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CHEMICAL DENUDATION, LATERITISATION AND LANDFORM DEVELOPMENT IN SIERRA LEONE

by

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RESUME

La part qui revient aux processus biogéochimiques dans les différents systèmes érosifs, reste difficile à préciser. La teneur en substances dissoutes d'une rivière par exemple, est d'une utilisation hasardeuse, notamment lorsqu'on tente de la traduire en une hauteur de sol érodé ou de l'associer génétiquement à un ensemble spécifique de formes de terrain. Pour caractériser l'érosion chimique, ses sites de départ, ses cheminements et ses zones d'accumulation, il est donc préférable de se fonder sur l'analyse géochimique des sols et des altérites in situ. C'est ainsi que la dynamique du fer a été suivie dans certains sites caractéristiques du Sierra Leone : les surfaces cuirassées des Sula Mountains, les glacis intérieurs des Tingi Hills et les larges dépressions marécageuses de tête de vallée (bolis).

Les cuirasses disséquées des *Sula Mountains* sont probablement très anciennes (Mésozoïque). Dans le système de dénudation actuel, ces cuirasses jouent essentiellement un rôle protecteur vis-à-vis de la surface d'érosion qu'elles couvrent. Elles sont le siège d'une mobilisation des sels de fer. Marginalement, elles sont affectées par des glissements de terrain. Les fragments qui en résultent sont souvent recimentés par des oxydes de fer en provenance de la cuirasse ou du substratum altéré (laves et schistes métamorphiques). La mobilisation géochimique de substances au sein de ce substratum a cependant été limitée et l'abaissement de la surface du fait de ce départ, a dû être assez faible.

Des glacis cuirassés forment entre les dômes granitiques des *Tingi Hills,* une sorte de bassin intérieur. La concentration du fer dont les cuirasses ont résulté, se serait produite pendant l'abaissement progressif des glacis. Des conditions temporaires d'hydromorphie locale ont mobilisé le fer pendant que les roches se désagrégeaient. Le transport aurait cependant été très court et la précipitation au niveau supérieur de la nappe a dû être presque instantanée. Ce milieu favorable à la concentration du fer, remplit cependant la fonction d'une surface de transport et même de départ vis-à-vis d'éléments solubles plus mobiles ou de sédiments détritiques fins.

Les dépressions à fond plat de tête de vallée *(Bolis)* qui ne sont pas sans rappeler les *dembos* d'Afrique Australe, restent inondées pendant toute la saison des pluies puis se déssèchent sur une profondeur d'un mètre pendant la saison sèche. On y rencontre des colluvions et des alluvions que des gravillons quartzeux séparent de la roche en place kao-

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linisée. Dans cette zone marécageuse où la tendance n'est cependant pas à l'érosion, l'élimination du fer est particulièrement active. Les concrétions ferrugineuses venant des versants environnants peuvent être mises presque complètement en solution et suivre ensuite les mouvements de l'eau. Si le niveau de l'eau est abaissé ultérieurement par un enfoncement des cours d'eau, le fer accumulé dans le profil peut produire un horizon de plinthite.

La distinction entre les concepts ou les modèles pédogénétiques et morphogénétiques est artificielle. Les formes de terrain devraient être considérées comme des "unités de réaction" insérées dans des systèmes ouverts plus larges. Ces unités peuvent agir en tant qu'unité de départ, de transport ou d'accumulation, différenciés selon la nature des éléments dissous et la taille des éléments détritiques. Il convient de faire un bilan des entrées et des sorties pour déterminer qui de l'érosion ou de l'accumulation prévaut dans un site déterminé. Ce bilan peut être établi pour les formations latéritiques étudiées, car peu d'entre elles sont autochtones.

En Sierra Leone, les dépôts latériques, cuirassés pour la plupart, contrôlent à leur tour le cours du développement des formes de terrain dans beaucoup de milieux. Ce phénomène est dû en partie à la dynamique des systèmes actuels mais il est également fonction des conséquences accumulées de l'histoire géomorphologique régionale.

INTRODUCTION

The geomorphological results of chemical denudation are imperfectly understood, and the evaluation of the role of biogeochemical processes in denudation systems remains difficult in spite of an increasing number of hydrologic studies. The quantitative importance of chemical denudation is difficult to determine, because the calculation of solute loads in streams cannot readily be interpreted in volumetric terms. The hydration of residual materials during weathering may result in what C. D. OLLIER (1967) has called 'constant volume alteration', and this makes the estimation of a rate for ground-surface lowering very complex. In most cases the data required for such an exercise are not available. The effects of temporal variation on ecosystems complicate the equations still further. Many hydrologic studies have recorded momentary conditions in stream systems which may be entirely unrepresentative (see D. A. LIVINGSTONE, 1963, for instance). This has been clearly recognised by many recent workers (I. DOUGLAS, 1968 ; Y. TARDY, 1971 ; G.G.C. CLARIDGE, 1975), but only scattered data are available even for one complete year, and longer term experiments have been very few (CLARIDGE, 1975).

The effects of past history and human disturbance create even more serious problems. For instance, where catchments are underlain by highly altered and deeply weathered rocks, it is likely that the runoff today will be very dilute (LIVINGSTONE, 1963), while changes in denudation systems as a result of land use practices are well documented (DOUGLAS, 1967). It seems doubtful therefore whether we can fully substantiate figures for regional rates of chemical denudation (LIVINGSTONE, 1963 ; S.N. DAVIS, 1964) or that we should accept the notion of an almost closed cycle of solutes within undisturbed, rainforest ecosystems without reservation. But even if the rate of chemical denudation in humid tropical environments is relatively slow, this does not allow us to evaluate this process in terms of the development of particular landforms or assemblages of forms, because studies of solute (and sediment) loads mask and integrate all internal heterogeneity upstream from the sampling point (TARDY, 1971).

