Mechanisms for lateritisation and the formation of erosion surfaces in parts of east and southern Africa

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Abstract

This paper provides a synthesis and discussion of lateritisation processes as an integral part of landsurface levelling, with particular reference to the African surface of east and southern Africa.

Processes for removal of kaolinite and quartz are key issues pertinent to accumulation of residual mandes. Quartz dissolution is well evidenced, despite geochemical assumption that it is negligible. Congruent kaolinite dissolution, involving simultaneous evacuation of Si and Al, presents serious problems in terms of strictly geochemical explanation. Similar problems are encountered with explanation of the differential leaching of other metallic elements which accumulate in the residua.

Variability in Ti, Zr and Cr concentrations epitomises the problems. Recourse to aeolian input, to explain the variability, lacks credence. Resolution of the problems appears to lie with alternative modes of metal mobilisation, organic binding providing the best option.

Analysis of shallow throughflow in Malawi demonstrated mobilisation of Al, Ti and Cr. Previous detection failure is attributed to pretreatment bias towards the detection of elements mobilised in solution.

Modem leaching now appears to be essentially similar to the differential leaching which yielded the "ancient" residua. Thus, the study of contemporary leaching processes can make a valid contribution towards the understanding of the processes by which the African surface residua accumulated and the mechanisms by which the extreme levelling of erosion surfaces was achieved.

Résumé

Cet article fournit à la fois une synthèse et une discussion sur les processus de latéritisation en tant que partie intégrante de la formation des surfaces d'aplanissement, avec une référence particulière à la surface africaine de l'Afrique de l'est et du sud.

Le départ de la kaolinite et du quartz constitue une solution pertinente pour expliquer l'accumulation du manteau résiduel. La dissolution du quartz est bien mise en évidence en dépit du fait que, selon les connaissances en géochimie, elle peut être considérée comme négligeable. La dissolution de la kaolinite, entraînant simultanément l'évacuation de Si et Al, pose de sérieux problèmes quant à une explication strictement géochimique. Il en est de même pour l'explication du lessivage différentiel d'autres éléments métalliques qui se trouvent accumulés dans les produits résiduels.

La variabilité dans les concentrations en Ti, Zr et Cr résume ces problèmes. Le recours à un apport éolien pour expliquer cette variabilité manque de crédibilité. La solution semble liée à des modes alternatifs de mobilisation du métal, les liaisons dues aux substances organiques fournissant la meilleure option.

Des analyses des eaux de percolation effectuées au Malawi démontrent les mobilisations de Al, Ti et Cr. Les détections défectueuses antérieures peuvent être attribuées au biais introduit par le prétraitement de la solution en vue de rechercher les éléments de solution.

Le lessivage actuel paraît essentiellement semblable au lessivage différentiel qui a produit les dépôts résiduels anciens.

