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ON WEATHERING AND DENUDATION OF HUMID TROPICAL INTERFLUVES AND THEIR TRIPLE PLANATION SURFACES[1]

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ABSTRACT

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Divide areas and associated interfluves of upstream tributaries, mark the outer boundaries of the wide, flatly concave final landscape forms resulting from BÜDEL's (1957) concept of double planation surfaces. The details of the weathering and denudation processes in these divide and interfluve areas have been studied during exploration work for placer tin and bauxite deposits, resulting in two distinct profiles: (i) the saprolite-mass flow profile and (ii) the saprolite-laterite profile. In addition to the denudation level and the weathering front level, making up BÜDEL's double planation surfaces, each of these profiles have one additional level. Both profiles are described in some detail; the effects of unequal downward progress of the various levels and the separation in space of both types of weathering profiles are discussed in the light of parent rock composition and climatic variation.

INTRODUCTION

The concept of double planation surfaces was introduced by BÜDEL (1957). It consists of an upper, superficial planar washing zone (Flächenspülzone) or concave denudation surface and a lower weathering front – at depths down to many tens of metres – where the fresh parent rock is being decomposed into easily transportable, friable and loose material. The denudation surface and the weathering front are essentially parallel; they both proceed downward or geopetal, but not necessarily at the same speed. BÜDEL uses this concept to explain the very broad (tens to hundreds of km), flatly concave valleys so characteristic for many humid tropical, often cratonic landmasses.

The environment of active, mainly chemical weathering and incipient erosion and denudation are found on divide areas and interfluves of in particular the furthest upward tributaries along the upstream edges of the regional concave denudation surface. Artificial outcrops, from sampling pits 0.8 m in diameter to mining faces several hundreds of metres long, have provided the author with numerous opportunities to study the weathering profiles developed in these areas. The parent rocks of these profiles included (leucocratic) granite, granogabbro, anorthosite, and the occasional dolerite and phonolite.

This contribution is mainly of a descriptive nature and without much discussion of the genetic processes or models. The motive for the preparation of this descriptive contribution is the course of discussions during the field excursion following the Second International Laterite Seminar of the International Geological Correlation Programme (IGCP), Project 129: Laterites and lateritization processes (São Paolo, Brazil, July 1982).

Chemical weathering may be considered as the re-equilibration of the mineral phases existing in the parent rock to the pressure, temperature, water and organic chemical conditions prevailing in the Earth's crust in contact with the atmosphere. In the continuously or intermittently humid tropical regions the resulting residual weathering products of the average parent rock is of two, distinctly different types.

(i) The saprolite (BECKER, 1895) type, characterized by intense chemical decomposition of the parent rock (which directly underlies it); retention of structural and textural

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features of the parent rock; abundant kaolinite (or other clay minerals when the parent rock is an ultrabasic or mafic rock); no other changes in overall chemical composition than a general loss in alkalies and earth-alkalies;

(ii) The laterite (BUCHANAN, 1807) type, marked by more intense chemical decomposition of the parent rock with all but complete destruction of its structural and textural features; the disappearance of kaolinite in favour of gibbsite and boehmite; often extreme changes in overall chemical composition; the frequent formation of duricrusts at or near the top of the weathering profile and mainly composed of either iron (hydr)oxides or aluminium hydroxides or both. A formal definition has recently been proposed by SCHELLMANN (1982): 'Laterites are products of intense subaerial rock weathering. They consist predominantly of mineral assemblages of goethite, hematite, aluminium hydroxides, kaolinite minerals and quartz. The SiO_2: $(Al_2O_3 + Fe_2O_3)$ ratio of a laterite must be lower than that of the kaolinized parent rock in which all the alumina of the parent rock is present in the form of kaolite, all the iron in the form of iron oxides and which contains no more silica than is fixed in the kaolinite plus the primary quartz' – (from the English abstract).

