its ability to provide a supportive skeleton, iron minerals are segregated and deposited in such a way that they take over the role of providing a supportive skeleton. Thus, many pedogenetic crusts (lateritic and bauxitic) retain rock structures sometimes right to the top of the profile and they are extremely permeable. In the case of groundwater pisolithic laterite (section 5), collapse and dissolution of matrix material is extensive but the rounded pisoliths, even when completely juxaposed, yield a highly permeable residuum. Such sheets of packed pisolithic laterite sometimes act as a conduit much as Aleva indicated for the quartz and cassiterite stone lines. In India, some wells are sunk into lateritic residua as far as the top of the saprolite, thus only tapping the water from the more permeable lateritic horizon (Raju 1982).

Lateritic structures or textures (and their evolution) is a thorny topic because we do not have adequate descriptive terminology and this seriously hinders inter-regional exchange of information which could facilitate better understanding of lateritic evolution and genetic variations. The distinction between the two classes of laterite, pedogenetic and groundwater, can often be made merely on examination of the structures but without internationally standardised descriptive terminology even this fundamental distinction cannot be applied. I don't think we are going to make much progress with understanding laterite genesis until we know what we are talking about, quite literally! A working party has now been established to promote the development of an international, interdisciplinary reference collection of laterites, to be housed at the International Soil Museum, Wageningen, Netherlands. From this we hope to produce standard descriptive terminology, classification of textures and structures and also an atlas of textural types. Until this is achieved (ca. ten years, I should think, at the rate we are going...) we remain with the problem of being completely misunderstood when we discuss any aspect of lateritisation or bauxitisation in relation to textures and structures..

If the leaching of Si, Al, Fe and trace elements and their entry into the groundwater are of concern, the problem of describing lateritic textures may not be entirely academic as concerns groundwater studies in tropical areas. As indicated in the sections on chemical progressions and profile genesis, the leaching histories of groundwater and pedogenetic laterite differ significantly in terms of the temporal supply of these elements to the groundwaters.

Concerning areal variations in depth of these various horizons, we have very little information. It is a great pity that Ni-laterite exploration companies are unwilling to divulge their results. They are the only ones concerned with the whole profile and the configuration of the various horizons within it. Since they are concerned with rapidly weathering rocks (ultramafics) in freely draining situations the configurational patterns are nicely exaggerated and could well apply in more subdued form to low lying areas.

We know that the base of the collapsed zone is very irregular. This locates local areas where the weathering of the saprolite is, for some lithological reason, more advanced (figure 105).

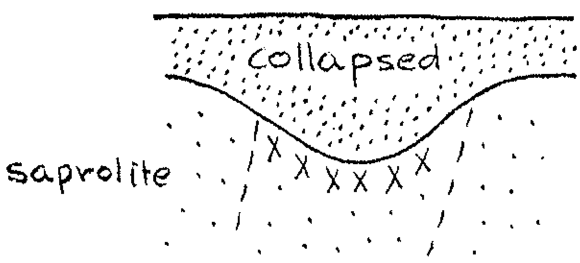


Figure 105

If it is more advanced at the top of the profile (at XXX...) then it seems reasonable to expect that it may be more advanced right down the profile and that the basal surface of weathering is lower below such deeply collapsed sites (figure 106).

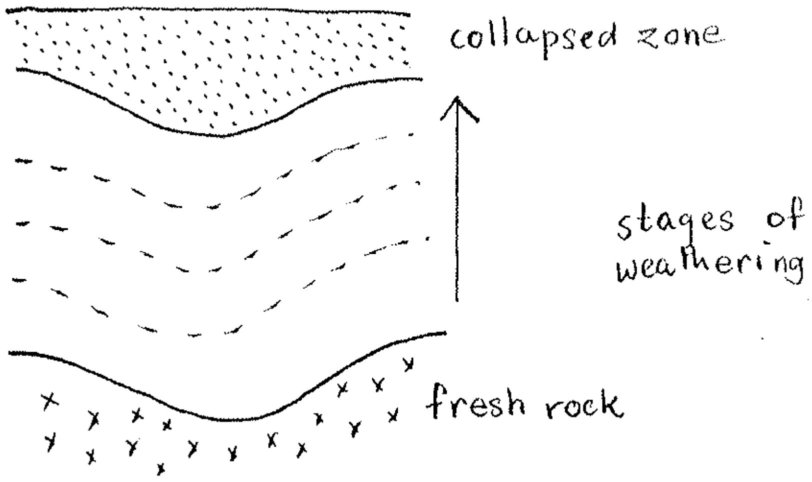


Figure 106

In freely draining profiles this seems a reasonable postulate and the link between surface palaeodrainage and nickel laterite 'sumps' in New Caledonia supports this. Would we expect a different pattern where the lower parts of the profile are permanently saturated? Except that the whole process of weathering tends to be slower below the water-table I cannot see why the pattern of events, the stages in the progression, should be very different. We might therefore expect, even in these situations, to find the basal surface of weathering depressed (possibly more subdued?) below areas where the surface collapsed zone is deepest. This topic has not yet been researched.

No areal study of any relationship between the zones appears to have been made, but if a relationship exists this could be extra-ordinarily useful. It would make it possible to 'prospect' for 'lows' on the basal surface by shallow prospecting in the collapsed zone (eg. by resistivity) and since vegetation is sensitive to soil conditions it could be that the vegetation pattern expresses the thickness of this water-holding collapsed zone and therefore, indirectly, the locus of the lows on the basal surface of weathering. With the present state of our understanding (non-understanding) this is close to pure speculation, but if the knowers don't know the guessers will guess. It certainly seems to me to be something worth looking at.

4.3.1. Grain size variations in the profiles

A bi-modal grain size distribution is generally characteristic of tropical profiles, with clay size particles and coarse particles (sand size or over) predominating. Silt size material constitutes a relatively small proportion and is often the result of segregation of Fe and Al (with kaolins incorporated).

The percent of clay size particles generally increases upwards in the profile (figure 107).

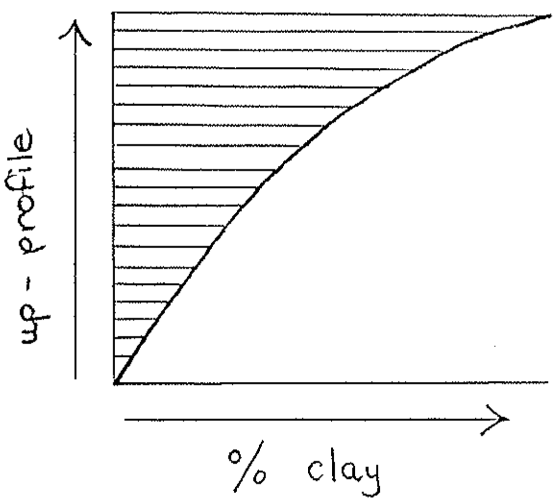


Figure 107

This corresponds with progressive alteration of primary minerals, e.g. feldspars and mica, to varius secondary minerals (clay minerals). Details of mineral progressions are provided in section 4.1. The increasing proportion of clay has sometimes been used as a measure of the degree or stage of weathering. However, this is unsatisfactory for the most mature profiles since highly weathered materials contain secondary minerals which tend to segregate into larger bodies especially towards the top of the profiles.

In the more mature profiles, where horizon differentiation is well developed, the percent of clay, after the initial up-profile increases, then decreases and may reach nil (figure 108).

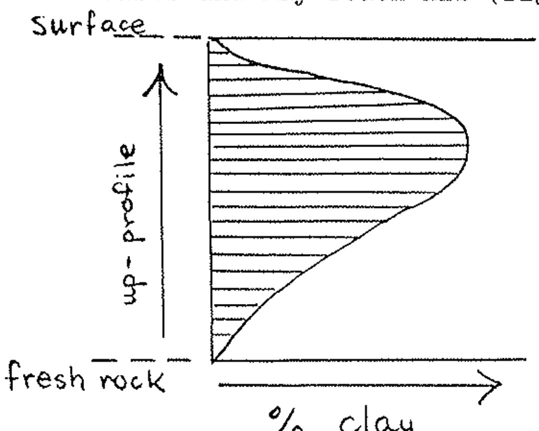


Figure 108

Such profiles can be divided into two broad classes: (a) those in which iron or aluminium is concentrated in the upper horizons (as segregations) - laterites and bauxites and (b) those in which quartz (residual) is concentrated in surface horizons.

(a) Profiles with Fe and Al concentrations in surface horizons.
In these profiles the proportion of clay minerals continues the earlier trend, increasing up profile. However, the oxides and hydroxides of Fe and Al tend to form segregations (nodules etc.) of interlocking crystals (especially goethite and gibbsite) and thus the 'grain' size is large. In effect if we use size as a definitive criterion of "clay" there are no clay minerals but the material may be entirely composed of clay minerals if by this we mean the various weathering products, including Fe and Al oxides and hydroxides (figure 109). Many authors exclude the Fe and Al minerals in any discussion of clays, in effect only considering kaolins as clay since these tend not to form segregations. In those terms, clays (kaolins) show a marked decrease into surface horizons. In the case of profiles with iron-rich segregations the kaolins are removed, while in the case of alumina-rich segregations the kaolins are desilicified, leaving the aluminium predominantly as gibbsite.

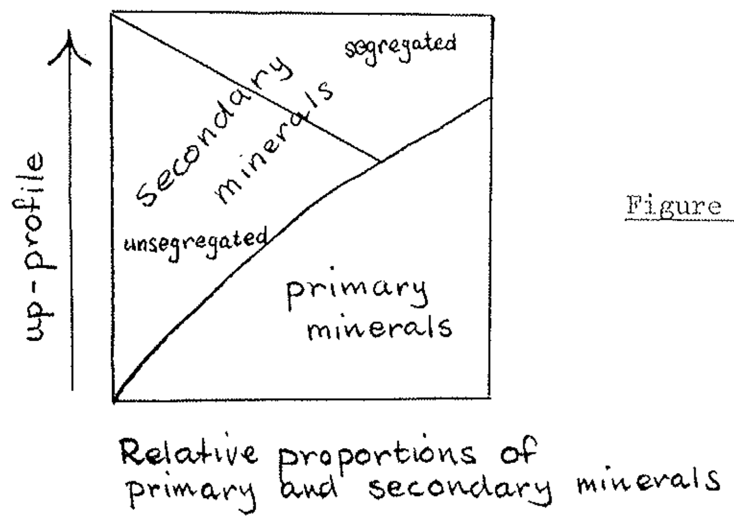


Figure 109

(b) Profiles with quartz concentration in the surface horizons

There was an early tendency to explain quartz concentration in the upper horizons in terms of an allochthonous addition of wind-blown sand and the roundness of the individual grains was held to support this hypothesis. As a general explantion, however, this is quite untenable. There may be some local re-distribution by wind but to postulate wholesale import of sand raises the unanswerable question of its provenance. Moreover, electron microscopy now allows better recognition of windblown sand by grain surface features, features uncommon in these surface sands. (N.B. roundness as such is an inadequate diagnostic criterion of aeolial transport.) Further, the heavy mineral suite in the sands often reflects that of the underlying parent material. The attempts to explain such sands in terms of an addition to the upper horizons of a static profile appear as attempts to 'go along with' the general belief that enrichments of Fe and Al were

additions to the upper parts of stable profiles; in this latter case enriched materials were widely believed to have been brought up-profile in solution. Since primary quartz grains cannot move up-profile the theory of an allochthonous material seemed the best answer. The only alternative was that it is residual after the removal of virtually everything else. This alterative was and is still unpopular because it raises too many problems, e.g. how to remove the kaolinite and how to remove the Fe under oxidising conditions and near-neutral pH. Also, if it is residual and these materials are removed, this opens the door to the possibility that the Fe and Al enrichments are residual and although a residual origin was the first hypothesis in the field, it had been completely over-ruled in favour of the upward-enrichment hypothesis. The last two decades have brought progressively more evidence to the effect that more serious consideration must be given to the original 'residual' hypotheses. In recent years attention has been focused on possible mechanisms for the removal of kaolinite and quartz from the Fe- and Al- enriched profiles. Some attention has also been paid to the removal of Fe from Fe-enriched profiles, for it is now known from mass balance studies that the concentration of Fe is only a small part of the Fe originally contained in the column of rock consumed to provide the concentrate, i.e. even in profiles where Fe has accumulated it is mobile to the extent that more is lost than retained (Esson 1982).The identification of credible mechanisms for removal of kaolinite and iron by microbial dissolution (section 5) inevitably reinstate the hypothesis that the quartz concentration is residual, though the research has not been directed to these particular profiles, but to the laterites. Thus, for both of these groups of profiles the problem has changed. It is no longer "how did the concentration get there? - wind or in solution or whatever". It has become "how did the other material depart?"e.g. the kaolinite and iron from quartz-enriched profiles and kaolinite and quartz from those enriched in Fe.
Since this section is concerned with grain size distribution, and in particular the distribution of quartz and clays (kaolins), only mechanisms relevant to kaolinite removal are considered here. The reader is referred to sections 4.4 and 5 for discussion of the responses of quartz and Fe.

Mechanisms for removal of kaolinite
Three possible mechanisms have been proposed for the removal of kaolinite, two mechanical and one chemical.
1. It has been suggested that kaolinite is eluviated from the upper horizons (figure 110) and washed down into lower horizons, rainfall through the profile being the agent.

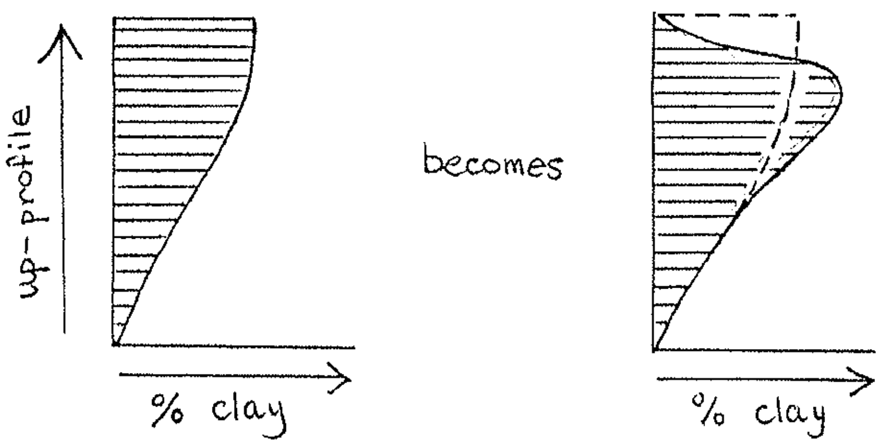


Figure 110

On a relatively small scale this certainly happens and it is particularly pronounced and may be specific to profiles upon which the vegetation is disturbed, e.g. by deforestation, overgrazing, burning etc. With reduced protective cover, clays are washed down profile and may accumulate at depth, filling voids and reducing permeability, to the extent that sudden rains produce a temporarily perched water-table. This, in turn, promotes various forms of accellerated erosion - small scale gullying with parallel retreat of slopes and sheetwash. As a general explanation for the removal of kaolinite from the upper horizons of both classes of profile this mechanism faces insuperable problems, essentially hinging on their age and scale. It has been argued that we can extrapolate from the disturbance of the vegetation by man's activities and the results that they produce. We can deduce that a change in climate from permanently wet to a rainfall regime sufficiently seasonal to inhibit forest would result in similar down-profile washing of kaolinite. Many ancient tropical profiles have been subjected to such changes. Nevertheless, profiles with strongly eluviated upper horizons occur in what appear to be 'core areas' which have remained forested throughout their period of development and this argues against the 'flushing' proposal. The proposal is more firmly invalidated by the depth of the eluviated horizons. It is common to find metres, even tens of metres of Fe-segregations, concentrated from five or ten times that thickness of segregation-bearing saprolite (figure 111).