In order to understand the geomorphological significance of chemical denudation it is therefore necessary to take account of other types of evidence, of which the geochemical analysis of soils and saprolites is the most important. The accumulation of weathering products in the landscape affords a means of spatial differentiation while it integrates both long and short term variations over time. In fact the relationships between pedogenesis and morphogenesis are close and complex (P. MICHEL, 1969), and many studies of soil geochemistry have singular importance for the understanding of tropical landforms (for example J. B. HARRISON, 1933 ; R. MAIGNIEN, 1958, and 1966 ; D. BLEACKLEY, 1964 ; Y. TARDY et al., 1971 and 1973 and G. BOCQUIER et al., 1974). Important among these relationships is the role of iron in laterite (plinthite) formation and induration as a duricrust (cuirasse).

The present paper attempts to apply some general principles derived from such studies together with the results of pedological and geomorphological research undertaken in Sierra Leone to some problems of interpretation presented by certain widespread landforms and deposits found in this part of West Africa. Sierra Leone offers an interesting context for such a study, because most of the country receives a large volume of precipitation (generally more than 2500 mm), but also experiences a severe dry season of from 4 – 5 months duration. Most of the areas referred to in this paper were formerly forested, but deforestation has been particularly widespread in this part of West Africa ; a factor which may have affected the denudation systems in important respects.

J. TRICART (1965), among others, has grouped morphogenetic systems into environments of 'exportation' from which rock constituents are removed in solution or as organic complexes ; environments of 'transportation' within which stable solutions are maintained over variable distances, and environments of 'accumulation' within which selective fixation of particular compounds takes place. Such concepts are widely accepted and particularly helpful in discussions of iron removal and accumulation in laterites. But the formulation of a landscape model to which these concepts may be applied without ambiguity or contradiction is less easy. The removal of ions from beneath interfluves, their transfer across mid-slopes of valleys, and immobilisation on glacis or in depressions, is by no means a simple, universal process, and it is of course well established that different groups of ions behave in constrasting ways within the landscape. This process is also greatly affected by the availability of water and therefore by regional climatic differences as well as by topographic contrasts (Y. TARDY, et al., 1973 ; G. BOCQUIER et al. 1974). The landforms studied in Sierra Leone may be divided into two principal caterogies :

1. The duricrusted (cuirassé) surfaces associated with :

1.1. plateaux developed across amphibolitic, volcanic and metasedimentary rocks, particularly in the Sula Mountains ;

1.2. more or less extensive sediments within or surrounding the major inselberg massifs of infra-crustal, granitoid rocks such as the Loma Mountains and the Tingi Hills, but also present in association with 1.1, and

1.3. remnants of extensive surfaces of low relief, developed over diverse lithologies. This last category is composite and does not enter further into the present discussion.

2. The forms and deposits of the river valleys and headwater swamps which include :

2.1. old floodplain and channel deposits subject to alternate inundation and dessication, and

2.2. contemporary floodplains and headwater swamps (locally called 'bolis') which remain waterlogged at shallow depth (less than 1 m) all year, and which are flooded to a similar depth for long periods in the wet season. Particular significance is attributed to these features, but studies remain at a very preliminary stage.

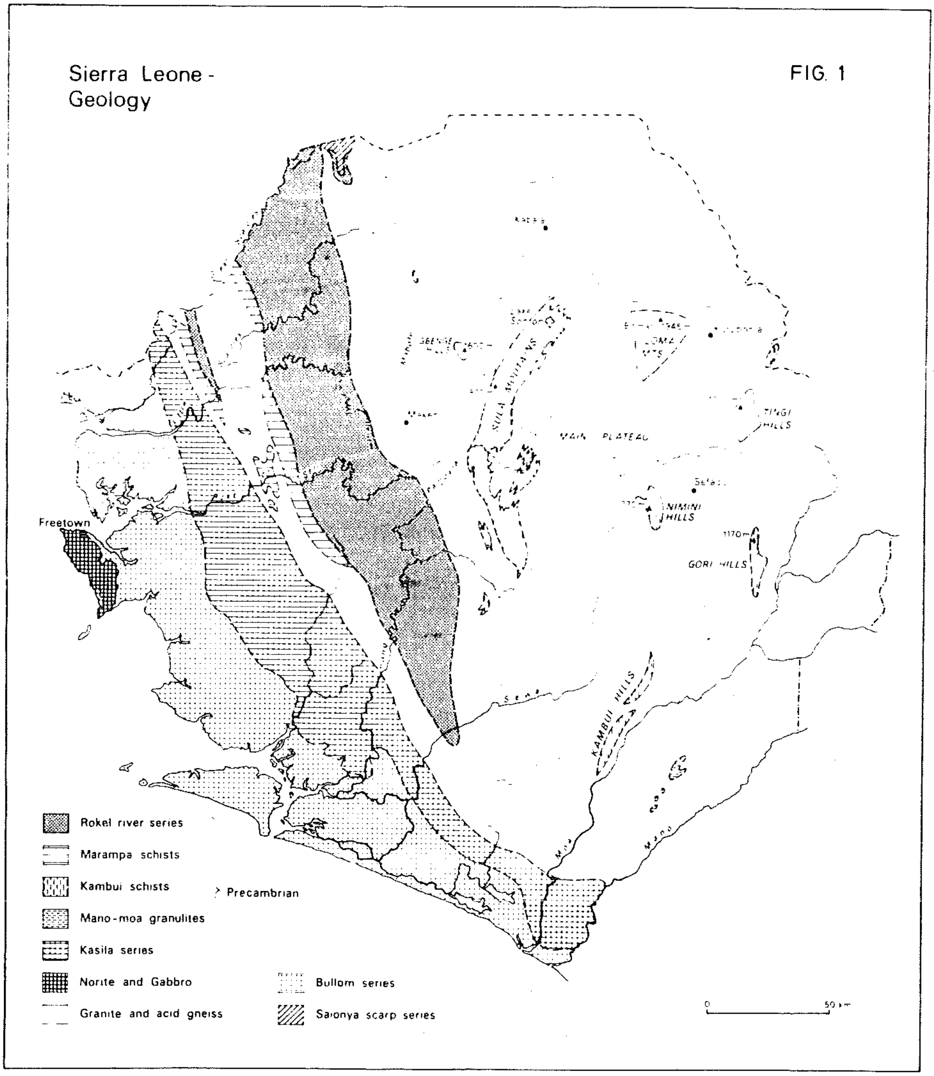

Sierra Leone - Geology
FIG. 1
Freetown
MAIN PLATEAU
NIMINI HILLS
GORI HILLS
TINGI HILLS
KAMBUI HILLS
1170m
Rokel river series
Marampa schists
Kambui schists
Mano-moa granulites
Kasila series
Norite and Gabbro
Granite and acid gneiss
Precambrian
Bullom series
Saionya scarp series