Ainsi, l'étude des processus de lessivage contemporains peut constituer une contribution valable pour la compréhension des processus qui sont à l'origine des dépôts résiduels de la surface africaine, ainsi que des mécanismes grâce auxquels l'aplanissement poussé des surfaces d'érosion a pu se réaliser.
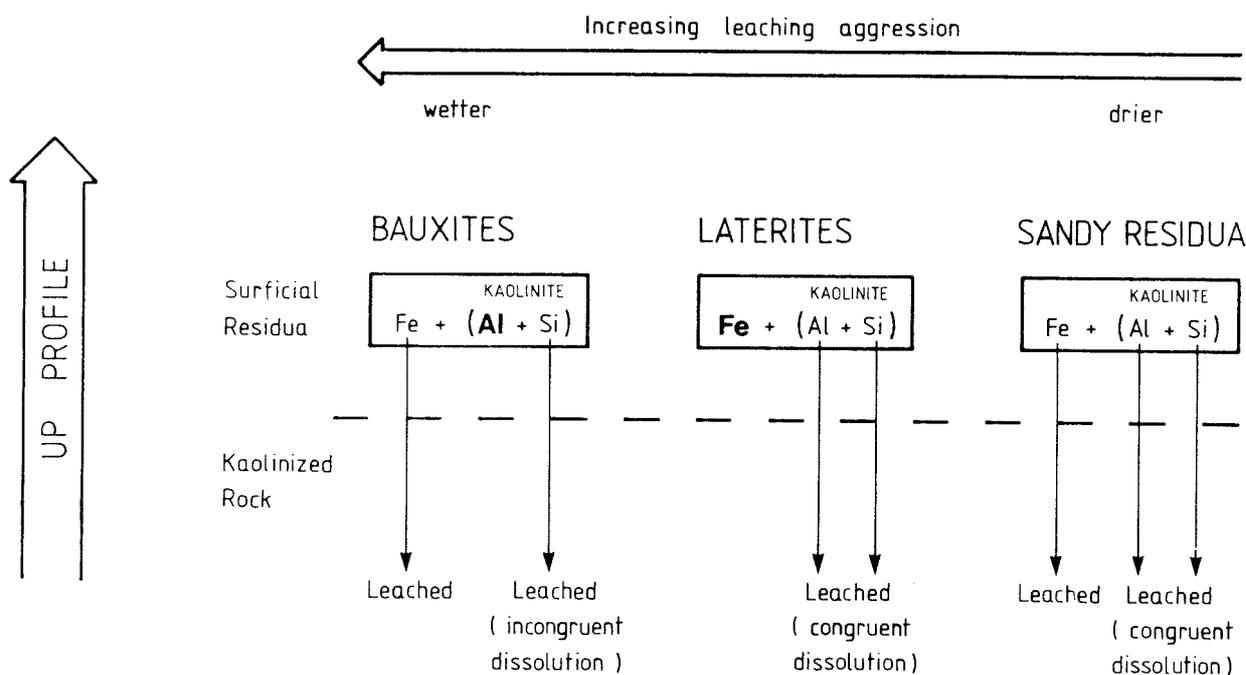
Increasing leaching aggression

wetter   drier

UP PROFILE

BAUXITES   LATERITES   SANDY RESIDUA

Surficial Residua

KAOLINITE
Fe + (**Al** + Si)

KAOLINITE
Fe + (Al + Si)

KAOLINITE
Fe + (Al + Si)

Kaolinized Rock

Leached   Leached
(incongruent dissolution)

Leached
(congruent dissolution)

Leached   Leached
(congruent dissolution)

Figure 1 : Diagrammatic representation of the progress of weathering to yield iron-rich lateritic, bauxitic and sandy residua.

I. INTRODUCTION

In eastern and southern Africa, planation surfaces occur with relief so slight that is extremely difficult to conceive of a mechanism which could achieve this degree of levelling. The most extensive is the African surface much of which is mantled by a laterite cover. The main hypotheses, peneplanation, pediplanation and etchplanation have been strenuously debated for decades. Extensive research into weathering and leaching processes has led to the recognition that any model of formation must incorporate synchronous leaching; the model must combine surface and subsurface processes. In these terms, etchplanation grows in attraction and THOMAS (1989a, 1989b) has recently reviewed the protracted history of the varied use of the term, paving the way for more serious consideration of its worth and for more precise definition of the processes involved. Despite the longevity of the hypotheses of planation surface formation and the serious debate of their merits and demerits, there has been remarkably little by way of hypothesis testing because the deterrents to this are substantial. One is the fundamental insecurity of the assumption that processes presently operating (and "available" for direct study) are those which fashioned these ancient landsurfaces; present processes could legitimately be regarded as surface-destructive rather than surface-creative. Another is the scale; it is difficult to justify the extension of a process recognised in a particular situation to the continental-scale processes. This paper provides a brief discussion of eastern and southern African planation surfaces, their formation and the development of their residual mantles, in an attempt to contribute to the reduction of these fundamental deterrents.

The laterites mantling ancient surfaces were for long regarded as formations quite distinct from the processes which levelled the planation surfaces. They were believed to have developed after the flat relief, supposed to be necessary for their genesis, was created. The last two decades have seen general recognition that the temporal and genetic distinction between landsurface levelling and laterite genesis is invalid. Rather, laterite has been recognised to develop in association with relief reduction. Instead of being a genetic post-script to planation surface formation, latente is a product of the processes which operated to level the landscape and thus the processes by which it formed hold the key to understanding the nature of the levelling mechanisms.