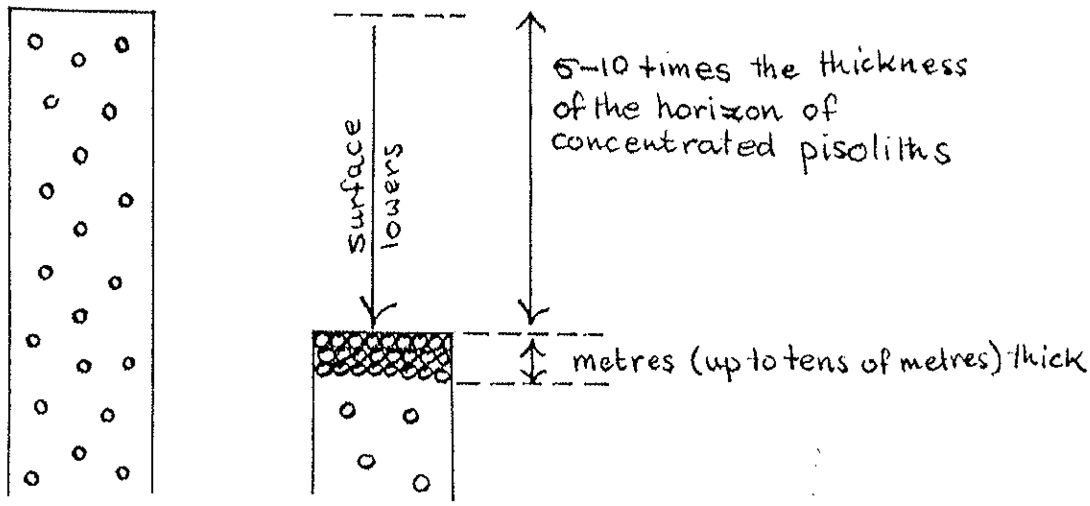


Figure 111

It is highly doubtful if the lower parts of the profile could accommodate inwashing of so much kaolinite (and quartz). Moreover energy loss of the water must make flushing to such depths impossible. The scale of the eluviation is simply too large for this mechanism of removal. It is only feasible on a very limited scale.

2. The second proposal for outflushing of kaolinite avoids the problem of how the voids in lower parts of the profile are supposed to accommodate the large quantities of kaolinite washed out of the upper horizons. It is postulated that the material is flushed out laterally. This hypothesis also has little to commend it (McFarlane & Heydeman, in press). The unrealistic depths to which the flushing is supposed to operate is a problem it shares with the first theory. Even more difficult is the answer to the question 'to where has all the kaolinite gone? (and quartz in the case of the nodular laterites)'. For every metre thick residuum of pisoliths there should be an equivalent deposit of kaolinite and quartz five to ten times as thick or extensive. Vast areas of the tropics are blanketed by pisolithic laterites but kaolinite deposits are small and patchy. As part of an argument to show that kaolinite removal cannot be

mechanical, an example of relief inversion, with associated pisolith accumulation and kaolinite removal was described from within the Western Rift Valley of Uganda (McFarlane & Heydeman, in press). The context was such that had the removal been mechanical, deposits must occur in the near vicinity. No such deposits were found.
In short, on the scale required, mechanical removal of kaolinite, either by vertical or lateral outflushing, is untenable.
3. Chemical removal of kaolinite is implied if only by the failure to find a reasonable mechanical process. Yet there was no known mechanism for chemical removal (de Dapper, pers. com. 1984). Mineralogists recognise two types of kaolinite dissolution - <u>incongruent</u>, in which Al remains as gibbsite and Si is leached out, and <u>congruent</u>, in which both Al and Si are leached out - but they admit to no knowledge of how congruent dissolution is achieved (Schellman pers. com. 1982). Direct evidence for congruent kaolinite dissolution is patchy. For example, a high level profile was found in Uganda in which a quartz vein was replaced by kaolinite 'shells' leaving only small 'core stones' of quartz in the centre. The only possible source for the Al necessary for this neomineralisation of kaolinite is Al passing downward through the profile in solution and the only source for this Al in solution is congruent dissolution of kaolinite higher in the profile (figure 112). Similar neomineralisation of halloysite from Al released higher in the profile occurs in the Pocos de Caldos bauxite in Brazil.

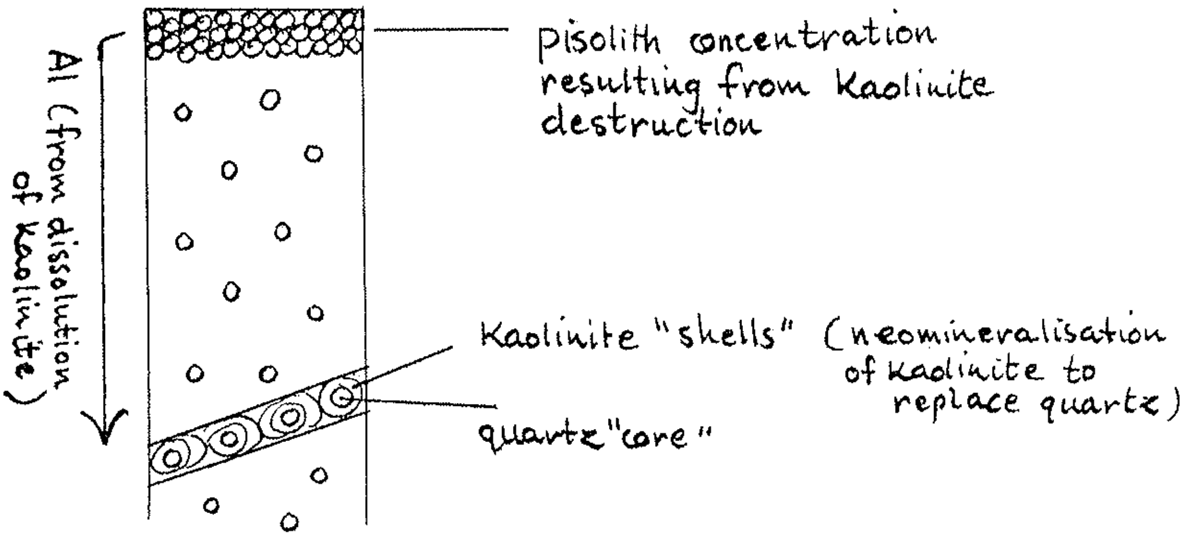


Figure 112

Hughes (1980) indicated, on a theoretical basis, that allophane may form by the breakdown of kaolinite but the most interesting observations on this come from Australia. There Killigrew and Glassford (1976) described amorphous alumino silicate matrix associated with sandplains and indicated that it derives from the disordering of the kaolinite in the underlying pallid zone. Subsequently Butt (1983) described alumino-silicate material which plugs voids in the profile and is responsible for its induration (? one kind of 'silcrete'). He suggested that it may be the precursor of neo-forming kaolinite. Piecing together the scanty evidence available, it seems that kaolinite can break down in all tropical profiles - the Australian occurrences being at the dry end of the spectrum and the Ugandan at the wet end. The absence of anything resembling a 'silcrete' in humid areas like S. Uganda suggests that under humid conditions, except for some neomineralisation of kaolinite, the bulk of the breakdown products are entirely leached from the profile. There is as yet no evidence of significant void plugging or induration. In contrast, in dry areas, for example Australia, the mobility of the breadown products is short-lived, reprecipitation occurring in a form which plugs voids and indurates the profile. As yet we know nothing about the form in which the breakdown products are mobilised but the possibility exists that in some profiles relatively impermeable horizons, which result from the precipitaion of Si or alumino-silicate 'cement', may coincide with the upper surface of the water-table. Climatic change or marked stages of landsurface incision and associated periods of water-table lowering and stability, may produce a series of such horizons in the profile (figure 113).

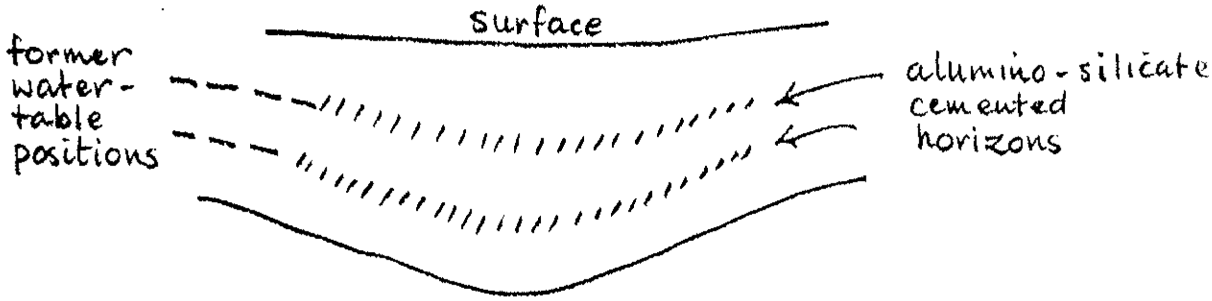


Figure 113

This could have important implications for hydrology. Semi-artesian situations may result and the water bodies in different parts of the profile may differ significantly in their content and movement.

There is recent evidence that the breakdown of kaolinite is achieved by microbial activity and that the 'dissolution' products are complexed. Several micro-organisms were isolated from Ugandan laterites. There, pisolith concentration is known to be by dissolution of kaolinite and quartz matrix. One organism, a bacillus, caused extensive kaolinite dissolution under laboratory conditions. The solid residue of the leaching experiment consisted of very varied material. Some of the kaolinite was entirely unaffected by the microbial treatment. Al- depletion of the majority of the remaining kaolins was associated with deterioration of crystal morphology and structural disordering. There was a bi-modal distribution of Al/Si ratios, indicating a preference for a form with approximately 1/3 of the Al content of normal kaolinite. Two crystals with this Al/Si ratio had perfect morphology and this appears to be a new mineral, an intermediate stage in the dissolution. The Al-depleted material strongly sorbed K as well as other elements (e.g. Fe, Ba, Zn and Na). Loss of sorbed K from the unaffected kaolinite indicated K transfer to the strongly adsorbing Al-depleted material. The final 'dissolution' product was a 'frass' of very finely divided Si. The extreme variation indicates that the dissolution is achieved by proximity to the organism rather than by any general change in the pH of the leachates, although before treatment the pH was 6.5 and after treatment 3.05 and 4.50 (duplicates). The implication that complexing occurs rather than pH controlled dissolution was supported by analyses of the leachates ('solutions'); although chemical analyses of the solid residue had shown loss of Al (table 8) the Al remained largely undetected in the leachates which were analysed by spectrophotometric methods.

In short, chemical removal of kaolinite is strongly indicated, probably biochemical, dissolution products being removed as complexes. Their nature and stability are unknown.

	Wt % Al in solid fraction	Wt % Al in liquid fraction	Final pH of liquid fraction
QKS (before treatment)	3.4 (avg. of 2 assays - 3.36, 3.45)		
3A) after treatment - duplicates	1.62 (avg. of 2 assays - 1.90, 1.34)	0.0014	3.05
3B)	1.16 (avg. of 2 assays - 0.81, 1.51)	-	4.50

Solids and liquids assayed by spectrophotometric methods of Hill (1959). Liquid samples were used directly; solid samples were first solubilized by fusion with NaOH.

(Williams 1981)

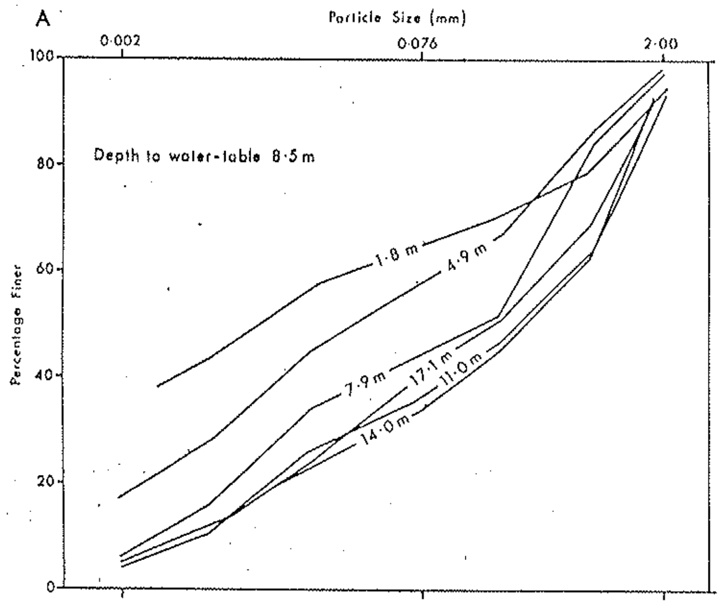
Table 8

Summary and implications for groundwater content

A bi-modal distribution of grain size characterises tropical weathering profiles - clays and coarse material. Clay (kaolinite) initially increases up-profile as feldspars and micas are weathered. In the upper parts of the profiles the clay content decreases rapidly. Coarse materials, either quartz or Fe and Al segregations dominate there. Consideration of the mechanism by which the kaolinite is removed from the upper horizons has led to the recent recognition that it is chemically removed. This gives cause to reconsider the long popular overview that tropical weathering is essentially pH- and in the case of iron Eh-controlled differential leaching, i.e. readily solubilised materials are leached out into the groundwaters and the resistant materials remain. This is certainly painting with too broad a brush. Very much more of the so-called resistant materials are going into the groundwaters than was previously appreciated, whether or not groundwater analytical techniques have identified them. If they are lost from the profile then there is nowhere else for them to go and if difficulty is encountered in identifying them in the groundwaters this only gives weight to the thesis that they are complexed by biochemical activity, which acts independently of the constraints imposed by pH.

4.3.2 Voids

Within the weathering profile, voids increase upwards as weathering advances and the percentage of fines increases (figure 114).



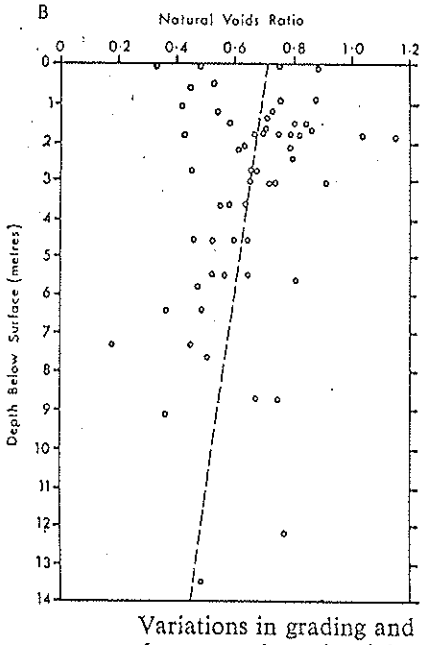


Figure 114

A. Grading curves for decomposed granite, showing variation with depth at a site on the University Campus, Kumasi, Ghana (after Ruddock 1967); B. Variation of voids ratio with depth in decomposed granites from Hong Kong (after Lumb 1962).

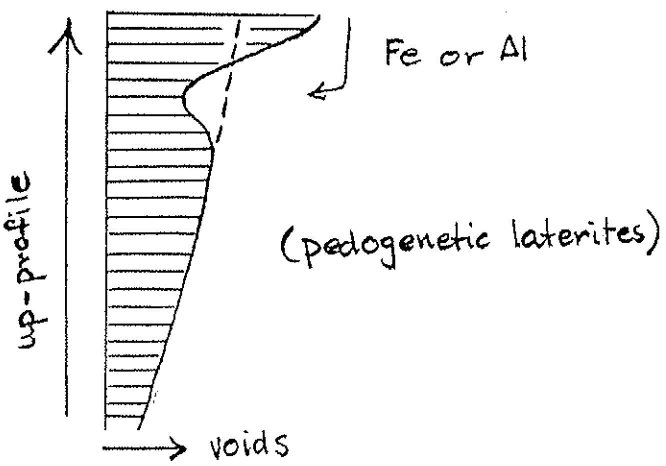
Variations in grading and voids ratio with depths in decomposed granites (after Lumb 1962, and Ruddock 1967).

In profiles where the saprolite has collapsed in the uppermost horizons, voids ratio decreases. Some measure of the scale of the decrease can be gleaned from the comparison, by Hermelin and others (1983), of voids ratios in uncollapsed saprolite developed from amphibolite, spilite and diorite and ratios in mud flows derived from them (table 7).