Figure 1

THE DURICRUSTS OF THE SULA MOUNTAINS

The Sula Mountains consist of a series of linear ridges and plateaux trending north to south through central Sierra Leone. The summit surface (between 600 - 700 m) carries a thick deposit of aluminous laterite over deeply weathered amphibolitic schists and lavas. They have been described by N.W. WILSON and V. MARMO (1958) and also by the author (M.F. THOMAS, 1968). Interest centres on the duricrust and the landforms associated with it. The deposit varies from 2 - 12 m in thickness, and forms a hard, almost continuous sheet over wide areas ; broken by joints and interrupted by slumps around stream heads. Rock structures are widely preserved in the laterite and its composition closely reflects the nature of the underlying rock. The proportion of alumina varies from 25 - 50 percent of iron (as $Fe_2 O_3$) and from 20 - 60 percent in the duricrust, while leaching of silica has been thorough, and generally constitutes less than 5 percent of the deposit to a depth of 4 m (WILSON and MARMO, 1958). These appear to be *primary laterites* in the sense used by J.B. HARRISON (1933) and D. BLEACKLEY (1964) in describing similar (and possibly related) deposits from Guyana. Their age is uncertain, but P.K. HALL (1969) suggests that they are downwarped towards the coast, where a similar duricrust is buried beneath Eocene, Bullom Sediments. This suggests a Mesozoic (possibly Cretaceous) age, comparable with similar deposits in the Futa Djalon and neighbouring areas of Guinea described by P. MICHEL (1959 ; 1969). Such summit surfaces in areas which combine high relative relief with ultra-basic parent rock and a high rainfall clearly come within the *allitic* province of weathering on both climatic and topographic grounds (G. PEDRO, 1968 ; Y. TARDY et al, 1973).

The functional role of such surfaces within the contemporary landscape depends upon two groups of factors. First, the mechanical behaviour of the duricrusted regolith under the prevailing conditions of climate and relief, and second, the biogeochemical mobility of the residual materials. The morphology of the Sula Mountains is complex and the duricrusted plateaux are dissected by deeply incised stream courses. The margins of the plateaux are subject to widespread slumping (N. W. WILSON and V. MARMO, 1958 ; M. F. THOMAS, 1968 ; 1974) around spring heads and suffosion processes are very active. Slide material however is frequently recemented by iron, indicating the active transfer of iron in solution. No water analyses are available from this area, but BLEACKLEY (1964) recorded as much as 70 ppm of iron in water from a pit towards the foot of a slope leading from a high level laterite deposit in Guyana, indicating a process of secondary enrichment of lower slope deposits and progressive bauxitisation of the high level laterite, a process also emphasised by P. SEGALEN (1971).

The functional role of these deposits within the contemporary denudation system is complex. Biogeochemical activity on the summit surface may be at a minimum, due to the absence of soil and forest cover. However, around the margins, where fragmentation and slumping of the duricrust occurs and forest cover is widespread, the slump material is commonly recemented by iron which is presumably leached from both the duricrust fragments and from the lower zones of the weathering profile. Within a broader context the Sula Mountains appear to have preserved an ancient, high level surface, and we may postulate that any lowering of the duricrust by geochemical processes has been at least *relatively* small, when compared with the denudation of adjacent landsurfaces developed over granites and gneisses at around 400 m. The morphological evidence favours C. D. OLLIER'S (1967) 'constant volume alteration' more than a continuous lowering as suggested for lateritised landscapes in Uganda by A. F. TRENDALL (1962).

THE DURISCRUST OF THE TINGI HILLS

Massifs of granitoid rocks comprising discrete areas of imposing inselberg landscape recur frequently over the African landsurface, and evidently present a considerable contrast in weathering environment as compared with the deeply weathered metasediments and lavas. In Sierra Leone, such massifs occur at different altitudes, the highest being the Loma Mountains (Bintimani 1948 m) and the Tingi Hills (Sankan Biriwa 1853 m), which may be horst blocks uplifted in the late Mesozoic (S. DAVEAU, 1965) ; others such as the Gbenge Hills, situated a few kilometres west of the Sula Mountains, attain heights generally lower than the adjacent duricrusted plateaux.

Weathering on the massive domes is generally regarded as minimal, due to the absence of water retentive debris, while in many instances, where the granites are deeply weathered they are not capped by thick laterites, but form landscape of low relief. However, the small interior plateau within the Tingi Hills is comprised of a series of duricrusted surfaces. The Tingi Hills rise abruptly from the 'Main Plateau' (P. K. HALL, 1969) of eastern Sierra Leone (circa 400 m) and attain heights of more than 1700 m. The interior plateau or basin lies at 1350 m and is traversed by several small streams, all incised some 10 – 20 m below the fan-like surfaces (pediments ?) which extent from the footslopes of the encircling domes (Figures 1 and 2).