II. LATERITISATION PROCESSES

There is general agreement that a definitive characteristic of laterite is that it is enriched in Fe or Al, in comparison with kaolinised bedrock (SCHELLMANN, 1986). It is also generally appreciated that the source of the enrichment is overhead and not, as was formerly believed, below the laterite. It is overhead in the sense that the laterite is a

residuum from differential leaching with has "consumed" the formerly overlying material. Such leaching is so severe that the saprolite collapses and the landsurface is lowered. This collapse results in a stratigraphic discontinuity between residuum and saprolite in the profile, often interpreted with dubious validity as indicating a detrital or sedimentary origin for such laterite (OLLIER *et al.,* 1988; OLLIER and GALLOWAY, 1990; MILNES *et al.,* 1985). The implication of that interpretation is that the laterite is genetically unrelated to the underlying profile. Clearly such detrital laterites exist but stratigraphic discontinuity is a feature both of residual and detrital materials and the security of its use as diagnostic of transport to the extent that the overlying material may be regarded as a chronologically distinct (younger) "sediment", is highly doubtful (ALEVA, 1983, 1991 in press; MCFARLANE, 1991a).

In some cases the surficial laterite or bauxite retains saprolitic structures and textures, without collapse. The enrichment process involves repeated solution of overlying material and redeposition lower in the profile, this allowing the original saprolitic textures to be preserved. When contemporary interfluve situations are demonstrably the loci of the interfluves of the original surface, only a directly overhead source for the lateritic enrichment can be evoked, but in progressively lower catenary positions there are greater contributions from upslope.

An overhead source for the enrichment provides an answer to longstanding problems of explaining laterite occurrences on interfluves underlain by rocks which could clearly not provide a source of Fe. For example the laterite-bearing quartzites in Kyaggwe in Uganda can be explained in these terms since they are steeply dipping and interbedded by phyllites which could provide the source of the Fe (MCFARLANE, 1991a). Recourse to the hypothesis that these quartzite areas must formerly have been low-lying terrain which received "absolute accumulation", i.e. extraneous additions (mechanical or in solution) from topographically higher areas, becomes unnecessary. Such a "relief inversion" hypothesis, to explain cases of laterite on quartzite, is quite illogical.

Towards the drier margins of the laterite belt, as for example in Malawi, retention of Fe in the leached profiles becomes weaker and laterite occurs dominantly in slope-bottom situations where Fe lost from the interfluve profiles is precipitated. Interfluve residua are dominantly sandy (quartz-rich).

III. LEACHING PROGRESSIONS

The fundamental variations in the leaching progression in the advanced stages of weathering, across the main bioclimatic belts in tropical areas, are shown in figure 1. The key variable is the fate of the kaolinite. In the case of bauxitisation, kaolinite dissolution is incongruent, rasulting in the leaching of Si and the retention of Al dominantly as gibbsite. However, bauxitisation is relatively

rare and restricted to situations where leaching is particularly aggressive (BARDOSSY, 1983; MCFARLANE, 1983; BARDOSSY and ALEVA, 1990). By far the most extensive residua are the Fe-rich laterites in wetter areas and sandy residua where it is drier. In both cases the kaolinite disappears and it is the mechanism by which it disappears that is the central issue both as concerns the lateritisation process and consequently also the process of surface levelling, since vadose leaching and surface lowering are constrained by the position of the stable water-table, which provides a regional base level. Coupled with the disappearance of kaolinite is the removal of quartz.

IV. PROCESSES FOR THE REMOVAL OF KAOLINITE AND QUARTZ

It seems reasonable to ascribe the disappearance of kaolinite and quartz from humid tropical profiles to the activity of running water and the fundamental question becomes "is it the activity of surface water (direct surface run-off) or infiltrating water?". The activity of direct surface runoff is largely mechanical but in the case of infiltrating water evacuation may be either mechanical or in "solution".

A. Erosion by direct surface runoff

Direct surface runoff, proposed as the essential mechanism of pediplanation, lacks support as a process capable of achieving widespread landsurface levelling in east and central Africa because :

1. Very low gradients are unconducive to the generation of appropriate flow energy.

2. Even towards the drier margins of the laterite belt where the vegetation and litter cover is less protective, for example on the African surface in Malawi, evidence to support the occurrence of direct surface run-off is remarkably elusive (MCFARLANE, 1986) and in Zimbabwe, the dominance of shallow through-flow over direct surface runoff is indicated from hydrological studies (BULLOCK, 1991a and b).