	Surface Formation	Saproliths						Mudflow Deposits					
Lithological Unit	Sample number		05	06	07		12		02	03	08	09	10
Amphibolite	Specific gravity		2.66	2.65	2.88		2.65		2.77	2.86	2.77	2.75	2.66
	Dry density		1.19	1.17	1.30		1.17		1.39	1.47	1.70	1.47	1.52
	Void ratio •		1.23	1.26	1.22		1.26		0.99	0.95	0.62	0.87	0.75
	Plastic limit		33.1	26.4	35.7		26.2		38.6	41.8	35.7	44.3	46.0
	Liquid limit		48.1	37.2	42.6		37.3		53.2	52.6	42.6	55.5	62.1
	Plasticity Index		15.0	10.8	6.9		11.1		14.6	10.8	6.9	11.2	16.1
	Fe content (1)		—	3	11		4		—	—	—	—	—
	Sample number	13	15	16	17	19	22	18	21	23	24	25	26
Spilite	Specific gravity	2,68	2.67	2,75	2.69	2.66	2.64	2.64	2.73	2.80	2.75	2.76	2.74
	Dry density	1.20	1.10	1.02	1.13	1.46	1.17	1.32	1.38	1.38	1.48	1.40	1.43
	Void ratio •	1.23	1.42	1.69	1.38	0.82	1.26	1.00	0.98	1.02	0.86	0.97	0.92
	Plastic limit	40.3	29.4	44.7	46.8	33.8	32.2	32.0	39.5	39.0	36.4	34.5	40.8
	Liquid limit	57.2	37.7	60.8	68.4	45.8	35.8	41.1	57.6	51.0	52.6	43.1	58.8
	Plasticity Index	16.9	8.3	16.1	21.6	12.0	3.6	9.1	18.1	12.0	16.2	8.6	18.0
	Fe content (1)	—	8	17	—	—	—	—	—	—	—	—	—
	Sample number	27	28	29	30	31	32	33	34	35	36	37	38
Diorite	Specific gravity	2.72	2.67	2.72	2.82	2.71	2.64	2.68	2.71	2.69	2.69	2.67	2.67
	Dry density	1.13	1.22	1.24	1.19	1.27	1.31	1.50	1.35	1.29	1.32	1.44	1.28
	Void ratio •	1.40	1.18	1.19	1.37	1.13	1.02	0.79	1.00	1.09	1.04	0.85	1.07
	Plastic limit	42.0	31.1	29.6	43.3	41.2	32.3	30.9	42.1	33.5	31.1	35.7	40.2
	Liquid limit	53.4	40.8	41.0	55.1	51.5	54.0	45.8	53.2	47.3	44.2	48.0	49.1
	Plasticity Index	11.4	9.7	11.4	11.8	10.3	21.7	14.9	11.1	13.8	13.1	12.3	8.9
	Fe content (1)	12	5	—	—	10	11	—	—	—	—	—	—

Table 7

In contrast, where the structures of the upper parts of the profile are lateritic or bauxitic, voids are very well developed indeed, between the supportive skeleton of Fe and Al minerals. Within the pedogenetic class of laterites and bauxites some variation may be introduced by the repeated solution and deposition effect. Iron or aluminium is dissolved in the upper part of the enriched horizon, leaving a very open 'skeleton'. Below this is a horizon in which voids are reduced (in comparison with both the surface horizons and with the underlying saprolite) by reprecipitation, as shown below.



In some profiles, void development significantly increases above the water-table, corresponding with rapid advancement of weathering, but, as indicated elsewhere, this would only be expected where the rate of weathering is significantly greater above the water-table than below it.

Serious problems exist for the description and classificaton of voids and for their quantification. Since 'void ratios' are measured in various ways (usually involving a suction process) and authors often fail to specify the procedures they used, direct comparison between published void ratios pertaining to different rock types cannot be made (Dalrymple, pers com.1984). For example, Thomas (1974) points to the 'high' voids ratio (0.6-0.9 within 4 m of the surface) of saprolite developed from granitic rocks. Yet ratios given by Hermelin and others (1983) for saprolites in which we might expect more poorly developed voids, is much higher (0.82-1.69). Before it is possible to begin to attempt to correlate void development with permeability there is a need for more precision about which voids are actually measured by any given procedure. In the case of saprolite we could possibly expect some relationship between voids and permeability, but in the case of lateritic textures, a direct relationship is unlikely to be found, since many of the larger voids are so placed that, although their size would be conducive to permeability, they are effectively out of the system. For example, within individual pisoliths, large radial shrinkage cracks (?) are enclosed within a fairly dense, iron-impregnated outer shell. Fortunately, the normally very high permeability of laterites obviates the necessity to attempt to look for any possible (but unlikely) reltionship. The problems facing void description and classificaton (with a possible view to assessing which size and shape of void contributes to permeability) are and promise to remain insuperable (and even such classification would be of little use without a spatial analysis of 'favourable' voids). A recent, elaborate attempt (Ph.D.Thesis) to crack the nut of voids description and classification, by measuring various parameters and computerising the data thus obtained, failed to provide any reasonable basis for void description and classificaton (Dalrymple, pers. com. 1984).

In short, void development is extraordinarily difficult to deal with and its study seems highly unlikely to make an early contribution to an assessment of groundwater potential. Since void development and mineral evolution are closely linked and since mineral assemblages are relatively easily examined, a study of the relationship between mineral assemblage and permeability seems much more likely to yield useful generalisations, within a given area, than is the study of the voids/permeability relationships.

4.4. Permeability

The term 'isovolumetric weathering' has introduced considerable confusion. It can only be used in the broadest sense, to mean that the original rock structures and textures in the weathered profile are undisturbed, i.e. there is no structural collapse. Within such horizons of 'isovolumetric weathering' porosity and permeability vary enormously. Rarely, if ever, is the weathered material strictly isovolumetric in the sense that the weathering products occupy the same volume as the parent material. To take an extreme example, the Trombetas bauxites are uncollapsed and therefore 'isovolumetric', but void development and permeability are enormous. A one metre core 'shakes down' to a mere handful of bauxite. Published accounts of tropical weathering profiles not infrequently include casual observations about the relative permeabilities of whatever horizons are represented. In other cases, relative permeabilities can be deduced from structures and textures. I have not yet found a systematic study which quantifies permeability throughout the profiles. Thus, only a very sketchy pattern of variations within the profiles can be provided. For example, in a saprolite profile, where there is no neomineraisation of kaolinite to refill voids formed during progressive weathering (i.e. a grain-supported texture survives), permeability would be expected to increase up-profile in the saprolite till the collapsed zone is reached, this being relatively less permeable (figure 115a). Where there is no collapse, i.e. where precipitation of Fe or Al minerals has taken over the supportive role, the permeability often increases dramatically into the crust (figure 115b).

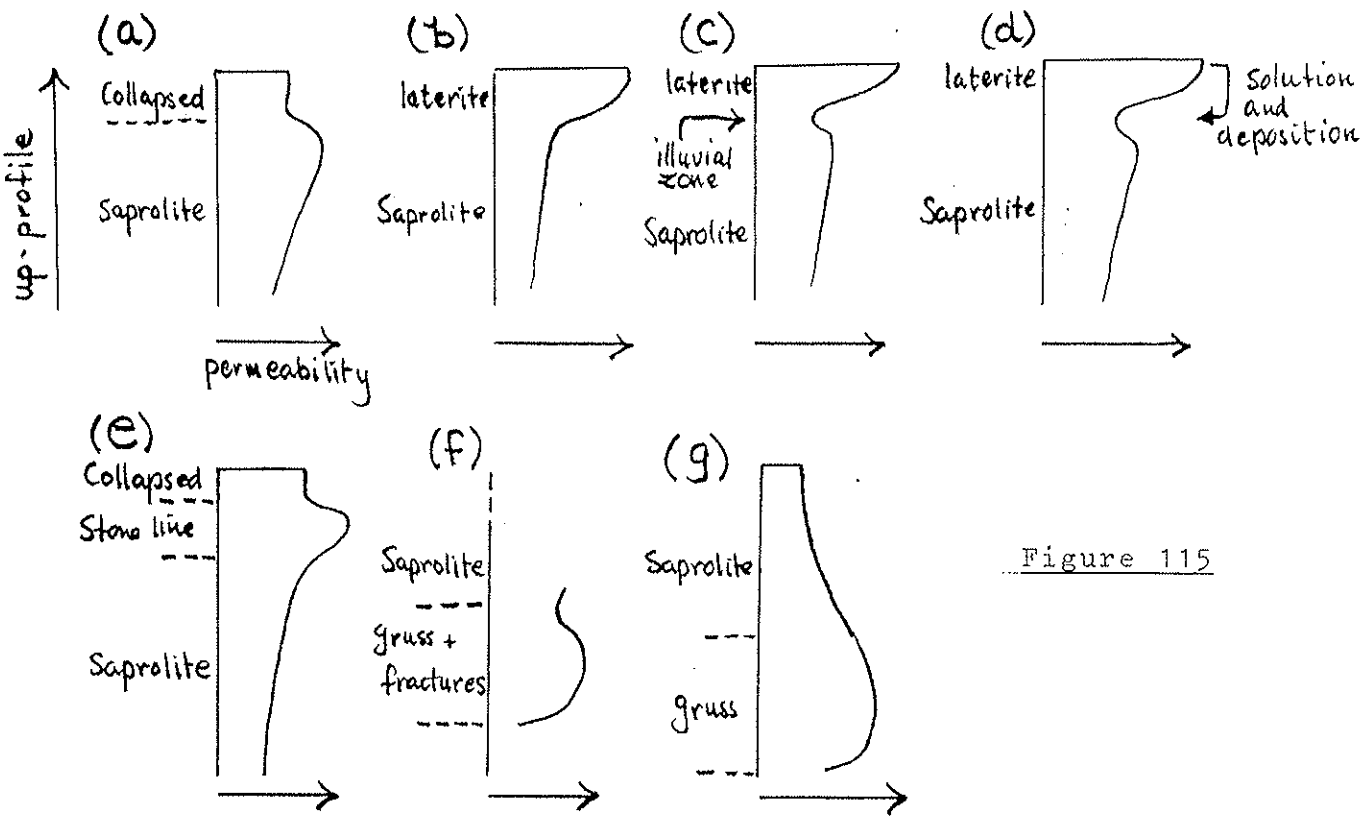


Figure 115

Locally, the permeability of incised groundwater laterite, where it has not become indurated by climatic change or man's interference, can be quite staggering. For example, Bowden (pers. com. 1984) studied laterite surfaces and cave systems in the underlying saprolite in Sierra Leone. He found three laterite surfaces flanking the uplands where fresh rock is exposed (figure 116). Below each surface he found a lateral system of caves, marking old underground river systems, extending for several kilometers. They appear to mark systems which ran over what was then the upper limit of the groundwater-table. The entrance to the largest cave system "could easily accommodate St. Paul's" (Bowden, pers. com. 1984). The rainfall is almost monsoonal here, but even so, the development of such systems speaks volumes for the permeability of both laterite and saprolite (altough we must probably allow for a major contribution from water shed directly from the upland area and flowing into the back of the pediment where the saprolite may be very coarse and open.

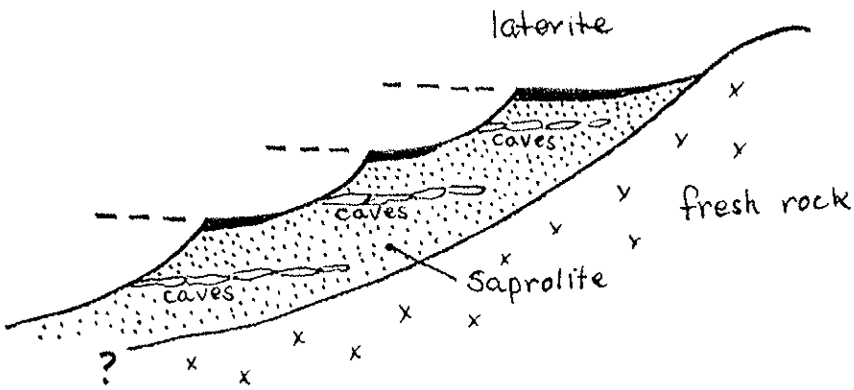


Figure 116

Their orientation is also very interesting. The tendency to flow radially away from the uplands (presumably following the slope of the water-table)is interrupted, dog-leg style, by reaches which flow parallel with the trend of the underlying rock, even though the flow is over saprolite (figure 117).

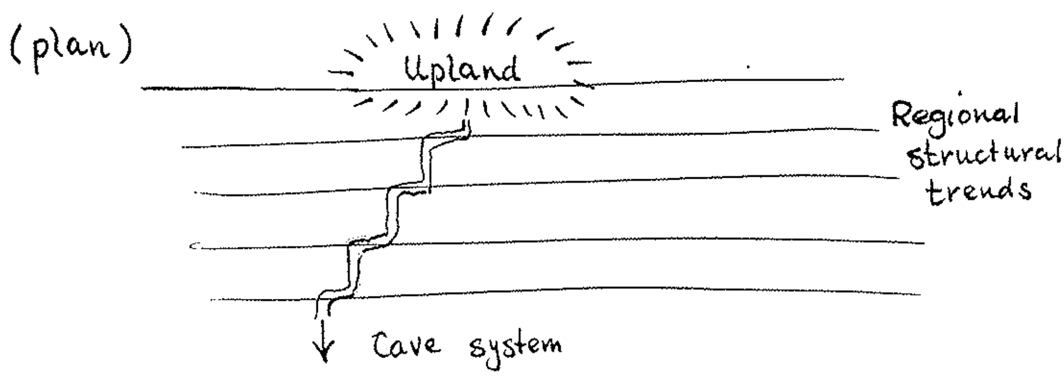


Figure 117

Does this indicate that the sensitivity of the streams was sufficient to pick out lithologicaly controlled variations in the saprolite itself? Or can we dodge the issue by postulating that the subterranean rivers then flowed over fresh rock which was subsequently weathered (figure 118)? This latter alternative seems just a bit too convenient for comfort. The systems are remarkably reminiscent of the lateral systems of caves within the Pennines limestone, systems which correspond with erosion surfaces and still-stands of the groundwater-table.

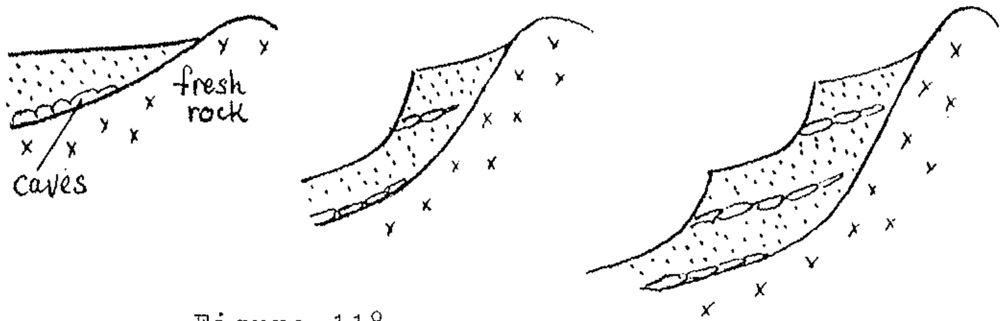


Figure 118

Whatever the answer, this study well makes the point that in some situations both laterite and saprolite may be very permeable indeed. In this case the laterite is a groundwater packed pisolithic laterite, a residuum of pisoliths which has partly altered to massive vermiform structure, i.e. inter-pisolith voids are nicely linked by open pipe systems of about 1/2-1 cm diameter.

In some profiles, clay eluviation from the laterite horizon decreases the permeability of the immediately underlying saprolite horizon (figure 115c). A similar effect is brought about in pedogenetic laterite profiles, where materials leached from the upper part may be deposited in the lower part to the extent that permeability is reduced (figure 115d). In profiles where there is a well developed stone-line (ge. quartz or pisolithic laterite), this may also be very permeable and if the permeability of the underlying saprolite is significantly lower, lateral flow along this inclined zone, which follows the landsurface, is favoured (figure 115e).

In profiles where there is a well developed gruss zone at the base, this, and the fractured rock at the basal surface of weathering, provide a particularly permeable horizon (figure 115f). The immediately overlying saprolite is usually less permeable, the individual clay minerals having filled most of the spaces created by leaching of materials. A recent study in Nigeria (Acworth 1981) suggested that the reduction in permeability, moving from gruss to saprolite, resluts from the halloysite to kaolinite transformation, the kaolinite plates being orientated in such a way as to block water passage. Reduction in permeability at this zone is widespread and does not generally correspond with this particular mineral progression. In profiles where the halloysite to kaolinite progression occurs at a higher level, no observations appear to have been made to the effect that permeability is reduced (but perhaps no-one has looked into this?). It may be that the kaolinite orientation, observed by Acworth, results from illuviation. Clay illuviation, and its orientation to block passages and reduce permeability, is commonly observed in <u>shallow</u> profiles. Wright (pers.com. 1984) has indicated that, in the case of low level profiles, permeability tends to decrease progressively up-profile (figure 115g). This might indicate that in these situations, neoformation of kaolinite, to plug developing voids, is the norm. Observations of increasing permeability in an up-profile direction come from <u>incised profiles</u>. In these situations, water loss during wet drilling is most marked directly below the laterite carapace and the up-profile increase in saprolite permeability is expressed as a marked tendency for pot-holes to develop immediately below the laterite capping, on the sub-carapace slope (figure 119).