Tingi Hills - Sierra Leone
Geomorphology and relief of the interior plateau

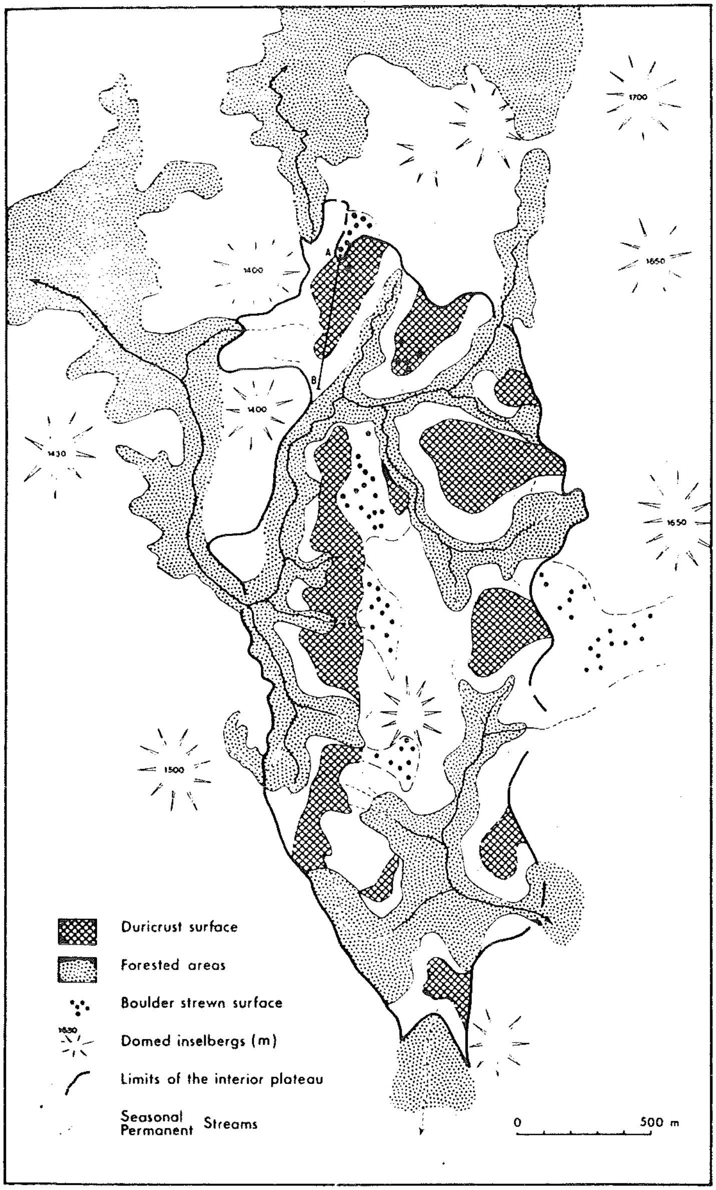
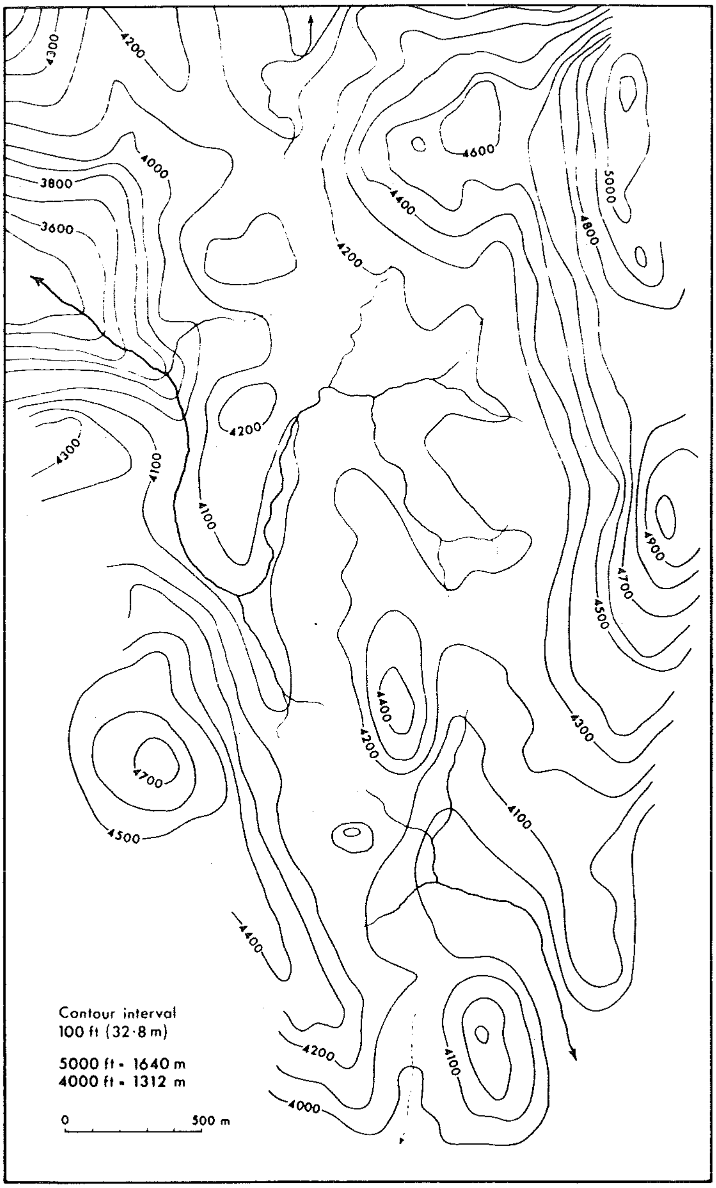


Figure 2 a.