Saprolites constitute the principal part of a typical weathering profile – the saprolite-mass flow profile – of wide-spread and common occurrence in regions with a humid tropical climate. Laterites, commonly underlain by a saprolite horizon, constitute the characteristic part of a more evolved weathering profile – the saprolite-laterite profile – which is of a more restricted occurrence in regions with a humid tropical climate in the past or at present. Table I lists the successive horizons of both weathering profiles.

THE SAPROLITE – MASS FLOW WEATHERING PROFILE

From the parent rock upwards, a characteristic succession of layers or horizons is visible. The lower part (from parent rock through the weathering front to the bottom of the saprolite) comprises the part of the profile where the physico-chemical re-equilibration takes place. The overlying saprolite zone is the principal weathering product found in thicknesses that may surpass 100 m. Higher up this weathering product undergoes changes of another type.

It starts with a transition zone where there is a more active solution of minerals, including quartz, and in addition eluviation or physical transport of the finest, mainly clay mineral particles. The result is a decrease of volume, gradually increasing in an upward direction and leading to a progressive shrinkage and collapse of all original parent rock structures and textures which were still maintained in the saprolite horizon – see figure 1. Collapse is the commonly used term for this phenomenon but the process to be described absolutely does not have the suddenness and unpredictability that is conveyed by that term. It is a slow, continuous, progressive process for which 'shrinkage' seems more appropriate. The end phase of the process is a stone-layer (stone-line, carpedolite) composed of angular to subrounded, coarse gravel mixed with coarse sand and some silt and clay.

This stone-layer is composed of those parts of the original parent rock that are highly resistent to weathering and solution: mainly quartz from broken up veins, but also other vein material such as greisen, tourmaline, topaz and cassiterite, and broken up fragments of intrusive (basic) dykes. The stone-layer overlies the top of the truly autochthonous or in situ material. All material above, including the stone-layer, is in a state of flux; it has a high moisture content, in particular during the rainy season, and moves slowly but inexorably downslope to be finally dumped into a fluvial valley. The process is best described with the term mass flow or mass

Table I
Successive horizons of weathering profiles.

(i) Saprolite-mass flow profile (with double denudation front)	(ii) saprolite-laterite profile (with double weathering front)
* surface = *denudation level II*	* surface = *denudation level*
– soil	– soil (if not already truncated)
– horizon of mass flow	– laterite horizon, often with an upper Fe rich and lower Al rich zone
* stone-layer = *denudation level I*	* *weathering front (II)*
– transition i.e. horizon of solution shrinkage or unstructured saprolite	– transition into partly unstructured saprolite
– structured or true saprolite	– structured or true saprolite
* *weathering front*	* *weathering front (I)*
– parent rock (fresh)	– fresh parent rock
on interfluves of low to medium slope	on approximately horizontal divide areas and on really low-angle sloping interfluves

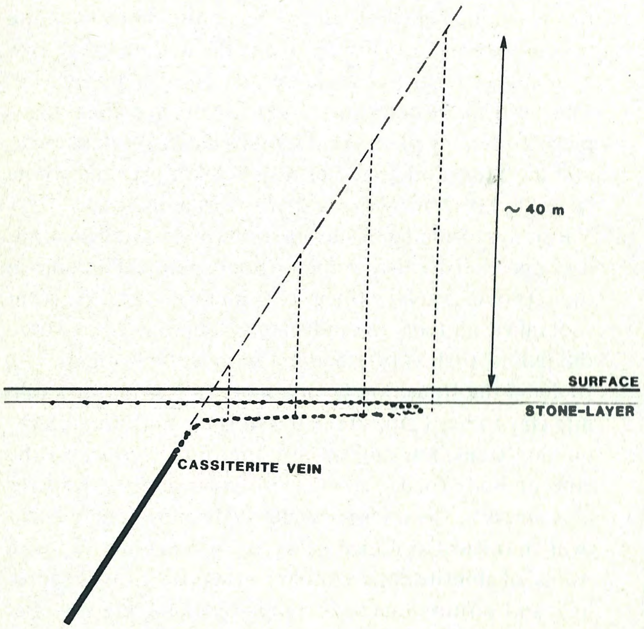

Fig. 1
Collapse or shrinkage of a cassiterite vein as observed in Belitung island. From vein dip and farthest upslope cassiterite occurrence the total thickness of the shrinkage zone is estimated at ~40 m. The surface slopes approximately 2 degrees. The downslope moving vein fragments contribute to the ubiquitous stone-layer. Partly after VAN OVEREEM, 1951.