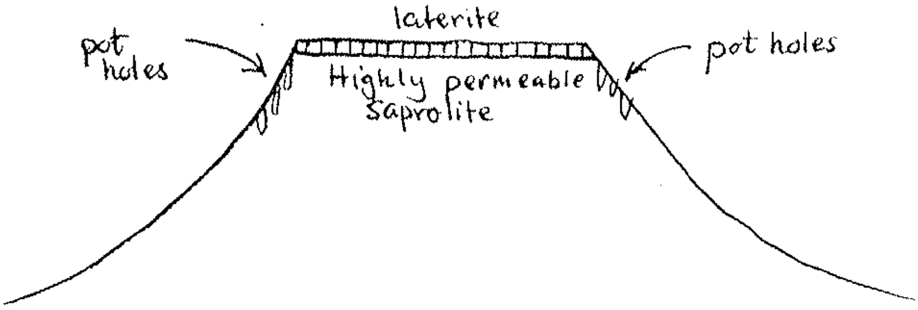
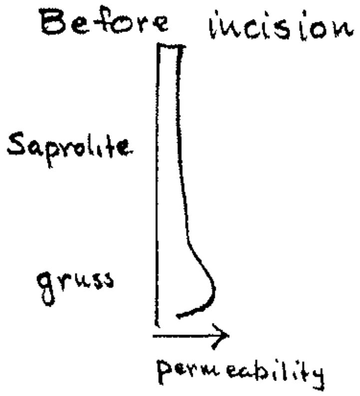


Figure 119

The formation of collapsed hollows on the carapace itself appears to be the ultimate expression of the up-profile increase in void size and hence permeability. In one case a large hole was found in this horizon, large enough to consume buckets of cement during casing (McFarlane and Heydeman, in press). It would seem therefore that the development of an up-profile increase in permeability may be a post-incision modificaton of the low level profile and this introduces the possibility that some saprolite profiles may express both trends - an initial decrease in permeability up-profile (pertaining to the original low level profile), followed by increased permeability in the higher saprolite zones (pertaining to the post-incision period), as shown in figure 120.



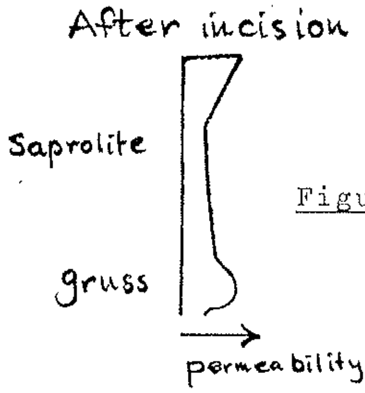


Figure 120

I must confess to having made no attempt to search the hydrological literature for permeability figures. The reason for this is partly the temporal constraints placed upon the writing of this report and in part the rather strong suspicion that it would only produce a list of variables which could not be places in meaningful context for want of subsidiary information about the general environment, in particular the associated mineral assemblages and the stage of weathering they indicate. We also need to place such information in its wider context. For example, does the permeability in a particular horizon truly reflect its nature or is it to some extent dictated by a relationship with a permeability barrier, eg. a clay dyke? To what extent does the permeability of a particular horizon reflect its spacial relationships within the basin, i.e. with a different position and different head of water, do similar horizons behave differently. The widest possible contextual information would seem to be necessary if individual observatons are to be placed in a meaningful context from which extrapolation can be made.

Section 5

Genesis of profiles

5.1 Profiles with an Fe-rich, lateritic crust

- 5.1.1 Water-table oscillation
- 5.1.2 Capillarity
- 5.1.3 Lateral enrichment
- 5.1.4 Diffusion
- 5.1.5 Residual enrichment
  - (a) pedogenetic laterite
  - (b) groundwater laterite

5.2 Profiles with Al-rich, bauxite crusts

5.3 Deeply weathered profiles with no residual concentration in the upper horizons

5.4 Profiles with Si-enriched horizons (silcrete)

5.5 Profiles with a calcareous upper horizon (calcrete)

5.6 Gypsum crusts

5. Genesis of the profiles

The genesis of weathering profiles formed under tropical conditions can be discussed in terms of two broad groups of profiles.

Profiles formed or forming under conditions where precipitation exceeds evapotranspiration. This includes (a) profiles with Fe-rich, lateritic, upper horizons, (b) profiles with Al-rich, bauxitic, upper horizons and (c) deeply weathered profiles with no residual concentration in the upper horizons.

These three groups of profiles pertain to both permanently wet and seasonally wet regions. It was formerly believed that these different climatic regimes induced fundamentaly different weathering conditions. Great play was made of the seasonal oscillation of the water-table in savanna regions. In fact the water-table oscillates in the so-called 'permanently wet' areas (McFarlane 1976). The essential genetic difference between these regimes lies in the variable duration of the leaching period. The longer the dry season, the less effective the leaching.

Profiles formed or forming where evapotranspiration exceeds precipitation.

These include (a) profiles with a Si-rich upper horizon (silcrete), (b) profiles with a calcareous upper horizon (calcrete), (c) profiles with gypsum crusts.

As indicated earlier, the development of horizon differentiation, characteristic of these dry areas, is often superimposed on profiles which developed under more humid conditions, constituting a relatively surficial modification of these profiles.

5.1 Profiles with an Fe-rich, lateritic crust.

The depth, and in particular the often spectacular surficial crusts are the features which caught the interest of the early students of tropical weathering profiles. Early opinion clearly favoured an entirely residual origin for the latter. Aggressive leaching was seen to favour deep weathering and the removal of the more readily mobilised materials, leaving a residuum of less mobile materials.

The early 20th century saw a significant change of view, the result of recognition of a 'pallid' or Fe-depleted zone beneath the Fe-enriched surface horizons. Complementary and synchronous development of Fe-enriched and Fe-depleted zones appeared to be indicated. Thus, the element concentration in the upper horizons was seen to indicate not generally downward movement of water and residual concentration of resistates but (a) downward movement of water to entirely remove the most readily mobilised materials combined with (b) upward movement of water carrying those materials which are concentrated in surficial horizons. The upward-enrichment hypothesis appeared to fit the geomorphological context in which these profiles were most commonly seen to occur, at that time, i.e. so-called stable profiles, associated with so-called stable landsurfaces (planation surfaces), in savanna regions, which experienced a seasonal climate, so that the water-table oscillated. Two mechanisms were evoked to explain the upward enrichment : (a) water-table oscillation and (b) capillary action.

5.1.1 Water-table oscillation This appeared the most obvious candidate in the search for a mechanism which could enable upward enrichment. Its inadequacies have been more fully reviewed elsewhere (McFarlane 1976) and maybe summarised thus :

(i) Profiles with enriched upper horizons are not exclusive to savannas. They also occur in the 'core areas' which have been permanently forested during the period of profile formation, and they occur in vadose profiles.

(ii) The rise of the water-table is by superimposition of fresher water which 'floats' in the underlying groundwater, presenting a barrier to the rise of these solutions.
(iii)Even where pallid zones, truly Fe-depleted zones, occur, the quantity of Fe lost from the pallid zone is inadequate to explain the concentration in the upper horizons.
(iv) Pallid zones rarely occur below laterites. They are not the norm. Many in situ laterites are quite without an underlying zone of depletion, sometimes resting directly on fresh rock.
(v) The huge range of oscillation required (to explain profiles with a 200 ft. pallid zone and 50 foot thick carapace for example) is unrealistic.
(vi) Pallid zones are exclusive to elevated profiles which are not reached by the groundwater table. They are entirely vadose.
(vii)The pallid zone in the Entebbe - Kampala area, Uganda, can be demonstrated to be a post-incision modification of the profile this (figure 121). It is absent below the relatively impermeable detrital sheets which result from reworking of the more permeable in situ laterite. If the pallid zone were an original feature of the profile it should also occur below the detritus.
Since it does not it must be a subsequent modification of the in situ profile. The exclusiveness of the feature to elevated profiles, together with the marked subsidence of the carapace where it occurs indicate post-incision leaching, through the carapace.

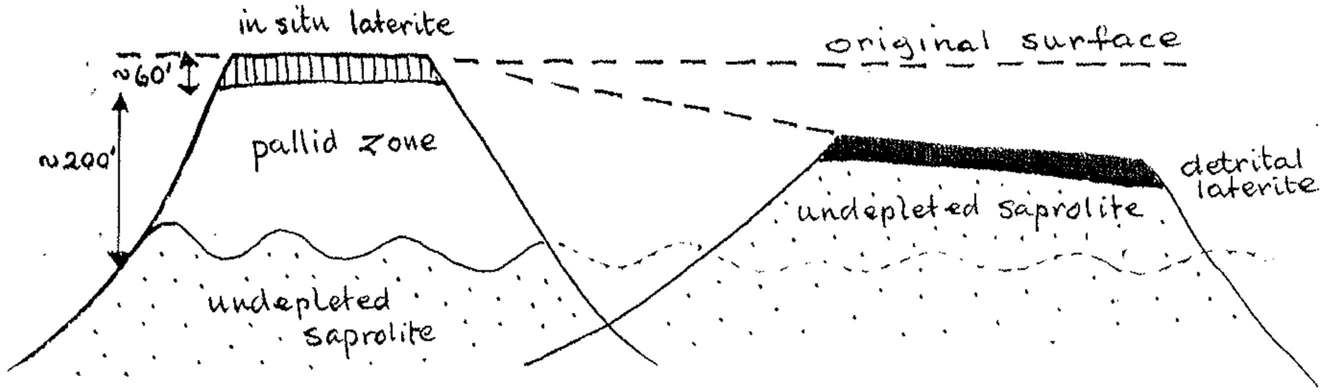
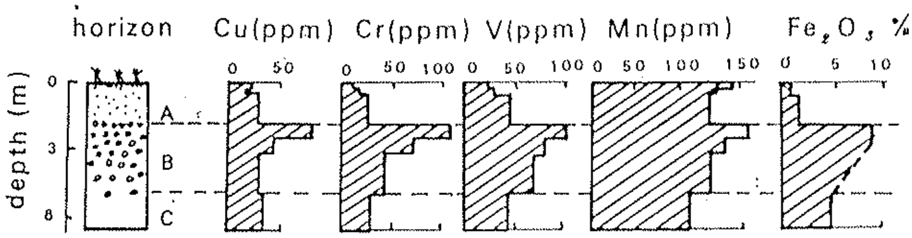


Figure 121

This conclusion is unacceptable to soil scientists and geochemists on the grounds that "there is no known method" for removing Fe from such a freely draining situation. This objection is fundamentaly unscientific and to quote Professor Stoop's comments on this : "if they don't know how it happens, perhaps they should spend some time trying to find out."

In short, there is no credible evidence to support upward enrichment by water-table oscillation.

5.1.2 Capillarity Capillary action appeared to be an alternative to water-table oscillation, as a mechanism for moving solutions up-profile. Theoretically, the maximum elevation by capillary forces reaches 0.1-1 m in sands and 10-100 m in clays, but in nature the latter, higher values generally do not occur, for various reasons (Stegena 1983). Advocates of capillary action as an explanation for typically lateritic up-profile concentrations of elements tend to be soil scientists who are only concerned with shallow profiles. Figure 122 shows concentration versus depth for various elements "in African soils" and this sort of distribution pattern has led, quite without justification to the assumption that capillarity forms "an essential process" (Stegena 1983).



Concentration vs depth function for various elements, in African soils. After Tooms and Kerbyson, in Hawkes and Webb 1962.

(from Stegena, 1983)

Figure 122

Since the porosity of laterites is comparable to that of sands, capillary action may reach 1 m at the most (eg Valeton, pers cm. 1981) and if this element distribution pattern were restricted to a 1 m scale it would be a reasonable hypothesis. However, exactly the same distribution pattern very frequently occurs at scales far in excess of this, indeed any scale commonly up to 50 m and sometimes more. It seems to me to be eminently unreasonable to explain the small-scale versions by one process - capillary action - and the larger-scale versions by some other process. What that process is, is usually left an open question, although occasionally, over-enthusiastic advocates of capillary action have claimed (and still do claim) it to be relevant even to these deep profiles. Capillary action is entirely inadequate to explain a very widespread distribution pattern which occurs at various scales, most of which are quite beyond its possible range of action.

Further, this distribution pattern occurs in 'core areas' which have been permanently forested, i.e. where surface evaporation must surely be minimal.

Moreover, this distribution pattern is not restricted to mobile elements. We now know that the very same pattern occurs for certain primary minerals, which could not possibly have moved up the profile. For example, Leprun (1981) has shown that primary feldspars and certain early weathering products increase up-profile, as shown in figure 123.

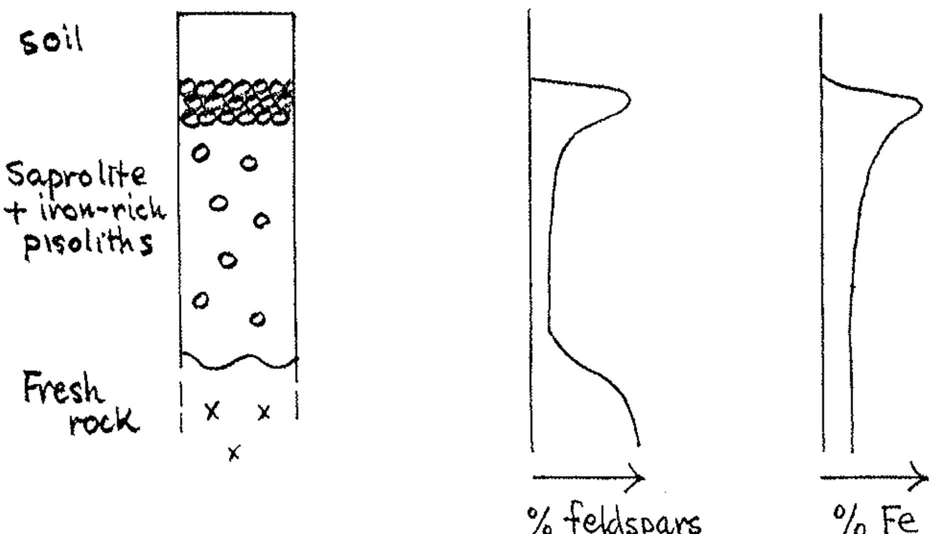


Figure 123

In the profiles which Leprun described, feldspar concentration is linked with Fe concretions - in particular their frequency. This pattern of concentration of Fe-concretions has popularly (and wrongly) been explained in terms of up-profile movement of Fe in solution and its preferential precipitation in the upper part of the zone of precipitation. Leprun's work strongly supports the hypothesis (McFarlane 1976) that the concentration of pisoliths in these groundwater laterites exists because the matrix has been removed. The pisoliths form at the bottom of the range of occurrence. This is known because they encapsulate and preserve the very early stage of weathering at the time they were formed. It is within the pisoliths that the feldspars and early weathering products occur and it is to this encapsulation that they owe their survival from on-going weathering. The up-profile concentration of feldspars is entirely dependent upon pisolith concentration. These cannot have moved up-profile into horizons where weathering is more advanced. Therefore they are there because of their superior ability to survive, in comparison with matrix material, which continues to weather and lose components through leaching, to the extent that the volume is reduced and pisolith frequency is increased, relatively.
A very comparable disribution pattern sometimes occurs with primary quartz. Thus, (figure 124), within the weathering profile, quartz concentration decreases up-profile as weathering advances and quartz is dissolved. Any quartz which survives this and reaches the surface, accumulates. Compare this with figure 63, the survival of fresh rock above the most aggressive near-surface, weathering horizons, during inselberg destruction. The quartz, like the fresh rock which 'survives' through the most aggressive subsurface leaching horizons, then enjoys relative immunity from weathering and can 'safely' accumulate at or near the surface. Similarly for anatase concentration during bauxitsation. Similar surficial accumulation of resistant minerals is now very widely reported (eg. Minarik et al.1983).

