EVOLUTION OF REGOLITHS AND LANDSCAPES IN DEEPLY WEATHERED TERRAIN— IMPLICATIONS FOR GEOCHEMICAL EXPLORATION

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ABSTRACT

Thick, commonly lateritic regoliths are widespread in inter-tropical regions of the world, and present particular challenges in exploration. These are best tackled through a sound understanding of the evolution of the landscapes in which they occur. The regoliths formed under humid, warm to tropical conditions and, although they may have been modified by later climatic changes, i.e., to more humid or more arid conditions, many chemical and mineralogical characteristics are retained. These include the geochemical expressions of concealed mineralization. Erosional and depositional processes control the preservation and occurrence of specific regolith units that may be used as sample media and, in turn, target size, element associations and contrast, thereby influencing sampling procedures, analysis and data interpretation. These parameters are best summarized in terms of geochemical dispersion models based on the degree of preservation of the pre-existing lateritic regolith. Regolith-landform mapping permits an assessment of the terrain in terms of such models. In relict regolith-landform regimes, in which the lateritic regolith is largely preserved, broad multi-element anomalies in the upper ferruginous horizons (lateritic residuum) can be detected using sample intervals of 1 km or more. In contrast, in erosional regimes, where this material is absent, anomalies in upper saprolite, and the soil and lag derived from it, are more restricted in area, and closer sampling intervals, (200 × 40 m or less) may be necessary. Lag and soil are generally ineffective in depositional areas, except where the sediments are very thin (e.g., <2 m) or overburden provenance can be established. Stratigraphic drilling is necessary to establish whether the overburden overlies a buried lateritic horizon or an erosion surface cut in saprolite. Lateritic residuum remains an excellent sample medium if present, again with widespread haloes, but where it is absent, leaching and the restricted haloes in upper saprolite present formidable problems. Ferruginous saprolite or composites across the unconformity may be effective, but otherwise carefully targeted drilling and sampling through saprolite and saprock may be necessary. Partial extraction analyses have yet to demonstrate significant results except in very specific environments. In arid regions, pedogenic carbonate (calcrete, caliche) may be a valuable sample medium for Au exploration, principally in erosional regimes, and in depositional areas where the overburden is shallow. Sample intervals range from 1 km for regional surveys, through to 100 × 20 m in prospect evaluation. Saprolite is an essential sample medium in all landform environments, but the restricted halos and possibility of leaching requires that drilling and sampling should be at close intervals.

INTRODUCTION

Deep regoliths, consisting of weathered bedrock, possibly with an overlying cover of transported overburden, are widely distributed, mainly in the present tropics and subtropics. The presence of this regolith presents numerous exploration problems and opportunities, affecting geological, geophysical and geochemical mapping and exploration techniques. Although these deeply weathered terrains now occur in a wide variety of climatic environments ranging from humid to arid, tropical to temperate, they were formed under broadly similar conditions in the past which have resulted in them having many petrographic, mineralogical and geochemical characteristics in common. The processes of weathering and regolith formation are the same as those of geochemical dispersion. In consequence, many features of the surface expression of mineraliza-

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tion in these terrains, and the exploration procedures used for their detection, are also similar. In this paper, the development and characteristics of deeply weathered terrains are described, and discussed in terms of their implications for mineral exploration.