3. It is difficult to sustain the argument that the essential mechanism for the intact removal of kaolinite and quartz is surface flow when deposits of an appropriate scale appeau to be lacking (MCFARLANE and POLLARD, 1989; MCFARLANE, 1991a).

4. In Malawi, on the African surface there is a very close correlation between relief and stream frequency (MCFARLANE *et al.,* in press) and the flattest areas are completely without channelled flow. The paucity of sheet flow from interfluves to bottomlands is attested by the maintenance of clear catenary colour variations, with red soils on interfluves and buff or greyish white soils flanking the seasonally inundated bottomlands (dambos) where soils are very dark grey or black. Similarly on the plainlands of Tanzania, Kenya and Uganda, black

smectitic sons are widespread in bottomlands, with red kaolinised sons on interfluves.

In short, direct surface runoff lacks substantiation as a mechanism for the removal of kaolinite and quartz.

B. Subsurface erosion or suffosion

Intact evacuation by shallow throughflow shares with direct surface runoff the problem of explaining where ail the missing quartz and kaolinite have gone. There is also a serious energy problem for water following a tortuous path through near-level residua. Although pipe-flow is indubitably capable of transporting particulate material (MOEYERSONS, 1989; BERRY, 1970) it appears to be associated with situations in which slopes are waxing and it is difficult to conceive of its sustained effectiveness where there is progressive slope reduction and gradients become very low.

C. Evacuation in solution

If the established geochemical constraints are taken as a starting point for enquiry into the hypothesis that the evacuation of kaolinite and quartz may be in solution, by infiltrating water, it is immediately clear that the prospects are poor since the solubility of quartz is generally regarded as negligible and the components of kaolinite, Si and Al, immediately co-precipitate when together in solution (OKAMOTO *et al.,* 1957). Nevertheless it is beyond question that both kaolinite and quartz dissolution happen, on a massive scale. Recent detailed descriptions of quartz dissolution are provided by SCHNUTGEN and SPÄTH (1983), TSHIDIBI (1985) and BORGER (1988, 1991). There is known geochemical explanation of congruent kaolinite dissolution (SCHELLMANN, 1981).

V. DIFFERENTIAL LEACHING OF METALLIC ELEMENTS

The geochemical problems surrounding quartz and kaolinite dissolution in laterites sets no precedent. The scale of the problems facing explanation of the behaviour of other elements, in strictly geochemical terms, is daunting.

Al and Fe would be expected to behave generally similarly, but in reality they often behave antipathetically. In the case of Fe-rich laterites Fe is selectively retained and Al evacuated. In the case of bauxite there is selective evacuation of Fe under generally vadose conditions.

The behaviour of minor and trace metallic elements is even more astonishingly contrary to expectations based on established geochemical constraints. This is particularly true of Ti, Cr and Zr which are commonly regarded as resistant to leaching and are used as indices against which the leaching of other elements is assessed. For example, in the Liberdade laterite profile in Brazil, the highest concentration relative to the parent material was for Ti (EssoN and SURCAN DOS SANTOS, 1978). By contrast, in Malawi, some 46 % of the Ti was calculated to have been lost in the conversion of saprolite to residuum (McFARLANE, in press) and in the Buganda surface laterite, despite massive concentration of Fe, the Ti values are comparable to those of the parent basement rocks. Comparably contrasting relative concentrations occur for Cr. A recent study of Deccan laterites (WIDDOWSON, 1991), showed that in terms of relative concentrations Cr was by far the greatest of all the elements, but in Malawi Cr concentration in the laterite was much weaker; over 75 % was calculated to have been lost in the saprolite to laterite conversion. Similarly for Zr. In Malawi this element has one of the largest relative concentrations in the laterite, but in the Deccan laterite it was very weak.