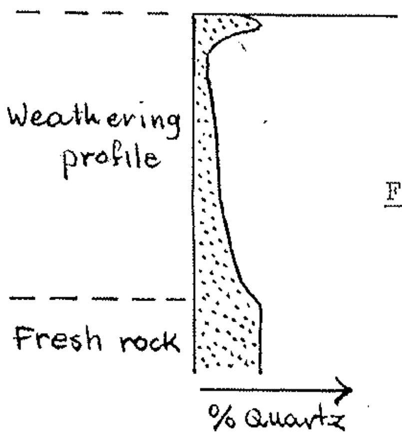


Figure 124

If the pattern of the up-profile concentration had been restricted to materials which can be solubilised then capillary action might have been a reasonable hypothesis. Since the pattern is not restricted to materials which can be solubilised but also extends to primary minerals, capillary action is quite impotent to account for it.

In summary, the scale of the concentration pattern, its occurrence in forested areas where surface evaporation is minimal and the nature of the concentrated materials (primary as well as potentially solubilised materials) quite invalidate the 'upward enrichment by capillary action' hypothesis as a general explanation for element distribution patterns in tropical weathering profiles, although small-scale, relatively surficial effects no doubt occur in more arid areas.

Although water-table oscillation and capillary action are quite unable to account for the surficial concentrations which characterise many tropical profiles, repetition of these hypotheses throughout a period of at least sixty years has given them such credence that their ghosts are proving hard to lay. They still appear sporadically, particularly in unrefereed publications.

Those who recognised their inadequacy sought other mechanisms to explain enrichments at the top of the profile ie (a) lateral enrichment and (b) ionic diffusion. Like the earlier attempts these also suffered from the fundamental misconception that the starting point for discusion is a static profile in a static landsurface, an understandable misconception planted by geomorphologists from Europe to whom the tropical landscapes seemed remarkably flat.

5.1.3 Lateral enrichment The literature provides numerous exampes of slope bottom situations in which surface concentrations are clearly forming today, enjoying enrichment which is or could reasonably be explained by addition from topographically higher positions, either mechanically or in solution (fig. 125).

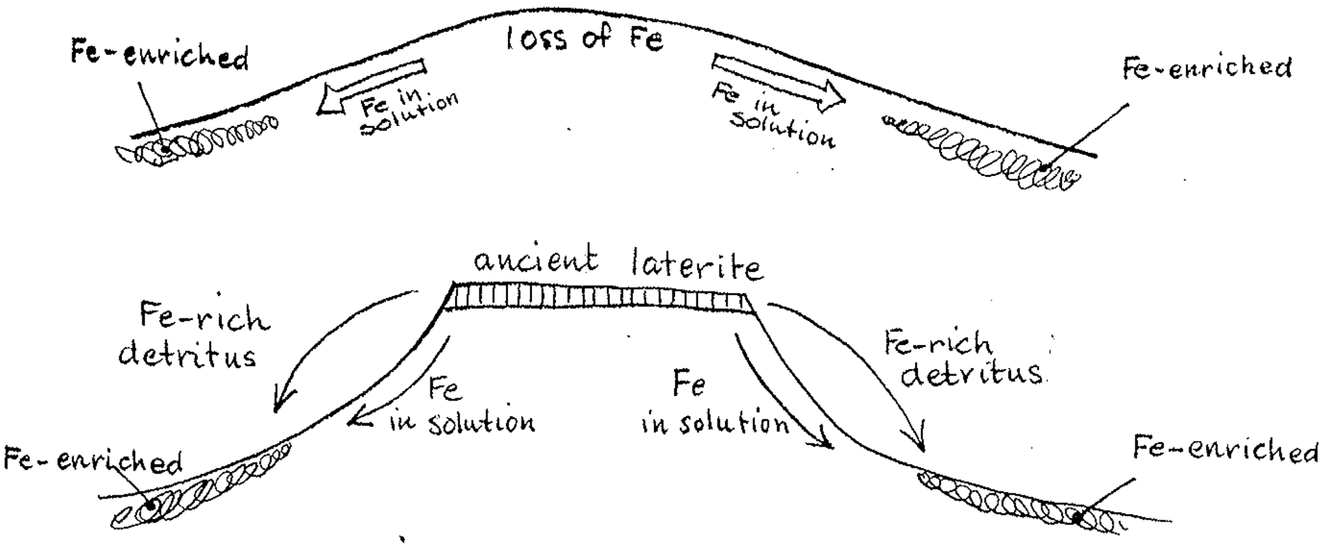


Figure 125

These models are certainly correct. The error lies in the belief that this is the whole story rather than only one ingredient of it. Where we have a flight of erosion surfaces we could argue that the lowest derived its surficial enrichment from the second lowest, which derived its enrichment from the third lowest etc. Where the interfluve is unlateritised and undergoing weathering, all seems well for this argument. However, in many cases the oldest and highest surface itself is strongly enriched, directly on the interfluves,and we are left with the problem of how this surface could have been enriched if we believe that all surface enrichment is lateral. Exponents of this belief then become involved in quite remarkable and totally unrealistic postulates. Relief inversion has been demonstrated in some situations. Laterite-capped lowlands may become uplands, by virtue of their protective cover, when erosion proceeds further (eg. figure 126).

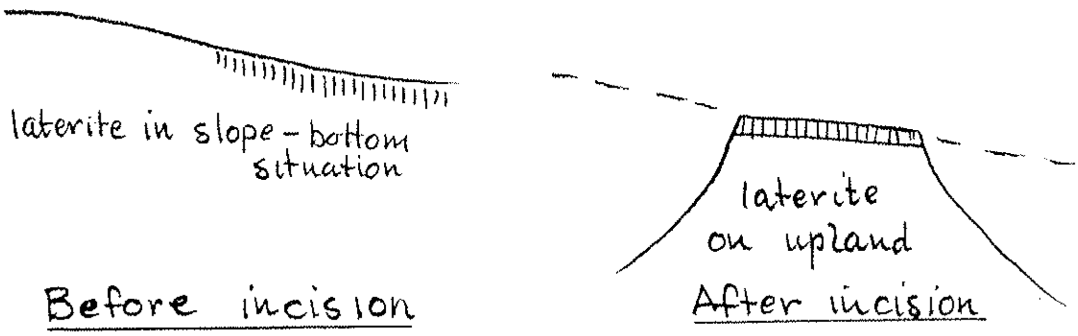


Figure 126

Advocates of the 'lateral enrichment only' theory feel obliged to postulate that those laterites today on interfluves occupied slope-bottom situations in some former landscape (which has now conveniently disappeared altogether). This is manifestly unworkable. For example, in Uganda there are four laterite-capped planation surfaces. Preservation depends on the depth to which weathering has extended. That is, each succeeding surface developed where weathering was then deepest. Thus there occurs a flight of lateritised surfaces with the oldest over the most resistant and least deeply weathered rocks (figure 127).

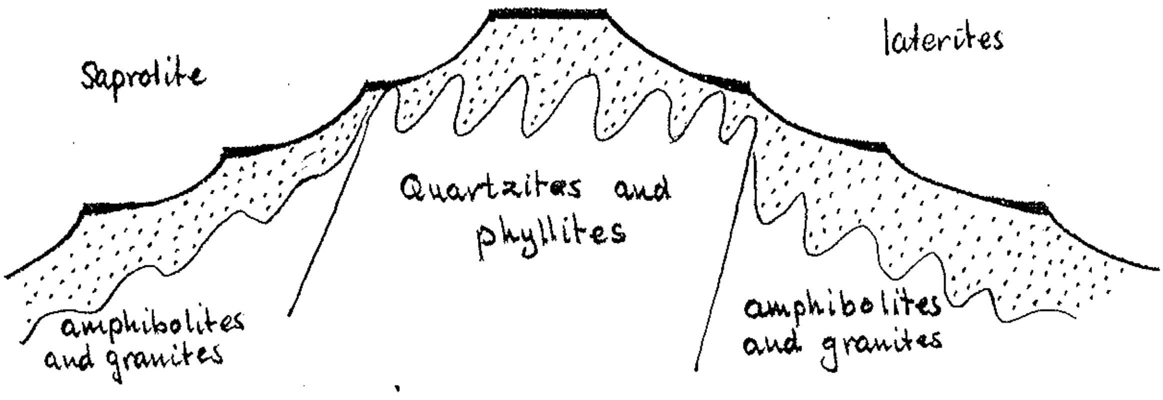


Figure 127

Yet protagonists of the relief inversion and lateral enrichment hypothesis would have us believe that at some stage in the past the lowlands were underlain by quartzites and the uplands by the more easily weathered rocks. This is quite unrealistic. Proof positive of the inadequacy of this thesis comes from examples of lateritisation or bauxitisation in situations where topographically higher landscape elements simply could not have existed. For example, Pocos de Caldos, in Brazil, is an enormous volcano which, since its eruption, has been maintained as the highest topographic element. The perimeter of the caldera is strongly bauxitised and there is no possibility whatsoever of lateral enrichment. In situ bauxitisation extends down the inner slopes of the caldera, so it is a post-caldera formation and in fact it is clearly still forming today.

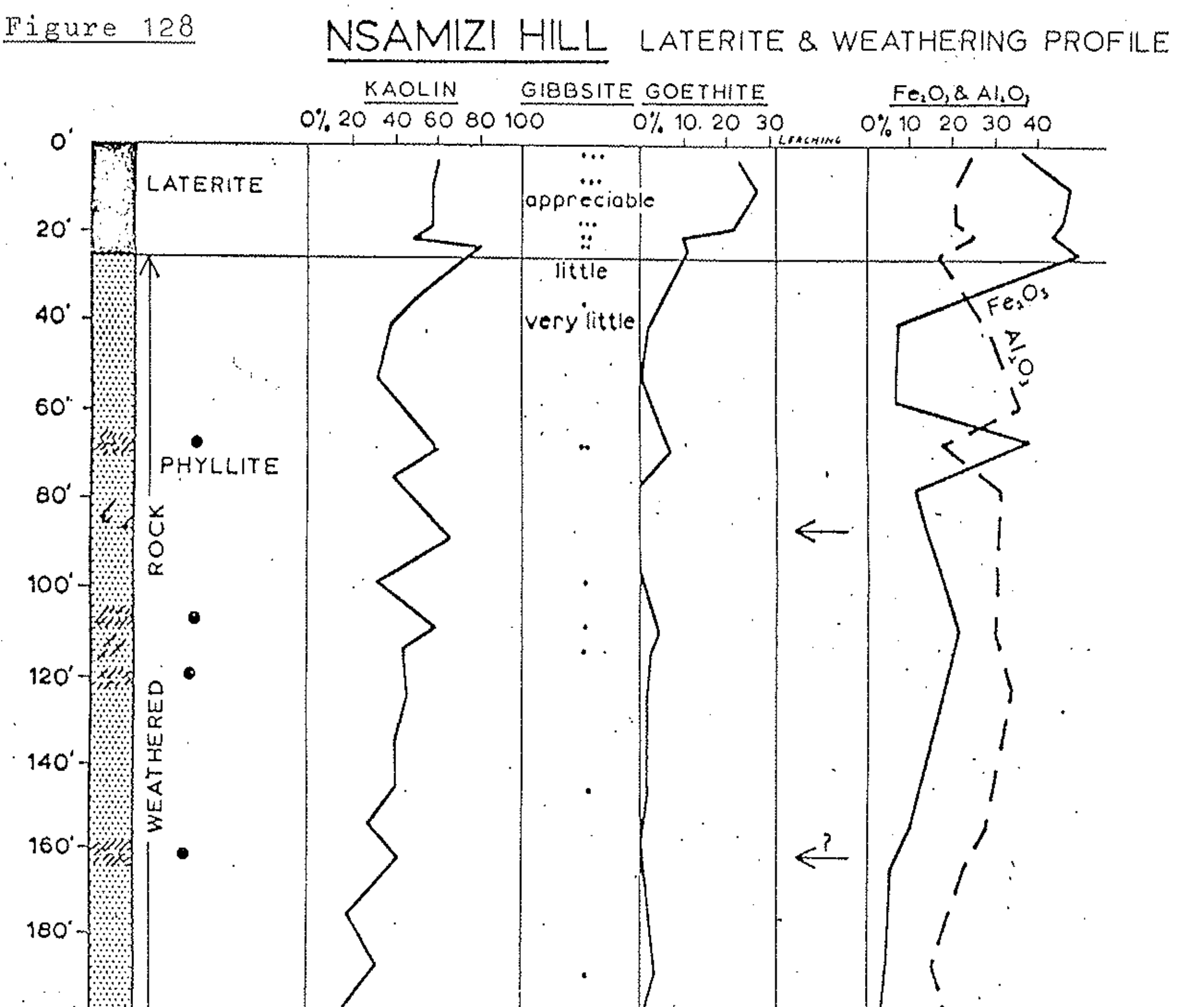
In short, although lateral enrichment of surface horizons does occur, the fact that the surface horizons are also enriched in topographically elevated profiles, which could never have enjoyed a lateral contribution, indicates that this cannot provide a general explanation for the pattern of enrichment.

To summarise, there is no credible evidence that up-profile concentration is brought about by physical movement of material up the profile either by water-table oscillation, capillary action or ionic diffusion. Some surface enrichments may be attributed to laterally downslope movement of materials, but this does not provide a general explanation for the pattern of element distribution in tropical weathering profiles.

We have in fact come full circle, to the point where we must examine more closely the earliest hypothesis, that the horizon of differentiation is attributable to generally downward leaching and the variable resistance of elements to it. If this thesis is correct, then we are bound to reach the conclusion that neither the profile nor the landsurfaces are stable. Both must migrate downwards, so that in effect a column of rock is consumed to provide the residual concentrates.

This system of differential leaching is clearly demonstrated by element patterns in the lower parts of the profiles. For example, figure 128 shows the distribution of iron in a 215 foot saprolite profile from Nsamizi, Entebbe, Uganda. The profile is now elevated and preserved by a capping of detrital laterite (relatively impermeable). This 'foreign' surface horizon does not detract from the main message which the underlying horizons reveal, that is, that iron is enriched in the saprolite (kaolinite/quartz/goethite) in comparison with the fresh rock. The average of 11 saprolite samples was 11.38% Fe_2O_3. Although the core itself just failed to reach fresh rock, Dr. Nixon of the Geological Survey of Uganda was able to select 14 fresh rock samples from the Survey's collection which corresponded with the weathered material at the base of the core. These averaged 5.1% Fe_2O_3. The saprolite is not enriched because iron has been added (; the Fe_2O_3 content directly reflected the variable nature of the sediments) but because other materials have been leached out and thus the iron content is relatively increased, on a weight percent basis.

Figure 128



An even better example is provided by the low level laterite at Busia, Uganda, a complete, undisturbed, presently forming profile which clearly shows that the saprolite, both below and above the water-table is relatively richer in iron (15.32% Fe_2O_3) than is the parent rock (7.05% Fe_2O_3) (figure 129). Loss of other, more easly mobilised materials explains this relative enrichment without recourse to addition of iron.

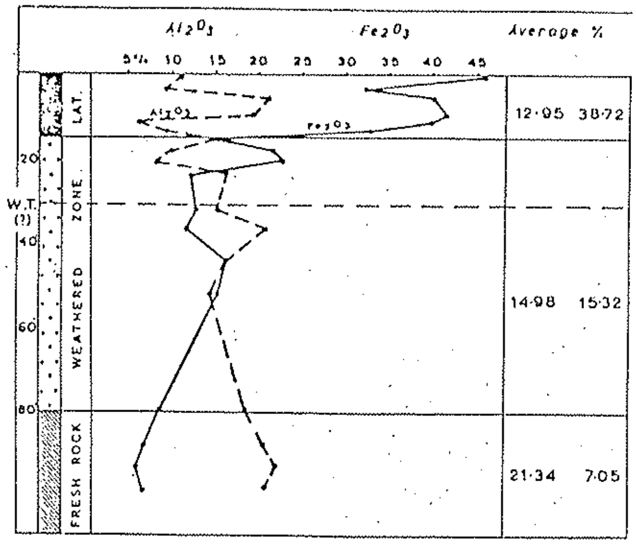


Figure 129

The Zr pattern in Australian saprolites (Mulcahy, 1960) provides a similar argument. It is clearly enriched in the saprolite, not by addition of Zr but by subtraction of other more mobile materials. This pattern of relative enrichment of resistates during early weathering is also nicely demonstrated by Minarik's analysis of granite weathering in Bohemia (Minarik et al. 1983). Many other examples occur in the literature. I can see no valid objection to the thesis that the upper parts of the profiles, with their more marked concentration, are essentially an extension of this process of differential leaching and accumulation. But there are objections. The theoretical and laboratory work does not provide us with an explanation for the removal of the various materials which must have been removed if the remainder is residual. This work has provided us with constraints on element mobility (Eh/pH) and constraints on mineral stability (solution concentrations etc.). The 'residual model' clearly indicates that in nature these constraints do not apply, certainly not to the extent that we have been led to believe.