DISTRIBUTION AND EXPLORATION SIGNIFICANCE OF DEEP WEATHERING

Deeply weathered, commonly lateritic, regoliths are widespread in the inter-tropical belt, particularly on the continental landmasses between latitudes 35°N and 35°S. Similar features are observed at much higher latitudes, for example, 35–42°S in southeast Australia (Victoria and Tasmania), 40–45°N in the United States (Oregon and Wisconsin) and 55°N in Europe (Northern Ireland, Germany), although these are not regionally extensive. The thickness of the regolith, which encompasses weathered residuum and continental sediments overlying basement rocks, varies from a few metres to over 150 m, depending on the age of the land-surface, tectonic activity, climate, climatic history and the nature of the bedrock. In parts of Africa, India, South America, southeast Asia and Australia, the regolith has been forming continuously for over 100 million years, evolving and continuing to evolve under various climates ranging from humid to semi-arid, tropical to temperate. Indeed, parts of the Precambrian Shield of Western Australia may have been exposed to sub-aerial conditions since the Late Proterozoic (Butt, 1989a,b). The regolith, and landforms in which they occur, are an expression of the cumulative effects of this long weathering history. Accordingly, the petrophysical, morphological, mineralogical and geochemical characteristics of the regolith are commonly profoundly different than those of the rocks from which they were derived, and give rise to numerous exploration problems. These affect geophysical and geochemical procedures and apply a number of constraints on their use. Conversely, deep weathering causes the formation of many important secondary and supergene ores, notably bauxite, some Fe ores, lateritic Ni-Co(-Mn), lateritic and saprolitic Au, supergene Cu, surficial U, heavy minerals in residual accumulations and placers, and industrial and building materials.

The usefulness of many geophysical techniques is constrained in regions having extensive deep weathering. Apart from the obvious effect of increasing the distance between the sensor and the target, problems associated with the use of specific techniques include:

1. Magnetic surveys. The concentration of resistant magnetite and secondary maghemite in lateritic duricrusts and gravels mask magnetic and electromagnetic responses from bedrock sources. Conversely, detrital magnetic gravels in depositional areas give spurious anomalies.
2. Electrical methods. The low resistivity of the overburden (10–50 ohm-metres), saline ground waters (in arid areas) and resistivity contrasts within and at the base of the regolith, screen the target from electromagnetic (especially frequency-domain) and induced polarization techniques and superimpose spurious signals.
3. Seismic and gravity surveys. The complex zonation, transitional contacts and density contrasts of the regolith attenuate responses and/or give false anomalies in shallow seismic and gravity surveys.
4. Radiometric surveys. Transported overburden may suppress or eliminate radiometric responses; false anomalies may be produced by the separation of U from its daughter products by ongoing weathering.

These particularly affect exploration at the prospect scale, so that geophysical procedures appear to be most appropriate for regional appraisal and area selection. Remote sensing, gravity, radiometric and, in particular, airborne magnetic surveys indicate broad scale geological and structural features in all terrains. However, because the limitations on geophysical techniques are due to specific properties of the regolith, some research is now focussing on their use in mapping the distribution of regolith materials.

Many geochemical procedures, utilizing soil and other regolith materials as sample media, are most valuable for exploration at sub-regional to local scales, although laterite residuum and calcrete (caliche) sampling have importance for regional sampling. Where there is a connected drainage, reconnaissance and regional stream sediment surveys can be used for general appraisal and area selection. However, the evolution of the terrain and the development of the regolith give rise to several problems that may hinder their effective application. These include:

1. profound mineralogical, chemical and physical alteration of bedrock and associated mineralization, so that distinctions between even broad lithological classes is difficult;
2. strong leaching of most ore-related elements (e.g., Cu, Au, Zn), particularly from upper horizons of the regolith, resulting in only subtle surface expression of mineralization;
3. the development of spurious secondary concentrations of target elements in weathered, unmineralized rocks;
4. lateral changes in the nature of the regolith, due to variations in the depth of truncation of earlier, pre-existing profiles by the present erosional surface;
5. the presence of a cover of transported overburden, which may itself have been weathered after deposition;
6. the superimposition, in a single profile, of the effects of weathering under different environmental conditions.

Effective geochemical exploration can only be achieved by the recognition of these problems and other properties of the terrain, and by the selection of sampling and data interpretation techniques appropriate to the target being sought.

FORMATION OF DEEPLY WEATHERED REGOLITHS

Environmental conditions

Conditions for the formation of deeply weathered, lateritic regoliths are considered to be:

1. long periods of tectonic stability. Net weathering rates of 20 mm/1000 years (20 m per million years) suggest that deep regoliths require several million years to develop (Nahon and Tardy, 1992), and that landscapes characteristic of a climate require up to 10^7 years (Budel, 1982). Significant tectonism will promote instability and hence erosion of the regolith.
2. moderate relief. For a deep regolith to form, the rate of chemical weathering and downward progress of the weathering front must exceed the rate of erosion. The relief must be sufficient for there to be adequate drainage to allow leaching of the products of chemical weathering.