The inter-regional variations in elements with the maximum relative concentration is remarkable. In Malawi the greatest concentration is of Mn, a relatively mobile element, with Zr as a close second, substantial proportions of both Ti and Cr being leached out. In the Liberdade profile (ESSON and SURCAN DOS SANTOS, 1978) Ti has the greatest concentration, Cr suffering partial evacuation. In the Deccan laterites Cr concentration is massive, Ti and Zr being very weak.

If these relative concentrations are the result of variable mobilities, that is they are the result of differential leaching, then it is clear that beyond the kaolinisation stage in the weathering progression there are very serious difficulties facing explanation in strictly geochemical terms. This appears to leave two options :

  a. The concentrates are not simply the product of differential leaching; they have an overprint of aeolian input (e.g. BRIMHALL *et al.,* 1988).

  b. Mobility is not synonymous with solubility; minerai breakdown and element mobilisation are achieved by other means.

Explanation in terms of aeolian input is attractive and it is undeniable that such input must occur. However, at present assessment of the aeolian contribution lacks security because it is based on geochemical assumptions as concerns the immobility, in weathering profiles, of specific elements and minerals. In paraphrase the argument runs "since Zr (for example) is immobile it can be regarded as a resistant index and if the concentration of anything else is greater than that of Zr (e.g. Al or Tu) it must have been blown in". If such argument is valid, then it becomes necessary to accept that : (i). There is an astonishing input of other elements. For example, with respect to the Darling Range bauxite, BRIMHALL and others (1988) deduced (essentially on the assumptions that Zr is immobile and that quartz is insoluble) that virtually everything that is enriched in the bauxite is aeolian input (Fe, Al, Zr, Ti, Cr and Mo). In the case of Malawi, if it is assumed that Ti or Cr are immobile, then about half of the concentrates are allochtonous. If

Zr is used as resistant index in the Deccan Plateau laterite, then, as in the Darling Ranges, the bulk of the laterite is exotic. (ii) Aeolian input is remarkably varied. In Malawi it is Mn- rich, in the Darling Range A1-rich, in the Deccan Cr-rich and in Liberdade Ti-rich. (iii) Aeolian input is astonishingly local. In drier areas near the margins of the laterite belt, laterites only occur on basic rocks or are conspicuously better developed over them, for example the Great Dyke of Zimbabwe. To this it can be added that in some cases, where laterite is immature (e.g. on PIII in Uganda), it is possible to map the underlying geology from the nature of the laterite (MACDONALD, pers. com.).

It is extremely difficult to accept the conclusion that laterite deposits are dominantly aeolian, a conclusion evoked by assumed immobility of resistant elements. It follows that the basic assumptions are highly suspect.

Following this argument, explanation in terms of mobilisation in forms other than in true solution provides a better option. The problem now appears to be reduced to one capable of direct examination. The studies of quartz corrosion have already demonstrated that the assumption that it is invulnerable to dissolution is invalid and the question becomes "are Al, Cr, Ti, Zr, etc. also mobilised in the groundwater (mobilisation not necessarily being synonymous with solution) ?"

This question can be addressed by two means :

a. analysis of materials precipitated from groundwater by evaporation to dryness.

b. direct analysis of the groundwater itself.

Hydrogeological studies in Malawi showed that the circulation system comprises two main components. Shallows throughflow discharges laterally downslope into the seasonally waterlogged bottomlands (dambos). Such water would be expected to carry the dissolution products of the advanced stages of weathering in the highest parts of interfluve profiles. Deeply circulating water discharges upwards into the bottomlands carrying elements released during the early stages of weathering in the lower parts of the profiles (McFARLANE, in press).

Examination of precipitates was possible by two means. (i) A sample of shallow (throughflow) water, collected unfiltered, was evaporated and its chemistry mapped by scanning proton microscope (PIRE). Analysis of the precipitate confirmed the presence of Al, Ti and Cr, elements deduced (from mass balance) to have been lost from the interfluve profile during the saprolite to laterite conversion (McFARLANE and BOWDEN, in press). (ii) Both shallow throughflow and deep water continue to discharge into the dambo bottomlands in the dry season. As there is no surface runoff, the discharging water evaporates. Precipitates occur as glaebules encrusting grass stems (Mc FARLANE, 1988). Analysis, by SEM and EDAX, of a representative selection of individual particles comprising these glaebules showed that Al ranged

widely, reaching over 40 % and Ti is also a substantial component of the chemical assemblage (Fig. 2). Since Al and Ti are present as pseudomorphs after fungal hyphae, translocation in the shallow throughflow must have been in a form that was "free".