The problem can be seen more clearly if we look in detail at the proposed mechanism.

5.1.5 Residual Enrichment

The accumulation of a chemical residuum clearly requires that relief be sufficiently low to allow the products of chemical selection to accumulate more rapidly than they are removed by mechanical erosion. Steep slopes therefore prevent accumulation of residua. As slopes are reduced, a progressively greater part of the rainfall infiltrates the profile to effect chemical selection and a lesser part comprises run-off which may remove the residual products of that selection. The efficiency of the residual accumulation process will vary from small beginnings when slopes are sufficiently steep for some mechanical removal of residua to occur, to small endings when slopes are so low that chemical selection is hampered by the proximity of the water-table to the landsurface, which reduces the rate of leaching of the more mobile components. Thus, in a tectonically stable area, lateritisation (that is the residual accumulation of horizons rich in Fe or Al) can be placed within the late stages of landsurface reduction. Although this is essentially a system of relative accumulation, the residua can be subdivided into areas where either relative or absolute accumulation predominates (i.e. enrichment by removal of other materials or enrichment by addition of materials, respectively). On interfluves, where no addition from topographically higher positions is possible the accumulation is entirely rèlative. Surface lowering is at a maximum (figure 130). Downslope, the potential for surface lowering decreases, reaching a minimum near the more stable drainage lines.

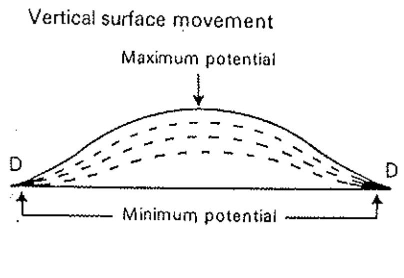


Figure 130

Residua in slope bottom situations usually owe much of their enrichment to absolute accumulation. Fe escaping retention in topographically higher positions moves in solution down-profile and downslope and tends to be precipitated (in part) in slope bottom situations where the water-table approaches the landsurface (figure 131). There is also downslope mechanical movement of residua from topographically higher positions.

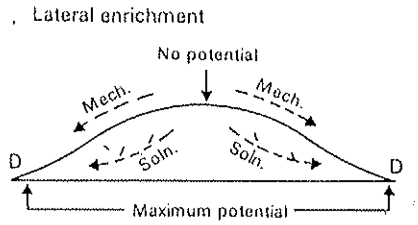


Figure 131

In the early stages of the process of landsurface reduction and accumulation of residua, slopes are comparatively steep and downslope movement is most favoured. Thus slope bottom situations are usually the first to show accumulation, and with progressive slope reduction the accumulation, in effect, extends upslope to cover the interfluve. Consequently slope bottom laterites are very common and this contributed to the popularity of the "lateral enrichment" hypothesis.

Since drainage lines are not stable, but are lowering slowly, landsurface lowering occurs right across the catena, as does residual accumulation.

The developing profile shows, from the base upwards the stages of formation (figure 132).

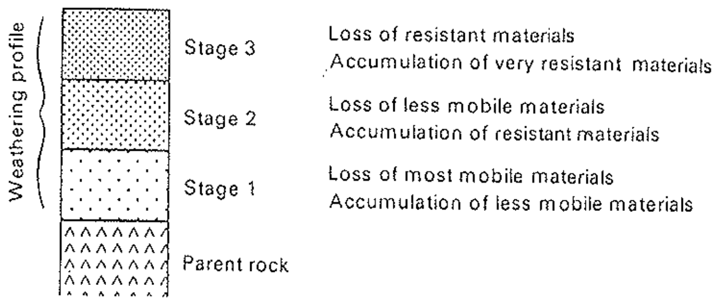


Figure 132

Since stage 3 is more advanced than 2 and stage 2 is more advanced than stage 1, the process must have begun earlier at the top than the bottom. In effect, stage 1-type weathering occurs at progressively lower levels as the weathering front deepens (figure 133). Stage 2-type weathering develops from a 'parental material' of stage 1-type and stage 3 develops from stage 2. So, it is not only the weathering front which lowers, but also the interfaces between the weathering stages and the landsurface itself. The products of each stage of weathering provide parent material for the succeeding stage and the accumulation of the most resistant components which characterises stage 3 thus derives enrichment from an overhead source, S.

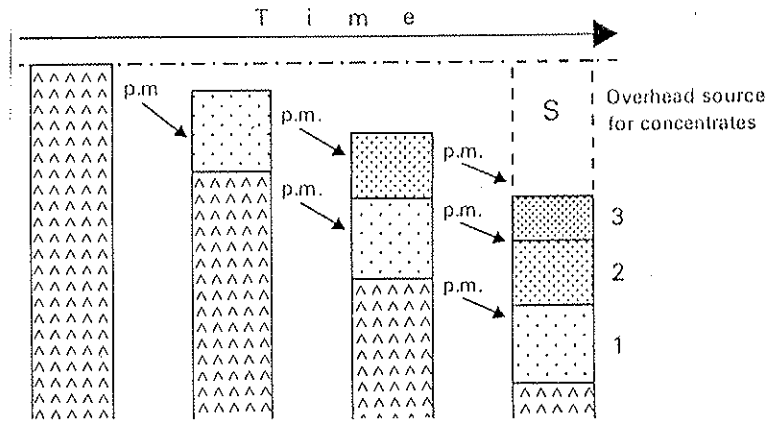


Figure 133

That this process operates is quite clear from the textural evolution of the residual materials. Thus, we know that the weathering front has lowered because 'core stones' of fresh rock occur suspended above the basal surface of weathering in its present position. Similarly 'cores' of stage 1-type weathering occur in horizons dominated by stage 2-type weathering. These and surviving relics or 'cores' of stage 2 type weathering may also survive into horizons dominated by stage 3-type weathering (figure 134).

The real problems emerge when we look more closely at the mobilised materials. There are two different categories of problem area, pertaining to the two genetic classes of residua, the groundwater and pedogenetic laterites and bauxites.

(a) Pedogenetic laterites This class of residua develops in vadose profiles. Weathering of primary minerals and formation of 2:1 clays is followed by weathering of 2:1 clays and formation of kaolins and Fe minerals. The Fe is retained in the profile and accumulates as other materials are leached out. Within the profile there is improvement in crystallinity and phase alteration of the iron, towards surface horizons.

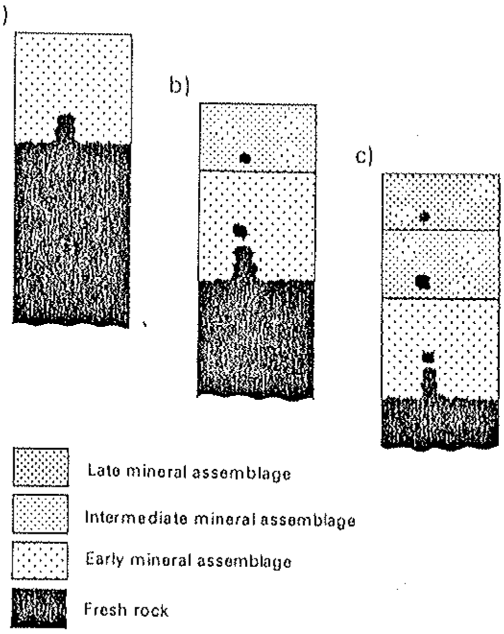


Figure 134

This raises the first problem, i.e. how to explain alteration of, for example, ferrihydrite to goethite and goethite to haematite. The latter transformation has popularly been explained in two ways, neither of which is adequate. The suggested 'dehydration' in near surface horizons seems unlikely since goethite dehydrates at over 300 degrees C. 'Ageing' also seems unlikely in view of the fact that laterites even as old as Late Proterozoic may be dominatently goethite, while Pleistocene profiles display the goethite to haematite transition. A further and related problem is the explanation of the retention of rock structures in these laterites. This is only possible if Fe is mobile and accumulates by a process of repeated solution and deposition (figure 135).

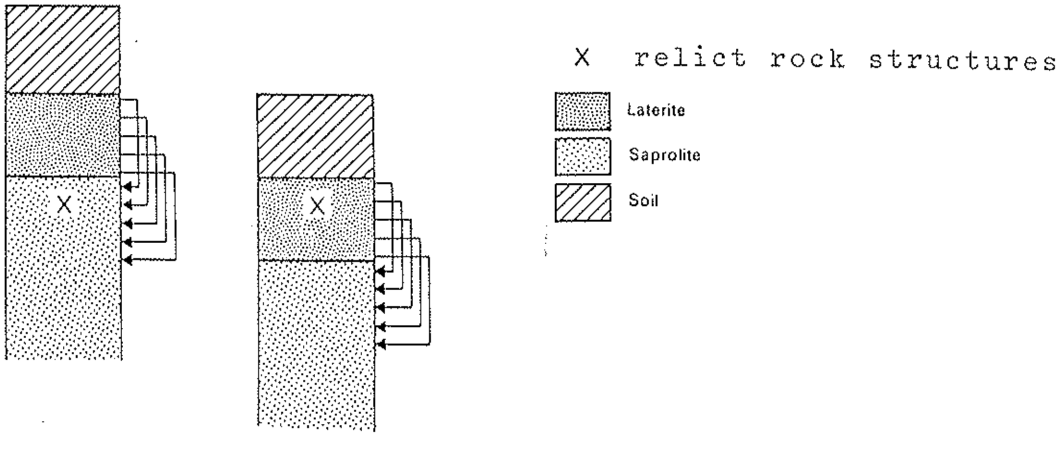


Figure 135

This proposed mechanism has been strongly opposed on geochemical grounds, since the pH is near neutral (6-7) and it is an oxidising situation. Yet there is abundant textural evidence, in addition to the survival of rock structures, to show that it does occur. For example, manganese platelets, which are typical of the base of the Fe-enriched horizons, form the nuclei of pisolihs near the top of the profile (Weber 1968). Since the platelets cannot move up the profile then the profile must have moved down. Also, Fe- and Al-rich secondary minerals form pseudomorphs after primary minerals which contained very much less Fe and Al. Thus Fe and Al have physically moved into the sites. The problem of this proposed short term mobility of Fe, to give the necessary cumulative effect of repeated solution and deposition, has now been spectactularly overshadowed by the results of more recent work (Esson and Surcan dos Santos 1978). By means of a very detailed mass balance study of one kind of pedogenetic laterite, a Ni-laterite from Liberdade, Brazil, it was shown that some 75% of the iron originally contained in the parent rock, (which was consumed to provide the residuum) had been entirely leached out of the profile. To the problem of the proposed and disputed short-term mobility of iron must be added that of explaining protracted mobility under entirely unfavourable Eh/pH conditions.

What alternatives are there to explain this mobilisation? The possibility that humus complexing is responsible seems unlikely since biological recycling is virtually complete in laterite profiles. The vegetation derives nutrients from the decay of its litter, very little being available in the extremely leached sub-surface horizons. Such a system cannot be maintained if substantial loss of humus by leaching occurs. If it did, the vegetation would, in effect, die of starvation before the requisite Fe mobilisation were achieved. Mircobial complexing was discounted because the depths of the profiles. "Below about 1m soil scientists no longer look for micro-organisms because they are so few." Recently, however, Chukhrov (1981) presented evidence for a microbial role in the goethite to haematite transition. By a process of elimination, microbial activity seemed the best candidate to explain the mobilities indicated by textural studies and this gave cause to search for micro-organisms indigenous to deep laterite profiles (at Readng University). Their discovery at depths formerly regarded as impossible, eg up to 60 m, co-incided with the independent development, by soil scientists in southern France, of new extractive techniques which have shown micro-organisms to occur in abundance at hitherto unsuspected depths (Bisdom, pers. com. 1982).

Preliminary leaching experiments simulating vadose conditions with a range of organisms indigenous to a pedogenetic laterite yielded significant mobilisation of Fe and Al (Perviz 1983). It is of particular interest that although the effects of the treatment produced changes in the pH, there was no correlation between mobilisation and pH. Further experiments, in progress, have indicated that microbial activity can mobilise Al which occurs substituted in the goethite lattice. After microbial treatment, the % Al substitution is less. Since it is extremely unlikely that the Al is extracted from the crystal lattice, it must be deduced that the goethite is solubilised and recrystallises in a purer form. This solubilisation appears to be the key to answering the problems concerning the behaviour of Fe in these profiles. It has long been known that even in soils where Fe is in abundance the quantity in solution is inadequate for the metabolic requirements of micro-organisms. To overcome this, they secrete special chelating agents with high and specific affinity for iron, the hydroxamates and phenolates ('catechols') (Byers 1974) which attack already formed iron hydroxides. Amorphous iron is preferably affected, but better crystalline material evidently also succumbs, eg goethite. If iron mineral 'dissolution' is achieved by microbial activity this creates the opportunity for two things to happen. First the dissolution products may be re-precipitated in the profile in a purer or better crystalline form, or as a new phase. Second, the mobilised materials may be leached out of the profile as complexes, thus 'by-passing' the Eh/pH constraints. Both of these processes are indicated by the 'repeated solution and deposition' model and excellent confirmation comes from a recent study, by Zanyah and Bisdom (1983), of iron pisoliths which contained fungal hyphae 'fossilised' by goethite precipitation. Thus, the up-profile improvement of crystallinity and phase changes of the Fe could reasonably be deduced to be an expression of increasing microbial activity in the direction of increased nutrient supply. The repeated solution and deposition process, both to account for the cumulative effect and the retention of rock structures can also be explained, as can the protracted mobility of Fe and its overall loss from the vadose profile.

The pedogenetic laterite progression can be summarised thus (figure 136):

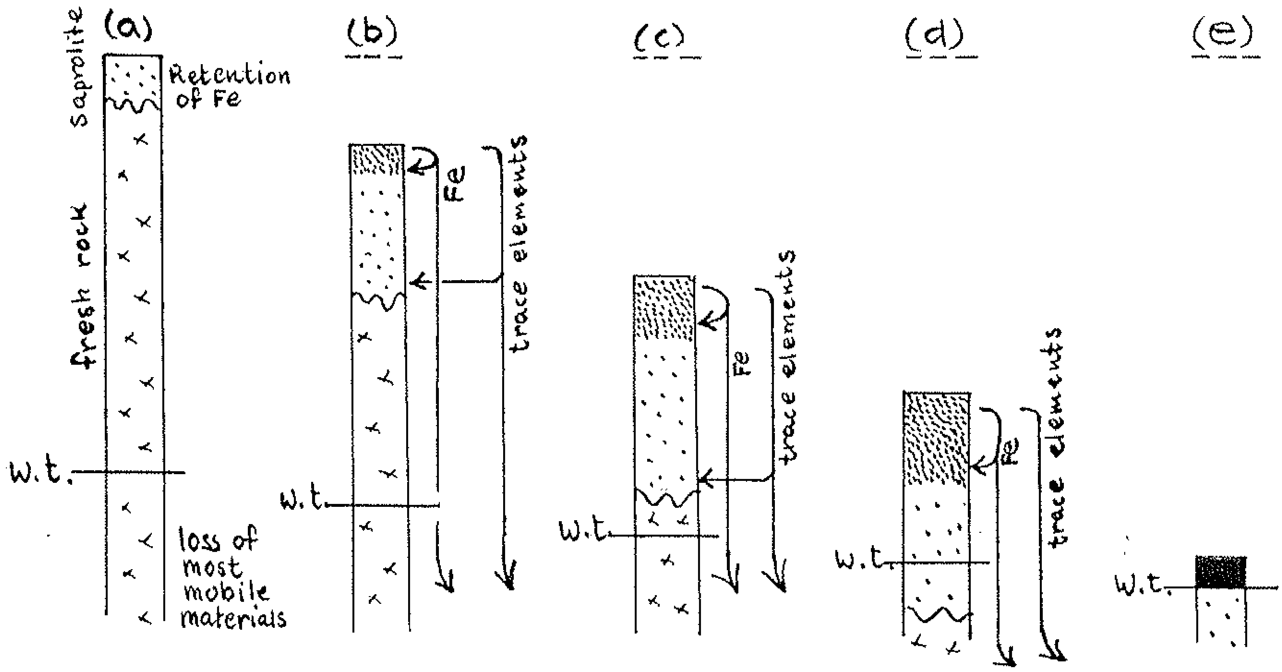
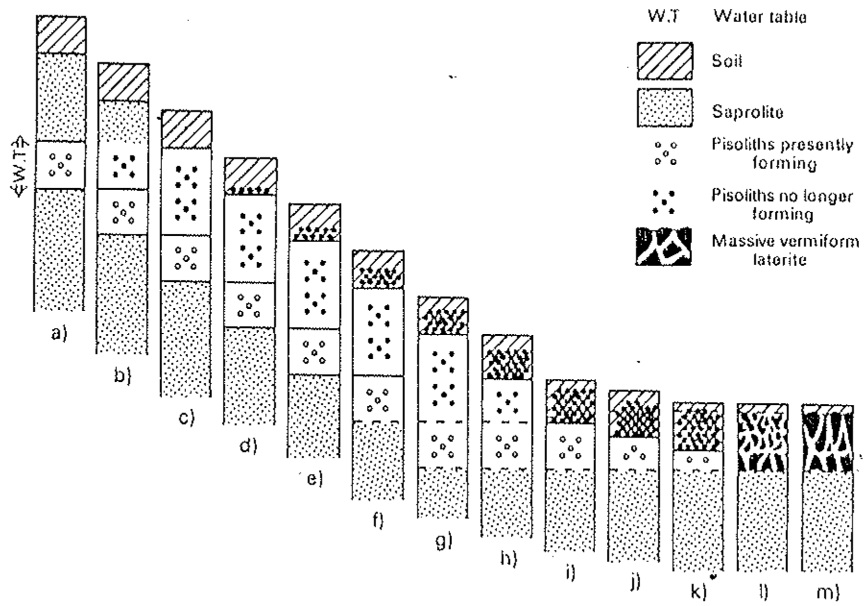