creep (HUTCHINSON, 1968); the shape of weathering resistant veins in the transition zone between kaolinized parent rock and transported weathering mantle indicates a lamellar movement, in upward direction increasing in speed. Also, the accumulation of the coarse, weathering-resistant components in the stone-layer seem to result from a fluid bed type of material flow movement*. It must be mentioned at this place that in the tropics with a humid climate during part or all of the year, the author has never seen indications for the stone-layer to be principally the product of termite or other animal activities. Neither is there any reason to invoke an extremely dry climate in order to explain the stone-layer as a burried, fossil desert pavement.

The stone-layer is an important feature although it may locally be restricted to a horizon of single small gravel particles at an interval of a few decimetres to several metres. At other places it may be present as a continuous layer a metre thick; it may even constitute an economically attractive mineral deposit where it contains cassiterite or gold (many so called eluvial deposits of cassiterite and gold in the Far East, Brazil and Suriname) – see photographs of figure 2. Because of its blanket nature, the stone-layer may be used as a mapping or prospecting help: its mineral content is representative

Fig. 2A
Two extreme examples of stone-line development.
Small miner's pit with tunnel to mine the stone-layer, here represented by a layer, 0.9 m thick, composed of angular to subangular vein quartz and coarse cassiterite (5-10 kg Sn/m^3).

Fig. 2B
Bulldozer trench, dug for drainage purposes, containing the stoneline as a horizon, at the point of the geologist's finger, on which small, sub-rounded, vein quartz pebbles occur at intervals varying between 0.5-3 m. Oriente Novo, T. F. de Rondônia, Brazil.

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* During exploration drilling, the high moisture content of the zone above the stone-layer is used to determine the top of the in situ saprolite material below the often intermittently developed stone-layer; the saprolite is generally much drier and more compact.

for the whole slope from the sampling point upwards to the actual divide ridge. Hence the stone-layer, and the unconsolidated mass flow material on top, are of an allochthonous nature, although it may range from barely to completely foreign to the place where the material is now found.

The stone-layer is also the main ground water conduit, and springs often occur at this level in places where retreating fluvial erosion produces steep, amphitheater-type cuts in the saprolite layer.

The mass flow horizon overlying the stone-layer is an unconsolidated mass of weathering products in transit from its place of weathering to the nearest potential drainage conduit. It is a horizon of slow, continuous or intermittent denudation, the material of which may choke or clog the receiving valley when surface and groundwater run off from precipitation is insufficient. The author has seen examples of various stages of this choking in Rondônia, Brazil. In other places, parts of the mass flow horizon may become fossil, i.e. the flow stops due to local changes in the drainage pattern.

The top horizon is the local soil, a product of changes starting from the surface and largely caused by living organisms. This soil is certainly not residual or autochthonous in sensu stricto, as it overlies the zone of mass flow. The surface of the soil horizon is also a denudation surface, although of a higly intermittent nature, only active after heavy rainstorms; at those periods, however, with far higher material transit speeds than in the zone of mass flow.

In summary, the saprolite-mass flow profile contains three planation levels: the weathering front on top of the fresh parent rock, and two denudation levels; level I over the saprolite and shrinkage zones is marked by the stone-layer, while level II is the actual surface of the soil.