Contour interval
100 ft (32·8 m)
5000 ft - 1640 m
4000 ft - 1312 m
0
500 m
4300
4200
4000
3800
3600
4600
4400
5000
4800
4200
4100
4900
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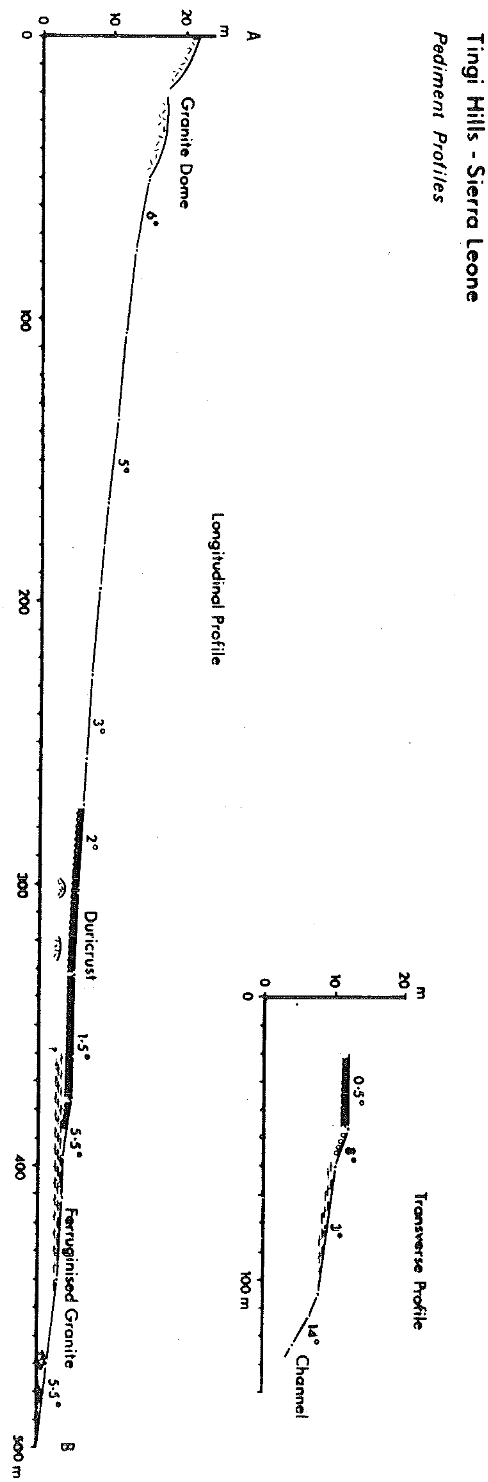
4200
4100
4000

Figure 2 b



Tingi Hills - Sierra Leone
Pediment Profiles
A
B
m
Granite Dome
6°
5°
3°
2°
Duricrust
1·5°
5·5°
Ferruginised Granite
5·5°
Longitudinal Profile
0
100
200
300
400
500 m
Transverse Profile
0·5°
8°
3°
14°
Channel
100 m

Figure 3

These pediments are from 200 - 400 m in length and decline from 6° on upper slopes to under 2° on the lower slopes (Figure 3). The lower slopes carry a hard duricrust 1 – 2 m in thickness which forms a low breakaway (corniche) of laterite rubble around the edge, leading down to a narrow bench of ferruginised granite. Etched and weathered granite boulders protrude from the surfaces to the pediments in places, and, where the duricrust has been incised by recent gullying, fresh rock is usually reached within 2 – 3 m of the surface. There is no evidence of deep weathering associated with the laterite deposit.

The parent rock is a pink, porphyroblastic biotite granite. Samples of the unweathered rock were analysed and found to contain 2.27 percent iron[1]. The surface duricrust, however, was found to contain on average 37.07 percent iron as Fe_2O_3 (preliminary analysis of eight samples ranged from 28.78% to 44.04% Fe_2O_3), while samples of ferruginised granite from beneath the duricrust had an iron content of around 9.0 percent. This grades into fresh rock within 1 – 2 m from the surface. The surface soil is no more than a few centimetres of grey silt and supports a cover of tussock grasses. After firing, these expose up to 60 percent of the surface to the direct impact of the early rains, but, when left unburned, form an almost continuous cover of rank grass.

The duricrusting of glacis and pediments is well documented by R. MAIGNIEN (1958) and P. MICHEL (1969), who describe the precipitation of the lower part of the glacis, wedgind out towards the top. In this case there is no higher laterite from which iron may be derived today, although fragments of ferruginised rock are scattered widely across the adjacent domes, and may represent the remnants of some former sheet at a higher level. The climate of the Tingi Hills is little known, but by analogy with neighbouring areas, the wet season will be characterised by very heavy rains from July through September, and it is possible that 500 – 750 mm falls during each of these months. Mobilisation of the iron likely to take place during the wet season, as a result of local and temporary hydromorphic conditions on the pediments themselves (P. SEGALEN, 1971 ; A. R. VAN WAMBEKE, 1973). But, in spite of powerful sheet wash, it is necessary to suggest that most of the iron is re-deposited close to its site of mobilisation. The high iron content of the deposit ; the shallow weathering profile ; geomorphic position and detailed morphology of these deposits, combine to suggest

(1) this and the following analyses were obtained by X-Ray fluorescence undertaken for the author by Dr. F. HUBBARD of the Geology Department, University of Dundee. Further work has yet to be completed on these samples, to determine the abundance of other elements, and to assess the structure of the laterite from thin section analysis.

a process of continual lowering of the surfaces by the action of strong sheet wash, by which much of the rock residue is evacuated, but not most of the iron which has accumulated as a duricrust[2]. This type of development was recognized in part by J. VAN SCHUYLENBORGH (1971) and was invoked by A. F. TRENDALL (1962).

Transported fragments are common in the duricrust, and lateral transfer of material across the pediment surfaces is clearly important. As functional units in the landscape, however, they do not act only as surfaces of transportation, but they also provide environments for evacuation of more mobile ions and fine sediment, and the accumulation of the least mobile elements, iron and aluminium. Seasonal variation in the denudation system is essential to the mechanism of iron accumulation ; induration of the duricrust taking place during the prolonged dry season.

The roles of recent drainage incision, past climatic change and of deforestation cannot easily be determined, but the ability of the pediments to concentrate iron oxides in a crystalline state appears largely to control the course of denudation on the interior plateau which occupies the depressions between the surrounding domed inselbergs of the Tingi Hills.

THE FORMS AND DEPOSITS OF THE HEADWATER SWAMPS

The so-called 'inland swamps' of Sierra Leone still await detailed study and classification, but several soil surveys have been undertaken in areas where they occur (A. R. STOBBS, 1963 ; R. T. ODELL and J. C. DIJKERMAN, 1967 ; S. SIVARAJASINGHAM, 1968, J. STARK, 1968, and W. VAN VURRE and R. MIEDEMA, 1973), and additional information has come from studies of diamondiferous deposits found within these swamps (P. K. HALL, 1969).