Figure 136

1. Fe is retained in the weathering profile, as the more easily mobilised materials are leached out (a).
2. The weathering profile deepens and the landsurface lowers. The upper parts of the profile become enriched by the cumulative effect of repeated solution and deposition of Fe, although a large part of the iron is lost downwards along with the other more mobile materials. Solution of iron minerals and recrystallisation results in loss of ability to retain trace elements. Some are 'recaptured' by clays near the base of the profile (or may be precipitated), but the more mobile are lost from the profile (b).
3. As this process continues the land surface lowers, the Fe-enriched horizons become progressively richer and the basal surface of weathering lowers (c).
4. When the basal surface of weathering goes below the groundwater table the process continues essentially unchanged except that trace elements which would have been retained near the base of the profile are lost into the groundwater (d).
5. The process continues till the concentrated residua lie very close to the water-table (e).

This is the sequence through which a profile in a topographicaly high position might evolve as the landsurface is reduced. A comparable range of profile variations occurs down catena.

(b) Groundwater laterites In this case (figure 137), Fe is segregated into 'pisoliths' within the range of water-table oscillation. Below the water-table it is dispersed in the kaolinitic saprolite. As the water-table lowers, during the late stages of landsurface lowering, the locus of pisolith formation lowers, leaving a spread of pisolith-bearing saprolite in the vadose zone. The pisoliths are concentrated up-profile, ultimately yielding a laterite with a grain-supported texture. This is achieved by the removal of the kaolinite and quartz matrix. Transformation of packed pisolithic laterite to vermiform laterite occurs relatively rarely, as very low relief is required. It occurs most commonly as a low catena facet, with pisolithic laterites further upslope.



The groundwater laterite familial progression. (a) Fe is segregated to form pisoliths within the narrow range of oscillation of the groundwater table; (b) and (c) lowering of the groundwater table lowers the locus of pisolith formation, leaving earlier-formed pisoliths in the vadose zone; (d, e, f and g) the pisoliths accumulate at the base of the soil; (h, i, j and k) the water table stabilizes and continued leaching reduces the vadose zone to bring the residual sheet of pisoliths into the zone of intermittent saturation; (1 and m) the pisolithic residuum is altered to goethite-rich massive veriform laterite.

Figure 137

The removal of the kaolinite and quartz matrix presented problems. Geomorphological explanations tended to concentrate on lateral, near surface mechanisms by way of explanation - rain splash or sheet flow, but these are inadequate. The sheets are often many metres thick and neither mechanism can offer the required depth of penetration. Nor can we find the appropriate deposits of quartz and kaolinite, which in bulk should far exceed the concentration of pisliths. Chemical removal was clearly implied. Although incongruent dissolution of kaolinite can be achieved in the laboratory (Reesman and Keller 1968) at the pH levels which pertain here (commonly 6-7) incongruent dissolution and also extensive dissolution of quartz were unexplained in these terms. Experimental microbial dissolution of kaolinite has now been achieved, using an organism indigenous to this kind of laterite. Although, of the range of organisms used in this particular experiment, none appeared to achieve quartz dissolution, the evidence for dissolution is clear and a range of organisms is now known to achieve it (Krumbein, 1984).

The distribution of groundwater and pedogenetic laterite:

1. Groundwater laterite formation is common in areas of quartz-rich rocks.
2. Pedogenetic laterite formation is common in areas of basic rocks.
3. The climatic limits of groundwater and pedogenetic laterite appear to be different. The former are apparently restricted to, or better developed in wetter areas. The latter also occur in very wet areas but appear to extend further into the dryer areas and near the climatic limits of iron-rich crust formation it is commonly the case that laterite occurs only on basic rocks (figure 138).

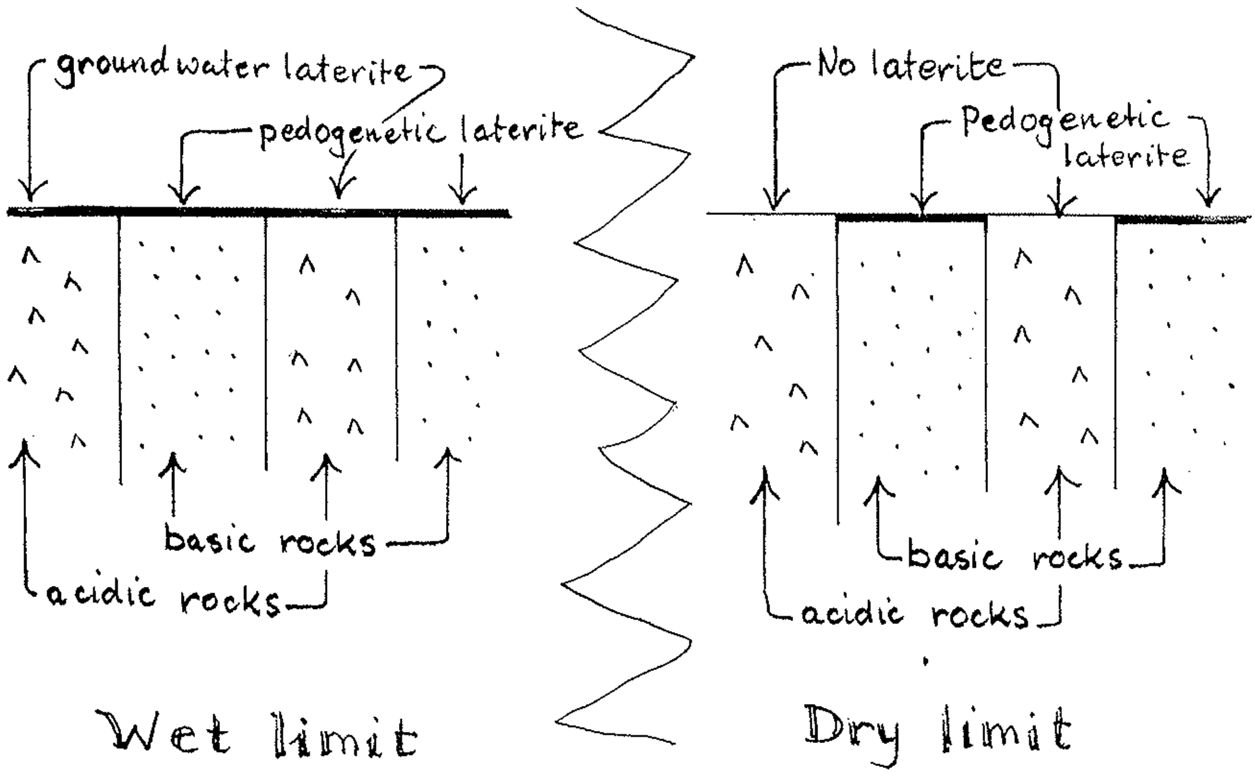
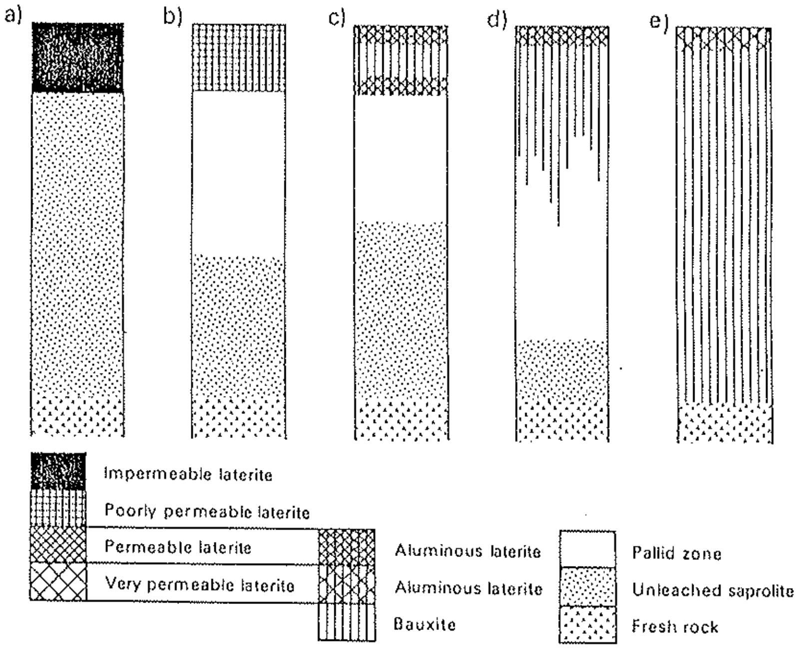


Figure 138

The distinction between these two types of laterites can be made on the basis of colour, textures and associated mineral assemblages (McFarlane 1969).

5.2 Profiles with an Al-rich, bauxitic crust

There is good evidence from textural and mineral evolution that the attainment of this stage of the weathering progression requires very agressive leaching, i.e. it usually comes after the formation of an Fe-rich, kaolinitic protore. This appears difficult to reconcile with the formation of lateritic crusts in the geomorphic context of the lowering landsurface because leaching becomes less active as the low relief situation is attained and the vadose zone is squeezed out. There is now clear evidence to show that bauxitisation of groundwater laterite is a post-incision leaching phase. After tectonic activity elevates the low relief, lateritised profiles, leaching is once again strongly vadose and the Fe and Si are leached out. The geomorphological arguments for bauxitisation as a post-incision modification of ancient laterite protores are varied (McFarlane 1983c) and clearly a post-incision model fits the requirement of agressive leaching. Some variations in the elevated profiles are shown in figure 139.



Some high level laterite profiles: (a) and (b) Kyaggwe, Uganda (after McFarlane, 1969); (c) Phutkapahar, India (after Ghosh and Dutta, 1978); (d) Darling Ranges, Western Australia; (e) Galikonda East Coast bauxites, India.

Figure 139

The chemical problems facing explanation of the removal of Fe and Si, leaving Al have already been indicated (section 4.2). Laboratory experiments using Eh/pH have failed to bring about the separation. Even examination of the conditions under which gibbsite stability is achieved, leaving aside the leaching of Fe, presents problems for the reconciliation of laboratory experiments and the situation in nature. Garrels and Christ (1965) indicated that gibbsite stability requires less than 1 ppm Si in the leaching solutions, and this appears to provide a means of dating bauxites which are presently forming and where the quantity of water moving through the profiles can be measured. Jepson and Schellman (1974) attempted to do this for the Weipa bauxite, yielding a date of 57 m.y. for the onset of bauxitisation. The authors themselves conceded that this was a very long time. If their methods are correct, then it is an even longer time, because they did not allow for a period of unknown duration when no bauxitisation could have occurred; the Gulf of Carpentaria is floored with calcrete, indicating a period when evapotransiration exceeded precipitation in this region. This appears to lead us to the conclusion that the onset of bauxitisation of the parent material predates parent material formation. A similarly nonsensical conclusion can be reached concerning the dating of bauxites in Amazonia, formed from Plio-Pleistocene deposits.

It is quite clear that bauxitisation can be achieved with Si concentration in the leaching waters much higher than these theoretical values required, eg. Grubb (1983) cites a range with a minimum of 3ppm and often up to 32 ppm for presently-forming bauxite. Further work is clearly required on the nature of such 'solutions'. The massive increase of bauxitisation to the present time, despite global cooling and increasing aridity, indicates a microbial role and thus microbial complexing of Si appears to offer a reasonable explanation for element differentiation which occurs despite very unfavourable Eh/pH conditions and 'solution' concentrations unfavourable to gibbsite stability.

5.3 <u>Deeply weathered profiles with no residual concentration in the upper horizons</u> In many profiles the saprolite extends right up to the surface, with only a thin covering of reddish or buff coloured soil and no surficial accumulations of Fe, Al, Si or Ca. They commonly occur where slopes are steep, so that surface erosion prevents accumulation of residua. In other cases, the profiles, formerly with surficial crusts, have been truncated by erosion. However, neither of these explanations can account for the often very extensive low relief areas with no crusts, in many parts of the African tropics, for example. These usually occur in the savanna regions and their explanation presents serious problems which, like my colleagues, I have previously dodged. Slopes are low and there is little or no evidence of detritus which could comprise former upper horizons which have been translocated. We are forced to the conclusion that either these former upper horizons have been completely destroyed, rather than merely translocated, or that for some reason they never formed in the first place.

Such crust-free, low relief areas usually occur in regions with a sufficiently seasonal or dry climate for pediplanation rather than downwasting to be the dominant process of landsurface reduction. King (1962) has said that the occurrence of laterite is proof positive that pedimentation occurs. He was implying that pedimentation produces, in effect, an 'instant planation surface' and his comment was made at a time when the upward enrichment theory was popular, i.e only <u>after</u> a planation surface formed was it possible for laterite formation to begin; with a stable landsurface in a seasonal rainfall regime, water-table fluctuation or capillarity can begin the work of translocating Fe from depth to the top of the profile. Since lateritic accumulations are now understood to involved rock consumption, their development is clearly associated with landsurface reduction. It might therefore have been more appropriate to say that the absence of laterite is proof positive that pedmentation occurs, if pedmentation does in fact produce an 'instant peneplain', with no potential for surface lowering and accumulation of residua, and it is widely believed that this is the case. However, while it is clear that pediplanation reduces the extent to which landsurfaces lower and hence reduces the potential for accumulation of residua, it by no means excludes this possibility. If pediments did not lower, the scarps at their backs would die out (figure 140).

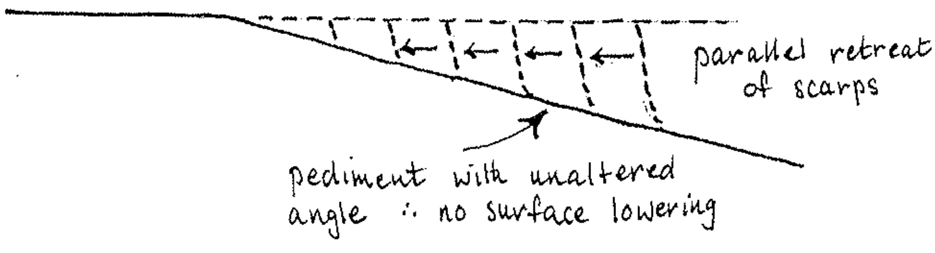


Figure 140

This may be the case in some situations, and detailed slope analysis of the resulting 'plain' should reveal the two slope elements. However, in many cases scarps survive and retreat, sweeping across wide expanses of country. For a scarp to survive in this way pediment lowering is essential (figure 141).