3. humid tropical to (possibly) temperate climate, probably seasonal (savanna or Mediterranean). The interpretation of the tropical origins of landforms and lateritic regoliths, especially in the higher latitudes, is not universally accepted. However, since the effect of temperature is largely kinetic, higher temperatures merely enable reactions to occur more rapidly. Deep weathering may occur in cooler climates, but over longer periods of time.

The principal effects of deep lateritic weathering on element distributions are outlined in Table 1, which relates leaching and retention of a range of elements to mineral transformations in the principal regolith horizons (derived from Butt *et al.*, 1991; Butt and Zeegers, 1992, and references therein). This summary is, of course, a gross simplification and it must be noted that no mineral is entirely unaffected by weathering, no element is entirely leached from any regolith horizon and no element is entirely immobile.

Table 1: ***Element mobility during weathering (derived from Butt et al., 1991; Butt and Zeegers, 1992, and references therein). Mobility under dominantly humid conditions.***

Host minerals	Leached	Partly retained in secondary minerals
Released at weathering front:		
Sulphides:	As, Cd, Co, Cu, Mo, Ni, Zn, S	As, Cu, Ni, Pb, Sb, Zn (Fe oxides)
Carbonates:	Ca, Mg, Mn, Sr	
Released in the lower saprolite:		
Aluminosilicates:	Ca, Cs, K, Na, Rb	Si, Al, (kaolinite); Ba (barite)
Ferromagnesians (pyroxene, olivine amphiboles, chlorite, biotite)	Ca, Mg	Fe, Ni, Co, Cr, Ga, Mn, Ti, V (Fe and Mn oxides)
Released in upper saprolite:		
Aluminosilicates (muscovite)	Cs, K, Rb	Si, Al (kaolinite)
Ferromagnesians (chlorite, talc, amphibole)	Mg, Li	Fe, Ni, Co, Cr, Ga, Mn Ni, Ti, V (Fe oxides)
Smectites	Ca, Mg, Na	Si, Al (kaolinite)
Released in the mottled and ferruginous zones:		
Aluminosilicates (muscovite, kaolinite)	K, Rb, Cs	Si, Al (kaolinite)
Iron oxides	Trace elements	
Retained in stable minerals:		
B, Cr, Fe, Hf, K, Nb, Rb, REE, Th, Ti, V, W, Zr		

Weathering front and saprock

Sulphides are some of the most unstable minerals in humid, oxidizing environments and only persist high in the profile if preserved within vein quartz. This is consistent with observations that S has been strongly leached from the deepest levels of the regolith and appears to be the element most susceptible to weathering. Many elements hosted by sulphides (e.g., Cd, Co, Cu, Mo, Ni, Zn) are also commonly strongly leached deep in the profile, although a proportion is retained in Fe oxides derived from the sulphides. Carbonates are similarly highly susceptible to weathering, especially in acidic environments, hence elements dominantly or significantly hosted by them, such as Ca, Mg, Mn and Sr, are strongly leached. Calcium and Sr, for example, are thus commonly reduced to very low concentrations throughout most of the regolith.

Lower saprolite

Weathering in the lower saprolite causes the destruction of feldspars and ferromagnesian minerals. Sodium, Ca and Sr are leached from the former, with Si and Al retained as kaolinite and halloysite. (Smectites may be intermediate products but are usually only retained in less freely-drained or more arid environments.) In addition, K, Rb and Cs will be lost if hosted by orthoclase or biotite but, if present mainly in muscovite, concentrations are maintained or residually increased through much of the regolith. Barium, commonly hosted by feldspars, is released early during weathering, but is reprecipitated as barite, which remains stable through the regolith and is only partly leached in the duricrust. Weathering of less stable ferromagnesian minerals (pyroxene, olivine, amphibole, biotite) results in the formation of Fe oxides, partial retention of minor and trace elements such as Ni, Co, Cu, Mn and Ni, and progressive loss of Mg and Si, except where retained in smectite (Mg, Si), kaolinite (Si) or quartz (Si).