STOBBS (1963) divided these features into contemporary and older types, and this has considerable significance for their functional role in the landscape. All are locally called 'bolis' (a flat treeless grassland subject to annual flooding) and many resemble the 'Dambos' (E. ACKERMAN, 1936) of central and eastern Africa. However, some of those described in Sierra

(2) According to the preliminary analyses the ratio of iron in the duricrust to the amount present in the parent rock is 16.33:1. If the iron is derived largely from below the deposit, only 8.16 m of granite need be removed by denudation to concentrate 37.07 percent of iron in 0.5 m of duricrust. With lateral transfer from the upper glacis this might be reduced by as much as 50 percent (4.08 m), if all the iron is retained in the deposit. It is not however known how much iron is lost from the glacis surfaces altogether, during rock weathering. With a thin duricrust, however, it is evident that very large thicknesses of rock decay are not required to account for the features described.

Leone are riverine flats, while the term 'dambo' correctly refers to "periodically inundated grass-covered depressions on the headwater end of a drainage system in a region of dry forest or bush vegetation" (J. BALEK and J. E. PERRY, 1973, after ACKERMAN, 1936). Many such features appear streamless, although BALEK and PERRY (1973) report that channels may be detected from infra-red photography.

The distribution of these 'inland swamps' in Sierra Leone is very widespread. The 'Bolilands' proper, as described by STOBBS (1963), are developed over the mudstones and shales of the Rokel River Group of late Precambrian rocks in the lowlands of central Sierra Leone. But headwater swamps are found widely over the interior plateaux developed on gneissic and granitoid rocks, wherever the drainage has not become incised. Most of the 'older bolis' are abandoned riverine flats which are now flooded from adjacent rivers only during very high floods (A. R. STOBBS, 1963). These depressions dry out to depths of several metres during the dry season, and thus experience a wide fluctuation of water-table. They are commonly underlain by more or less massive laterite accumulations, and they therefore appear to function as reception zones for the immobilisation of illuvial iron (A.R. STOBBS, 1963 ; A. VAN WAMBEKE, 1973).

The contemporary or active bolis are inundated for periods and do not dry out at depths much below 1 m even at the end of the dry season. Characteristically, these headwater swamps are associated with the shallow dissection of a lateritised landsurface developed across a variety of rock types. Deep rock weathering is commonly found beneath the swamp floors, and this suggested to SIVARAJASINGHAM (1968) that the weathering was antecedant and was in large measure responsible for the developement of the flat-floored depressions that comprise the swamps. From the duricrusted interfluves quite steep slopes may decline towards the swampy valley floors. Upper slopes are associated with 1 – 2 m of laterite gravel, but SIVARAJASINGHAM (1968, p. 9) observes that "further down, on the long gentle slopes, due to the intense leaching of iron, the laterite gravel buried under a thick layer of gravel free material is often smaller, corroded and less abundant. In the swamps, and the poorly drained terraces, the leaching of iron of the laterite gravel is complete. Only kaolinite and gibbsitic white clay and sand are left behind". Both B. CHOUBERT et al (1952) and D. BLEACKLEY (1964) refer to the leaching of iron from laterite blocks under staturated conditions, but VAN VUURE and MIEDEMA (1973) comment that iron leaching may always have been strong enough to prevent the formation of iron concretions below these swamps.

The valley floor itself is generally underlain by 1 – 1.5 m of gravel-free material, and below this there is commonly a coarse gravel layer, intervening between the fine alluvium and the underlying kaolinised bedrock. A typical profile according to HALL (1969) is :

0 – 0.6 m	black mud with high content of organic debris
0.6 – 1.6 m	grey clay, silt or sand
1.6 – 1.8 m	bleached, angular quartz gravel sometimes in a clay matrix
below 1.8 m	decomposed bedrock, typically a stiff white clay, containing kaolinite and sericite and irregular quartz fragments derived from granite.

Few records are available of the depth of rock decay but 3 – 15 m is thought to be usual. Bleaching of the kaolinised bedrock penetrates to a depth of several metres below which it becomes iron stained. There are, however, granite boulders outcropping in some of the swamps. The dominant features of the swamp soils appear to be a clay deficient topsoil having a very low cation exchange capacity (some soils of the "Keya" soil unit described by SIVARAJASINGHAM have a CEC of 2.14 percent in the top 15 cms) ; an increasing clay content with depth ; almost complete leaching of iron, and the presence of an angular quartz gravel over quartz-rich rocks.

The swamps occupy the floors of first and second order valleys. Downstream, an indefinite channel gradually appears, but according to HALL (1969) although "as small stream may flow along the swamp ... it is never deeply incised and rarely makes contact with the gravel bed. Under no circumstances does the stream transport gravel or erode bedrock". The residual nature of the quartz gravel which also contains corrundum and diamond in places is of interest, and may represent a relative accumulation of quartz as more mobile constituents have been removed from below the swamp floor.

The detailed hydrology of these features in Sierra Leone awaits investigation, but aspects of dambo hydrology have recently been documented by BALEK and PERRY (1973) and by J. ALEXANDRE and J. NZENGU (1974) in Zaïre. The former found that only small amounts of water were contributed from the surrounding slopes, by comparison with the volume of rainfall accumulating on the swamp surface. This accounted for a rapid rise of water level and early flooding of the swamp surface. However, in Sierra Leone, although the upper surfaces of the swamps dry out in the dry season, the water-table seldom falls below 1 m, keeping the subsoil, including the bedrock, saturated throughout the year.

The processes operating within these swamp environments are not fully understood, but reduction and leaching of iron under anaerobic conditions is well known (D. BLEACKLEY, 1964), and with a large lateral outflow from the swamp basins the evacuation of iron and other elements in solution would be ensured. R. BRINKMAN (1969) has described a process of 'ferrolysis' which is thought to take place within the upper layers of hydromorphic soils, where alternate aerobic and anaerobic conditions occur. The process is a complex one, but according to BRINKMAN accounts for the displacement and leaching of cations, and the destruction of clays (R. BRINKMAN et al, 1973), involving iron in repeated reduction/oxidation cycles. These comments appear to support a view of these swamps as systems leading to the evacuation of weathering products.