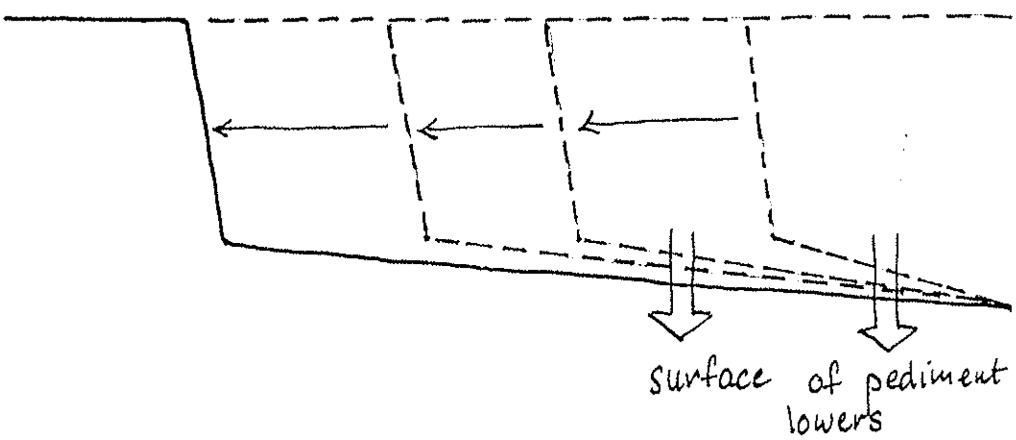


Figure 141

Also since the drainage lines are generally not stable, but lowering, albeit slowly, pediment lowering seems likely to be the norm. Thus, although the potential for surface lowering is reduced by pedimentation (say 5 degrees to less than 1 degree) as compared with downwasting (say 20 degrees down to less than 1 degree) that potential still occurs. Thus the problem of explaining the absence of a lateritic crust is reduced but still remains. The possibility exists that it forms and is destroyed as it forms. This possibility is raised by the observation that in the drier areas, inland from the Darling Range bauxite belt of W. Australia, iron enrichment fragments which fall from the 'breakaways' or scarps, progressively diminish in size and ultimately disappear downslope on the pediments.

No explanation for this can at present be offered, but it happens and this opens the possibility that residual material formed by pediment lowering may not survive to accumulate.

We should also consider the possibility that the residuum does not develop at all. This possibility can be reasonably contemplated when we consider that in both the case of pedogenetic laterite and groundwater laterite, accumulation is linked with Fe in a good state of crystallinity. With groundwater laterite the segregation of Fe into pisoliths is essential and a microbial role in this is possible (Young 1976). With pedogenetic laterite, microbial activity is also strongly implicated in the up-profile improvement in iron crystallinity; hence its survival. If such a microbial role is correctly implicated then we might expect it to be less in the drier areas where both water and nutrients must be in significantly poorer supply. This, if iron, liberated at the time of kaolinisation, remains in a poorly ordered state, the likelihood of leaching from the profile would appear to be greater and this could explain failure to accumulate. We do in fact have some evidence to this effect because in the case of groundwater pisolithic laterite, only the smallest and hardest segregations survive to accumulate (figure 142). Breakdown of the poorer, softer segregations may well contribute to the formation of the overlying red soil, but in large part they are unaccounted for and are apparently destroyed (leached out).

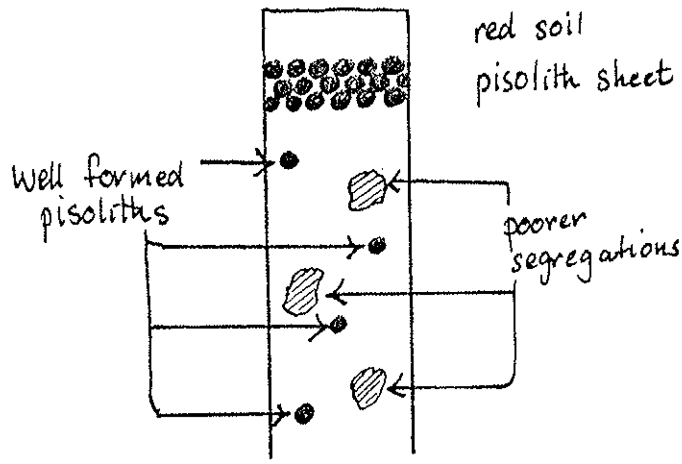


Figure 142

In short, the combination of reduced potential for landsurface lowering and also the possibly poorer state of order of residual iron could account for the absence of lateritic crusts in these crust-free pediment areas, but it is an as yet unexamined hypothesis. If it is correct, then it carries with it the possibly unwelcome implication that a considerable quantity of iron is to be expected in the groundwater in such areas. It also implies that not only is all the iron, yielded by landsurface lowering, lost into the groundwater but also all the Al and Si. In effect, since nothing accumulates, everything goes, and I am increasingly of the opinion that Budel's explanation for the formation of these plains is correct. Unlike most geomorphologists, who concentrated on search for a surface mechanism-sheetwash or whatever - to explain formation of these plains, Budel (1957) believed that the real work of planation is by solution within the profile. It is readily conceivable that the effects of local differential solution, which favours collapse of the saprolite, to form depressions, could be removed by local movement into the despressions, caused by rain splash for example (figure 143).

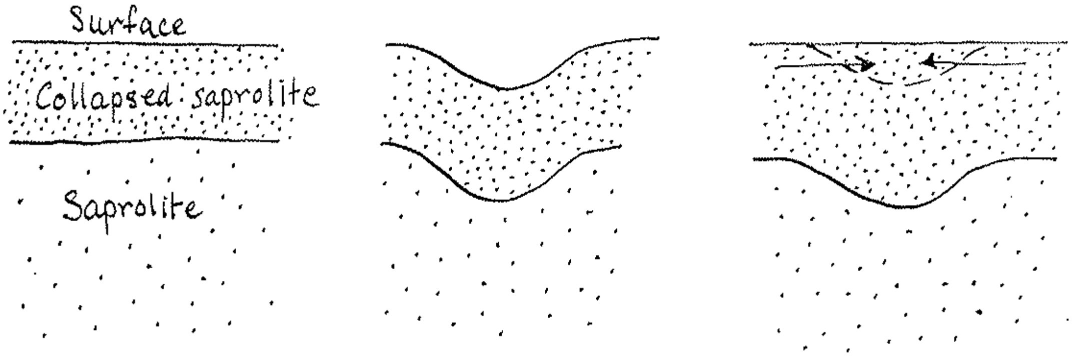


Figure 143

Such a hypothesis is attractive because it does not require large-scale movement or removal of loose, collapsed saprolitic material to form the plain. There does not seem to be a really satisfactory surface process which could do this. We can see, in shallow cuttings through such saprolite profiles, clear evidence that this process operates; the basal surface of the collapsed zone is often very irregular, yet the surface is very flat. Local redistribution of unconsolidated sandy saprolite is also well described in western Australia.

5.4 Profiles with Si-enriched horizons (silcrete)

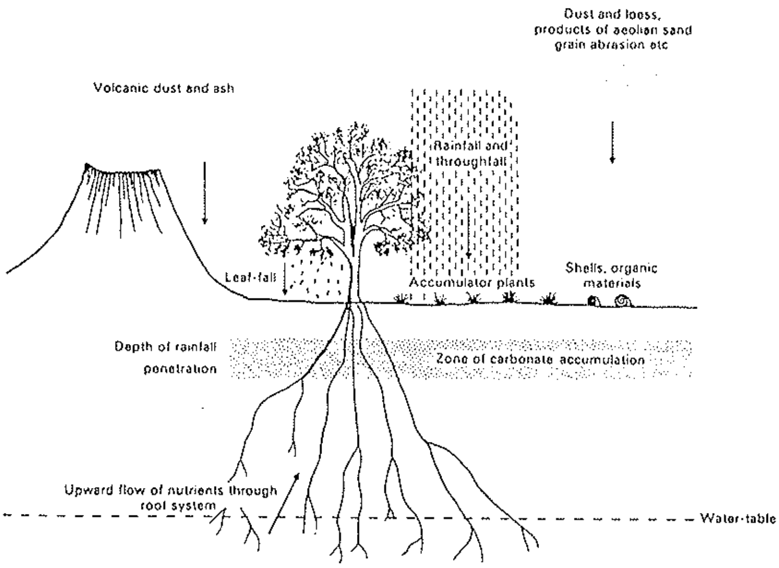
Summerfield (1983) has recently reviewed the literature on this subject. As has already been indicated, there is largescale release of Si during humid weathering. In wet areas this Si appears to be entirely lost from the profiles and moved out of the regions concerned, in the groundwaters. Precipitation of Si appears to be favoured by sluggish groundwater movement and the slow movement of water in very low relief areas therefore appears favourable for this. Thus Summerfield appears to be suggesting that lateritisation in areas of moderate relief may have as a natural complement the formation of silcrete in more distant, lower relief areas without there being a climatic difference between these areas. However, there seems little doubt that Si precipitation in profiles is favoured where conditions are generally drier than in lateritised areas and Bond (1964) proposed 250-300 mm as the annual rainfall limit. Watkins (1967) suggested a greater range, 250-750 mm for silcrete and calcrete formation, with Si tending to form at the higher rainfall end of the range. Lateral enrichment of this kind appears to be well supported. However it is also clear that Si movement may be much more limited. Si released in the weathering profile may be precipitated lower within it and it would seem logical to associate this with relatively low rainfall. In other cases multiple silcretes have formed within profiles, suggesting that Si precipitation is associated with the groundwater-table and its variable position. In very arid areas Si dust provided by aeolian sand abrasion appears to be a major Si source for silica hardpans forming between dunes, for example, where the water-table is close to the surface. To further confuse the issue it seems that some silcretes may have formed under very humid conditions and maybe the product of very low pH leaching, comparable perhaps with the Carboniferous gannisters. The Palaeoclimatic implications of silcrete formation are confused but

Summerfield has suggested that Ti enrichment of silcrete indicates more humid conditions of silcrete formation than is indicated by Ti-poor silcrete (those formed by solution and precipitation of Si dust from wind abrasion of sandgrains).

The likely occurrence of such relatively impermeable silcrete horizons within the weathering profiles of relativey dry areas, adjacent to more humid regions where Si leaching is or has been active, has important implications for groundwater movement and provides one possible explanation for considerably different water bodies at different levels within a saprolite profile.

5.5 Profiles with a calcareous upper horizon (calcrete)

Models of calcrete formation have been reviewed by Goudie (1983). They fall into two classes : non-pedogenic and pedogenic. The first of these involves deposition of calcium carbonate from a far distant source, that is, the absolute accumulation of calcium carbonate in low relief, arid areas, the source of the Ca being the leaching of rocks in relatively higher and wetter areas. The mechanism for transocation is groundwater. The favoured sites for deposition have already been outlined (figure 90) i.e. where the groundwater closely approaches the landsurface. The pedogenetic calcretes are believed to be relative accumulations, i.e. the Ca source is local and enrichment in the profile is vertical. The per descensum model of vertical enrichment from an overlying source is summarised in figure 144.



A model of calcrete formation by imputs of carbonate from above (the *per descensum* model).

Figure 144

The per ascensum model indicates that downward moving waters penetrate to a particular depth and return to the surface by capillary action, bringing with them dissolved carbonate which is precipitated. It is difficult to see how the last model could produce calcretes of any thickness and in the case of the per descensum model, the sources can hardly be described as entirely local. There seems little doubt therefore that a large part of world calcrete accumulation derives from areas outside the zones of accumulation.

5.4 Profiles with gypsum crusts

Watson (1983) has reviewed the distribution and various models of formation of these crusts and concludes that they are indicators of very specific climatic environments, generally where annual rainfall is less than 200 mm/year and where there is monthly excess of evaporation over precipitation throughout the year. Since most of the crusts occur near the landsurface, evaporation of groundwater combined with fluctuations in the depth of the water-table are held to explain most of the gypsum crystallisation. Pouget (1968) and Risacher (1978) suggested that fluctuations in the amount of sodium chloride present in groundwater may facilitate gypsum precipitation. If meteoric water recharging groundwater has a lower sodium chloride/calcium sulphate ratio than the groundwater, the solubility of gypsum may be reduced sufficiently to cause crystallisation. However, Watson is unconvinced of the need to evoke such a mixing model to explain most of the gypsum crust formation.

Part III

Recommendations for research.

Recommendations for research

Progress in this field of research is heavily dependent on the acquisition of more data, particularly on the lower parts of the weathering profiles. We have only a tantalizing scatter of data, sufficient to prompt proposal of a variety of possible inter-relationships which, if they could be substantiated, may be of considerable assistance in reducing exploration costs, by ensuring better success rates.

1. The configuration of the basal surface of weathering and its nature.
The fundamental requirement here is data from drilled cores (dry drilled), against which the results of seismic surveys may be assessed, so that we know precisely what the seismic data means. It would then be possible to use seismic traverses between the drilling stations, to provide a sufficiently close sample interval from which to map the basal surface of weathering with detail adequate to assess the influence of the several factors involved-lithology, fracturing, geomorphological history, etc.

2. The configuration of individual 'horizons' within the weathering profile.
If the up-profile weathering stages involve a sequence of mineral evolution which corresponds with development of porosity and permeability, the configuration of these stages or units would seem relevant to estimates of the recharge regime. In effect, what is required is to 'deposit model' for individual weathering stages within the saprolite body. Mineral analyses from the drilled cores could provide the necessary overview of their geometry. It may also be possible to correlate this data with seismic or resistivity data, particularly if this were available for contrasting periods, eg. end of dry season and end of wet season.

3. Water bodies and weathering zones.
In view of the possibility that the water may be stratified or may act as independent bodies within weathering basins, it would be very useful to be able to sample water from different horizons as well as from different areas, within the weathering profiles, if this is possible.

4. Relationship between parent rock, depth of weathering and mineral evolution in the profiles.
It is essential that the unweathered parent rock is sampled for each profile, to enable attempts to assess any relationships the three variables, rock type, depth of weathering and mineral evolution.

5. Relationships between lineaments and weathering depth.
Apparently contradictory comments on the benefit or otherwise of 'lineaments' for deep weathering and water supply, point to a need for a rather more careful appraisal of their nature. For example, brecciated zones, mylonite zones and intruded fissures (dykes) would be expected to behave quite differently on weathering and we need further information on this if valid generalisations are to be reached.

6. The wider context.
It is very important indeed to place all such data, and the relationships implied, in the fullest possible environmental context. Without this, there is little possibility of effective inter-regional extrapolation. Important contextural information includes:
1. the age of the landsurface. 2. subsequent, geomorphologically-controlled leaching history. 3. Palaeoclimatic conditions during profile development.

7.Remote sensing

If the ultimate objective of such research is not only to provide understanding of how the factors which affect weathering operate in conjunction with one another, but also to provide a means of cheaply and efficiently acquiring data on the lower parts of the profile, it is important to assess which of the remote sensing procedures is most effective in this respect. thus, a wide range of remote sensing techniques should be examined with this end in mind. I use the term remote sensing in its wider sense, to mean any technique, mechanical or otherwise, which provides information about profile characteristics without direct observation of these. For example, the worth of multi spectral scanning has been indicated by Dr. Greenbaum, to provide a small scale overview of the distribution and aspect of areas which are more deeply weathered. Within such areas, infra-red appears to hold considerable promise of providing important detail, if it is indeed effective at locating local variations in soil moisture retention capacity in the upper parts of the profile. It seems likely that where the profile is localy deeper, the upper horizons may have reached a more advanced stage of weathering (; they may have a higher proportion of clay or of sandy infill where saprolite weathering and collapse are more advanced). It is possible, therefore, that depth of weathering may be assessed by advancment of weathering in surface horizons and that IR may be able to locate relevant variations. If the ultimate aim is to provide exploration procedures which are relatively free from dependence on costly techniques, it would seem important to examine the variations of vegetation patterns and drainage densities in relation to variable surface horizons. It may not be overoptimistic to look for the means of mapping basal surface of weathering by mapping vegetation from normal stereopairs.

8.Methodology.

Most research proposals require the methodology to be specified. It seems to me that identification of the most appropriate methodology is an essential part of future research in this field. This, in itself, would comprise a major objective.

There is very widespread agreement about the need for a concrete effort to improve prognoses concerning the location of suitable groundwater supplies in weathered overburden in tropical areas. Research has been considerably handicapped by the difficulty of co-ordinating input from the range of disciplines required. The basic need for more data is matched in importance by the need for interdisciplinary co-operation, to provide a correlation of viewpoints on what is clearly an interdisciplinary problem.

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