THE SAPROLITE-LATERITE WEATHERING PROFILE

The lower part of this weathering profile is similar to the one described above; the differences start with the upward change of the structured saprolite into a transition zone of variable thickness (0-1 m). Structures such as sedimentary bedding or partly weathered aggregates of ferromagnesium minerals of leucogabbroic parent rocks may still be present, but the 'rock as a whole' has lost its crisp saprolite structure and texture.

In an upward direction there is usually a gradual change into the laterite horizon; this zone of change is the second weathering front, varying in thickness from 0-3 m, locally more, where gibbsite takes the place of the kaolinite from the saprolite horizon. Gibbsite is the ultimate weathering product and the diagnostic mineral of the more evolved laterite horizon.

This second weathering occurs in several modes:

(i) A gradual increase in size and frequency of generally ferruginous gibbsite particles and nodules contained in the kaolinitic saprolite up to the point where kaolinite becomes an accessory mineral and the texture of the now aluminous lateritic rock is largely determined by gibbsite. The vertical distance over which this transition takes place is in many places remarkably short, 1-10 dm or so, and the transition zone lies as a blanket over the whole saprolite horizon, without sharp rises and dips.

(ii) The newly formed gibbsite and iron (hydr)oxide minerals are deposited in existing openings and permeable zones in the saprolite, such as (incipient) joints and cracks, plant root tubes, and silty to sandy intercalations in cases where the parent rock is of a bedded sedimentary origin.
In detail the transition from a more or less plastic kaolinite clay to hard gibbsite material is mostly abrupt, lacking any transition and usually the outer surface of the gibbsite body (plate, column, irregular lump) is remarkably smooth. On a larger scale the transition may occur over a vertical distance of up to several metres, with 'roots' of gibbsite concretionary structures into the saprolite, and protuberances or diapirs of kaolinite material into the (incipient) lateritic horizon. The result may be a jagged contact between kaolinitic saprolite and (aluminous) laterite with its inherent problems of quality control during the eventual mining of an ore-grade laterite.

(iii) In places a sharp and often remarkably rectilinear contact between saprolite and laterite has been observed in both the weathering profile of more or less horizontally layered or bedded sedimentary parent rocks, as well as in profiles over massive igneous parent rocks. In the first case the sharp contact is directly related to physical lithological differences, such as permeability and porosity, between sedimentary layers or beds, which have become exagerated during the change from kaolinite to gibbsite. The abrupt contact of e.g. a leucogabbroic parent rock saprolite and the overlying aluminous laterite is difficult to explain but has been frequently observed e.g. in the Bakhuis mountains, Suriname – see photograph of figure 3.

(iv) The laterites of the type locality (Angadipuram, Kerala State, India – BUCHANAN, 1807) and the thick weathering profiles of similar nature elsewhere in Kerala State must possibly by considered as laterite horizons in statu nascendi, where the second weathering front attains several metres in thickness. The kaolin-gibbsite transformation apparently takes place over the full thickness of the horizon under the influence of very generous rainfall.

Above the second weathering front is the most intensively weathered zone of the whole weathering profile, i.e. the laterite horizon in which considerable enrichment of the sesquioxides Fe and Al occurs. In many places and at least partly the result of parent rock chemical composition, there is a distinct partition between an iron-rich upper zone with mainly goethite or hematitie or both, and a lower zone with