Thus, the chemical analyses of the evaporites (field and laboratory) show that there is contemporary mobilisation of elements such as Al, Ti and Cr, the loss of these elements from residuum on the interfluve being a fundamental part of the mechanism of its accumulation. A link has been made between present and past processes.

Thirty five samples of water, taken from shallow wells dug where the water table is close to the surface, were analysed by AAS-graphite furnace. Total Al levels were high, reaching 24 ppm (McFARLANE, 1991b; McFARLANE and BOWDEN, in press). Levels were substantially reduced by field filtration (0.45 microns). Acidification (nitric), normally used to stabilise solutions, further lowered the apparent levels, generally to below 0.1 ppm. These results confirm the contemporary mobilisation of Al and also indicate the reason for previous failure to detect it. The pretreatments of filtration and acidification remove particulate material, including organics, and the acidification has the opposite effect to that intended; it destabilises the mobilised Al, causing precipitation and hence underestimation of Al levels in the remaining solutions. This is consistent with mobilisation in organically-bound forms.
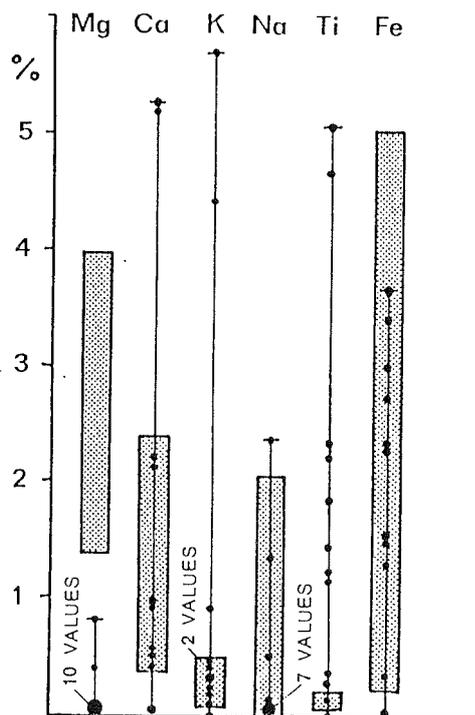

Figure 2 : Mg, Ca, K, Na, Ti and Fe values in particles comprising the dambo evaporites (glaebules attached to grass stems). The stippled columns represent the range of values for montmorillonites, published by GRIM (1968).

VI. PAST AND PRESENT LEACHING PROCESSES

The available information on contemporary mobilisation of Al, Ti and Cr, suggests that present leaching processes are very similar to those which operated to form the "ancient" residuum on the African surface interfluves. It also indicates that the differential leaching owes much to the mobilisation of elements in organically-bound forms. The key process of congruent kaolinite "dissolution" seems now to be something of a misnomer, since the Al appears not to be in true solutions. A variety of evidence has been assembled which indicates a key role for microbial activity in lateritisation (McFARLANE, 1987) and preliminary experimental work, using microorganisms indigenous to lateritic profiles supports this (Mc FARLANE and HEYDEMAN, 1984; MCFARLANE and POLLARD, 1989). The view that laterites are biogenic rocks is compatible with the opinion of KRUMBEIN and DYER (1985) that because of its purely climatic connotations, the term "weathering" is a pre-emptive misnomer, this being conducive to neglect of the role of microorganisms in earth surface processes. As these authors have said, "this planet is alive" and weathering and soil formation are exclusive to the living planet. The term "etchplanation" seems to suffer similarly pre-emptive disadvantages, since etching is by definition a process whereby a surface is worn away by the action of an acid, and in the tropics the processes operate at near-neutral pH.

This review raises more questions than it answers, but it would now seem that the differential leaching, which yielded the residual mantles of the African erosion surface and which is a key process in landscape levelling, is essentially similar to modern leaching. This gives a degree of security to the assumption that research into the formation of "ancient" landsurfaces may be validly approached by the study of contemporary processes.

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