But not all swamps function in this manner, and many are sites for the immobilisation of dissolved ions which accumulate in the vegetation and in 2.1 lattice clays. LIVINGSTONE (1963, p.G23) commented that "the swamps of East Africa are very effective in removing dissolved material from waters flowing through them". He was, however, referring to the role of large swamps interrupting the courses of large rivers. Such environments undoubtedly extract many dissolved constituents into the aquatic vegetation, and may also lead to dilution of the discharge as a result of incoming rainfall (although in some circumstances the rainfall may be more concentrated than the water discharged from the swamps).

The deposits of the swamps described here suggest that a slow lowering of the swamp floor has taken place as the upper levels of the kaolinised bedrock have become leached and subject to slow removal of clay particles. The accumulation of unrolled quartz gravel would have taken place concommitantly, wherever free quartz was present in the underlying rock. Colluvial material reaching the swamp margins from surrounding slopes would become subject to periodic reduction and leaching of iron from lateritic concretions as described by SIVARAJASINGHAM (1968), leading to the accumulation of sand and silt above the quartz gravel layer. A steady state in the system may be prevented by the accumulation of the residual gravels which in turn promote lateral subsurface drainage in the swamps.

Although such a model is attractive it ignores two intractible problems : namely the reasons for swamp development, and the effects of climatic change upon the hydrologic regime and therefore on history of sedimentation in the swamps. Factors leading to the development of the headwater swamps possibly include, shallow dissection of a previously weathered and lateritised surface (S. SIVARAJASINGHAM, 1968), and some slight degree of back tilting of the crust, as well as the nature of the hydrologic regime itself. Nevertheless, viewed within the context of an active morphogenetic system they appear to perform a distinctive function as processing units for the evacuation of dissolved ions and of fine sediment. With the gradual, lateral transfer of duricrust fragments from surrounding interfluves, the landscape may be very gradually lowered with only slight changes of form.

An important contrast in landscape dynamics exists between these 'active' swamps and those valleys in which streams are more or less incised. Here, drying out of the soil and subsoil to depths of several metres during the dry season leads to the immobilisation of iron and the formation of incipient duricrust or plinthite layers at the upper limit of the dry season water-table. Many such lateritic layers extend away from the rivers towards adjacent hillslopes, and may thus be regarded as active glacis. Thus the effects of chemical denudation will be reduced, while at the same time valley-side slopes are steepened, accelerating the processes of physical transfer, and altering the balance within the denudation system. This concept recalls ideas put forward by W. G. WOOLNOUGH in 1930.

More broadly, a geomorphological classification of swamps seems desirable, for some are virtually closed systems having no drainage outlet ; others function as open systems approaching a steady state and functioning as processing units for the transfer of earth materials into (or from) the drainage systems. Many different categories may also be recognised according to biogeochemical variations, particularly in terms of pH and Eh ranges.

In Sierra Leone the swamp environments are of particular importance, because they are being strongly recommended for paddy rice cultivation, and since exclude the effects of bioclimatic change require substantial modification when applied to field situations, and most models of pedogenesis which take account of such changes also invoke morphogenetic change. Models of *etchplanation* (M. F. THOMAS, 1965, 1974) and of *glacis formation* (P. MICHEL, 1959 ; 1969) involve sequences of climatic change and are closely related to theories of complex *ferrallitisation* (H. FOLSTER, 1968), and of *lateritisation* (R. MAIGNIEN, 1959 ; 1966). P. MICHEL (1969) has reviewed the interplay of morphogenesis and pedogenesis in West Africa, clarifying many problems common to both types of study. However, studies of chemical denudation, and of the influence of chemical deposits such as laterite upon relief development make it clear that the distinction between pedogenesis and morphogenesis is arbitrary, and that its value is pedagogic rather than scientific. The distinction rests largely upon notions concerning groundsurface stability (or of 'biostasie' and 'rhexistasie') which control the developement or truncation of soil profiles.

Landscape units are complex systems involving different directions and kinds of material transfer. In both geochemical and sedimentological terms landforms and soils are involved in differential transfers of elements, according to the mobility of dissolved and particulate material within the system. Few such units function separately as sites of exportation, transportation, or accumulation. Laterite deposits illustrate this situation clearly, since few are purely residual (autochtonous) in character, and both chemical and physical transfer of iron and other constituents in usually involved in their formation. Sites of iron accumulation may commonly be environments from which many other products of rock weathering are exported, as on the pediments described from the Tingi Hills. Conversely the inland swamps may mobilise and remove iron from the landscape into the drainage system, while accumulating many other elements in the growth of swamp vegetation.

The landform units described in this study should therefore be considered as *processing units* within much larger, open systems. Within these units which may be regarded as small ecosystems there is "a flux of elements which enter, take part in intermediate cycles within the ecosystem, and leave again" (C. G. C. CLARIDGE, 1975, p. 297). The balance between the amount of a particular element entering and leaving the system determines whether evacuation or accumulation is dominant in that case.

Laterite development is closely associated with hydromorphic soil formation in the tropics and this condition is controlled in large measure by the character of the relief. However once duricrusting of the deposit has they have not hitherto been used widely for agriculture, the effects of likely changes in hydrology and water chemistry should be carefully appraised before such development. Although VAN WAMBEKE (1973) has recently contended that recent, short-term changes in plant cover are not responsible for plinthite development in the tropics, even where water-table relationships are changed, the morphogenetic systems of swamp environments are nonetheless sensitive to hydrologic changes, and if slow chemical denudation has been responsible in large measure for their development, an acceleration of physical erosion through artificial channelling or other means might be as serious as any alteration to the biogeochemical balance within the swamp soils.