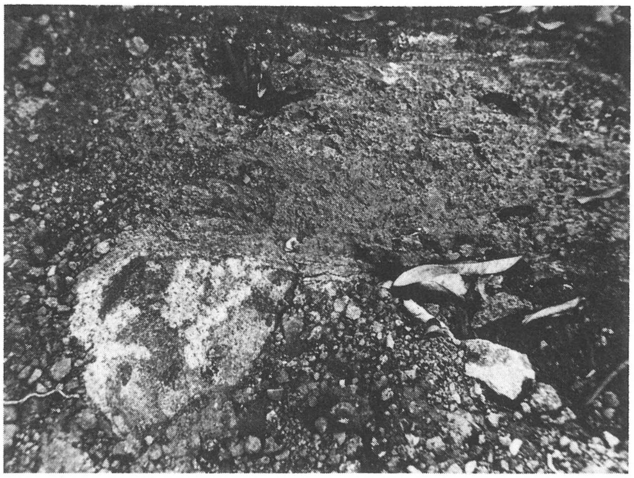

Fig. 3
Rounded block of fresh parent rock (leucogabbro) directly surrounded by aluminous laterite without a transitional kaolin-rich zone. Bakhuis Mts., Suriname. The same sharpness of contact has been observed in prospecting pits between clayey saprolite and overlying laterite.

mainly gibbsite and subordinate amounts of boehmite. There is good evidence that the aluminium enrichment is considerably more autochthonous in nature than the iron enrichment, while iron originally present may have been removed almost quantitatively by later soil and groundwater processes. The high mobility of iron in the weathering profile is ubiquitous and this is often highly confusing in the study of laterite and bauxite genesis. Some examples may illustrate this feature.

(i) Relict structures in laterites are generally composed of gibbsite material, while the iron (hydr)oxide phase occurs either as a crystalline coating of the gibbsite structure or in irregular masses, layers and void fillings with a fine, almost rhythmic layering.
(ii) In landscapes that contain a series of planation surfaces, with each lower one of later origin, it can be observed in several regions that the highest planation surfaces contain more aluminous laterites than the lower ones which are all but pure goethite (hematite) deposits of an infiltration nature (GRANDIN, 1976, in West Africa; ALEVA, 1970, Bakhuis Mountains, Suriname, South America).
(iii) In the Coastal Plane of Suriname, the Eocene-Early Oligocene lateritic bauxite is derived from Paleocene-Early Eocene sedimentary parent rocks that formed a thin veneer on the Precambrian Guiana Shield. Downwarping of the northern edge of the Shield resulted in the subsidence below sea-level of part of this lateritic cover and the transgressive deposition of Miocene and younger sediments. The aluminous laterites or iron-rich bauxites covered by these younger sediments (partly marine and partly terrestrial in nature) have lost most of their iron-rich upper zone (ferrite cap) through solution and transport of the iron phase (ALEVA, 1965).

During the study of laterites – and in defining the rock to be called laterite – care must be taken to identify the role of the iron component. In many places it is purely allochthonous; the iron compounds in the weathering profile seem to have their own history, quite frequently independent from that of aluminium (oral communication, MAIGNIEN, 1982; MAIGNIEN, 1966).

The thickness of the true autochthonous laterite horizon is highly variable, thicknesses of over 12 m are not uncommon (Suriname; Darling Range, West Australia). Other very thick aluminous laterites are almost certain, at least partly, of detrital origin, i.e. eroded and deposited after transport as clastic laterite particles.

The laterite horizon is originally covered by a mostly thin soil horizon. In most places, however, laterite is the hardest and most erosion resistant material in the deeply, chemically weathered landscape, resulting in laterite controlled plateaux and escarpments. In all but the youngest such plateaux all original soil cover has been removed from the laterite horizon; this is in particular true for the older laterites now covering the highest topographic culminations and divide areas in the landscape. The top of the laterite horizon is the ultimate denudation level in the saprolite-laterite profile.

DISCUSSION

Time, the fourth dimension, has not yet been taken into account in the foregoing paragraphs. Weathering and denudation are processes that proceed from the earth's surface downwards, they are geopetal. The downward progress of these simultaneous, successive or overlapping processes cannot generally be expected to proceed with equal speed. The rate of downward progress is largely dependent on characteristics such as parent rock chemistry, porosity and permeability, the local and regional aspects of drainage, the topography of the area under study, and the climatic history of the area.

The following examples illustrate the mutual relations of weathering and denudation, and their variability on a very local as well as on a regional scale.

(i) In Belitung Island, Indonesia, the primary cassiterite occurrences are related to relatively acid and alkaline granites, hence detailed mapping and petrographic studies of these granites is a first priority for tin exploration. During the search for fresh rock outcrops it was observed that fresh granitic bedrock was sticking through the ubiquitous saprolite mantle (generally 5-15 m thick, locally much more) at two types of locations only: at the culmination of the interfluve areas and at the convex break in slope from the interfluve into the numerous valleys. Except for the major divide ridges marked by larger monadnocks and inselbergs, the countryside as a whole is characterized by a gentle outward sloping plane (old planation level?) relatively recently incised by a partly consequent and partly fracture pattern determined valley system. Laterites are of scarce occurrence in granite underlain areas although argillite bedrock areas in many places are overlain by well developed laterite caps topping the generally thin saprolite horizon. Rather similar situations have been observed in Rondônia, Brazil, roughly 2000 km inland from the Atlantic Ocean along the Amazon and tributary rivers.

(ii) The Bakhuis Mountains in Suriname are a group of flat-topped hills composed of granogabbroic and anorthositic igneous rocks and high metamorphic rocks of enderbitic and gneissic composition; these hills are the inselberg remnants of a presumably Late Cretaceous-Early Tertiary planation level (Sul Americano as it is known in Brazil). Most of the flat-topped hills are covered with a locally aluminous laterite, followed downwards by a sticky clay saprolite up to several tens of metres thick which overlies the fresh bedrock. Locally, however, the laterites are directly overlying fresh bedrock while in other places loose blocks, measuring from a few dm^3 to several m^3 in volume, of fresh bedrock are found within the laterite horizon a few metres below the surface – see figure 3. There is a distinct preference for these fresh bedrock occurrences to occur along the rounded edge of the plateau top of the hills.

(iii) Poços de Caldas, Minas Gerais – Brazil, is a circular alkaline plug with a surface expression described as a caldeira. The parent rock of the ubiquitous aluminous laterites are phonolites, tinguaites and foyaites. The weathering profile from the surface downwards is in general laterite – saprolite – fresh parent rock, but locally the laterite is directly in contact with the fresh parent rock, either as loose blocks or as true bedrock piercing through the laterite blanket almost to the surface. It is in many places clearly visible that these fresh parent rock occurrences are of a finer grain size than the parent rock of the surrounding laterites, as these exhibit a distinct primary relict texture of coarser grain size. The other observation of interest is the distinct relict structure (fracture pattern) and relict texture (hypidiomorphic granular to trachytic) exhibited by the laterites, while the underlying saprolite is a dense, massive clay without structures or textures.

These examples illustrate the variety of profile development that can occur during chemical weathering; they can be summarized as follows:

- each higher weathering and denudation front may catch up and overtake the lower ones (the surfacial denudation level will proceed very slowly where the laterite horizon is capped with an indurated layer);
- the formation of saprolite and laterite, per unit of time, are strongly dependent on the parent rock composition, physically and chemically;
- saprolites and laterites seem to have independent existances; saprolite may be formed or continues to be formed, below an already existing laterite cap, elsewhere laterite appears as a cap on saprolite as if it were an intensification of the saprolite weathering process;
- saprolite and laterite preferably develop on relatively flat slightly sloping and horizontal areas (on steeper slopes the weathering products are removed by mechanical erosion directly after their formation);
- in many places the formation of saprolites and laterites must be polyphase due to the frequent changes in climate since the Late Cretaceous.

ACKNOWLEDGEMENTS

The above summary of my experience with and ideas on tropical weathering is the result of many years of observations and many interesting discussions with colleagues within and outside Billiton International Metals B.V., Leidschendam, my former employer. In particular, discussions with the delegates to the Second Seminar on Lateritization (IGCP Project 129) in Sâo Paulo, Brazil, in July 1982 has prompted me to write down this contribution; however, this does not absolve me of any responsibilities with respect to the ideas set forth. The Management of Billiton International Metals B.V. is thanked for the opportunities given to attend both Seminars of the IGCP Project 129.

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