DISCUSSION

The geomorphologist requiring specific data concerning denudation systems is still confronted with serious methodological an practical problems as well as by a simple lack of data. Hydrologic studies, even of small catchments, leave many geomorphological questions unanswered, and while pedologic research provides for the detailed subdivision of the landsurface, it is difficult to separate parameters of the present ecosystem from the aggregate results of past ecosystems by this means. In this paper an attempt has been made to view landforms as 'process units', with special emphasis upon the role of biogeochemical processes. In order to elucidate this approach further, reference will be made to recent developments in both the pedogenetic and morphogenetic approaches to landscape development.

Pedogenetic models derive from the concept of the *catena* or *toposéquence*. Perhaps the most valuable of recent studies in this field have been those by TARDY et al. (1973) and by BOCQUIER et al. (1974). The model produced by BOCQUIER et al. (1974) attempts to link the lateral and vertical dynamics of soil systems in a virtually closed system of autodevelopment, involving the accumulation of weathering products at the base of slopes and of soil profiles with a "vertical and lateral ascending invasion of the illuviated horizons into eluvial ones". Such models exclude alterations in external factors affecting the system.

Morphogenetic models, offering a sequence of landform development within a closed system have been largely abandoned in favour of open system reasoning based on hydrologic modelling. Two modes of landform development that are widely accepted in some form are those of *slope replacement* (pediplanation) and *landsurface lowering*. In the present context the latter is associated particularly with chemical denudation (and in part with the hypothesis of A. F. TRENDALL, 1962). Recent synthesis by J. BUDEL (1970) has combined elements of both concepts. Models of morphogenesis and pedogenesis which occurred, perhaps due to a fall of water level within the profile consequent upon drainage incision or climatic change, the deposit increasingly controls the course of subsequent relief development. Furthermore, over much of the African landscape there is sufficient iron available locally to ensure that laterisation can occur whenever and wherever the site conditions are favourable to iron accumulation.

Iron accumulation within laterite deposits is only one example of biogeochemical control over landscape evolution ; relative and absolute accumulations of other residual materials from the weathering processes may be of greater significance locally or regionally. However, from the evidence which can be adduced from Sierra Leone, it may be concluded that processes associated with lateritisation hold the key to landform development over diverse lithologies and within contrasting local environments. This is equally the case whether the environment is apparently one of powerful surface erosion, as on the duricrusted glacis of the Tingi Hills, or is on of low erosional energy as appears to be the case in the headwater swamps. This situation is only partly a function of the dynamics of contemporary systems, for the significance attributed to many of the landforms and deposits described in this paper is a function of the past history of the landscape and of the aggregate effect of denudational events over a long period of geological time.

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DISCUSSION

H. Mensching : deux questions relatives à l'évolution des "pédiments" dans la région granitique du Centre du Sierra Leone :

1) la distribution de ces pédiments est-elle en relation avec l'existence d'un climat plus sec que l'actuel ?
2) les cuirasses constituent-elles les restes d'une couche d'altération ancienne plus épaisse ?

M.F. Thomas :

1) I find it difficult to comment on this question. I would say in general that pediments sensu stricto are not widesprad in the granitoid rocks of Sierra Leone. But the dynamics of pediplantation are undoubtedly complex and it is not self evident that slope retreat, where this has occurred, requires a more arid climate than exists to-day, unless of course it is suggested that sheet flood processes are dominant in their formation. I would not hold to such a view in Sierra Leone. Around residual hills which retain a soil and regolith cover rimpediments (rand pediments) are sometimes apparent.
2) This possibility has been considered but two factors lead me to doubt it in this case :
   a. In certain sections there appears to be a continuity between the underlying granite and the cuirasse such that the transition from width altered rock to the cuirasse shows no clear discontinuity. In certain other sections however the weathering front is very sharp.
   b. The survival of a thin (less than 1 m) cuirasse overlying a deep profile, during a long period of denudation appears unlikely, because exposure and fragmentation of the crust would occur.

J.I.S. Zonneveld : Do you think that it will be possible to calculate or estimate the lowering of the original surface by comparing the amount of angular gravels and diamonds in the concentration that could be called a stone-line and those that are to be found in the saprolite that is still present ?

M.F. Thomas : This is an interesting question, but although the problem can be solved theoretically in quite a simple manner (analogous with the estimations of iron concentration in duricrusts) the practical problems could be great. If volumetric estimations of quartz content in underlying rocks could be made the amount of lowering might be calculated. At present no such figures can be offered, and it is thought that an accurate estimation would be difficult even if we allow the basic premise, that the "stone-line" has accumulated in this manner.

J. Dresch : compare les faits exposés aux études faites dans beaucoup de régions granitiques intertropicales notamment en Afrique Occidentale ou Centrale. Les travaux de Bocquier au Tchad sur une chaîne de sols au pied d'un inselberg apportent des éléments comparables. La présence d'une ligne de gravier ne pourrait-elle s'expliquer comme une stone-line, témoignant des conséquences géomorphologiques d'une période sèche entre deux périodes humides ?

M.F. Thomas : More data about the swamp deposits are required before this suggestion can be confirmed or refuted. The evidence so far offered suggests that there it is not necessary to invoke climatic change to explain the phenomenon. This does not mean that climatic change has not occured during the history of the swamps.

J. Alexandre :

1) Does your last section not show a change in the water-level in the saprolite ?
2) Was the angular quartz layer derived from a quartz vein in the granite and what happened to the granite that was surrounding the quartz vein ? Does it disappear by weathering ?

M.F. Thomas :

1) Changes in water-level that have been recorded indicate a fall to less than 1 m below the soil surface. It would appear that seasonal variations do not affect the water content of the saprolite at depth. The mottling due to segregation of iron below 2-3 m may represent features of an older deep weathering profile that is being modified by reducing conditions in the upper part to-day, leading to bleaching of the saprolite and other elements in solution.
2) It is not known whether quartz veins have produced the gravel layer in any particular case. But in general it is thought that the quartz is derived from the granitoid rock during weathering. The concentration of the quartz into a gravel layer would arise as chemical denudation removes the products of weathering in solution, and slow lateral water movement entrains the fine clay and silt particles into the subsurface or surface waterflow. In other words the upper surface of the saprolite is continually but very slowly lowered, the dominantly quartz gravels accumulating as a residual lag deposit.