Mid- to upper saprolite

The alteration of all but the most resistant primary minerals occurs in these zones; in addition, less stable secondary minerals such as smectites are also destroyed. Serpentine and chlorite are progressively weathered through the zone, but talc and, in particular, muscovite may persist through to the mottled clay zone and, in places, to the duricrust. Ferromagnesian minerals are the principal hosts for transition metals such as Ni, Co, Cu and Zn in sulphide-poor mafic and ultramafic rocks and are retained higher in the profile than sulphide-hosted metals. Nevertheless, they become leached from the upper horizons and reprecipitate with secondary Fe-Mn oxides in the mid- to lower saprolite. Some leaching and redistribution of Ni, Co and Mn is probably related to post-lateritic periods of lower water tables.

Mottled and ferruginous zones

Most remnant major primary minerals, except quartz, are commonly finally destroyed in these horizons, as is the primary fabric of the rocks. These horizons, in particular, demonstrate one of the principal characteristics of lateritic regoliths, namely domination by Si, Al and Fe, resident in kaolinite, quartz, Fe oxides (hematite and goethite) and, in places, gibbsite. The abundances and distributions of Si, Al and Fe broadly reflect their source lithologies. Thus, kaolinization of saprolites is strongest over the felsic rocks, and only tends to be well developed in the upper saprolite over mafic and ultramafic rocks. Although some dissolution can occur in ferruginous zones, quartz is commonly only slightly weathered and most is left as a residual, resistate mineral, most abundantly over felsic igneous rocks and quartzose sedimentary rocks. The ferruginous horizon (*lateritic residuum*) is commonly most strongly developed over ultramafic and mafic rocks, tending to be thinner, less ferruginous and less strongly cemented over other lithologies and almost absent over granitoids. Accumulation, partial dissolution and recrystallization of Fe oxides in lateritic residuum results in the development of a variety of secondary fabrics (e.g., pisoliths, nodules, vermiform voids) and the replacement of other minerals, particularly kaolinite. Released Si and Al either reprecipitates as kaolinite, e.g., in the mottled clay horizon, or is leached.

The distributions of several minor and trace elements are controlled wholly or in part by the distribution of these major elements, due to substitution or co-precipitation. Thus, Cr, As, Ga, Sc, V and, possibly, Au, tend to accumulate with Fe oxides; Cr, mainly derived from ferromagnesian minerals, is also associated with neo-formed kaolinite. Many resistate and immobile elements also tend to concentrate with Fe oxides in the lateritic horizons although, for most, no chemical interactions are involved. Thus, the distributions of Cr, K, Zr, Hf, Th, Nb, Ta, W, REE, Ti and V relate wholly or in part to their inertness during weathering, which is due to their relative chemical immobility (e.g., V, Ti) and/or to the stability of their primary and/or secondary host minerals (e.g., Zr and Hf in zircon; Ti in rutile and anatase; Cr in chromite; K in muscovite). Their abundances tend to increase upwards through the profile due to the gradual loss of other components, with marked accumulation in lateritic residuum, within which lateral dispersion by colluvial action can occur during the course of profile evolution.

Table 2: ***Effects on the lateritic regolith of changes from the conditions of formation.***

A. Tectonic activity	
Uplift	lowering of the water table; irreversible dehydration and hardening of ferruginous and siliceous horizons; increased leaching of upper horizons under more oxidizing conditions; increased erosion.
Downwarping	waterlogging of lower parts of the landscape and imposition of reducing conditions; decrease in erosion, increased sedimentation in valleys.
B. Climatic change	
To a more humid climate	increased leaching and deeper soil development; decreased erosion (due to thicker vegetation).
To a less humid climate	decreased leaching; increased erosion.
To a semi-arid or arid climate	decreased leaching; retention and precipitation of silica, alkaline earths and alkalis in silcretes, clays, calcretes, salts; increased erosion.

EVOLUTION OF REGOLITHS DUE TO ENVIRONMENTAL CHANGE

Chemical modifications

Changes from the conditions of formation may affect the composition and petrography of lateritic regoliths but, in general, many properties remain. The intense alteration occurring during deep weathering results in regoliths being composed of only the most stable secondary minerals (kaolinite, gibbsite, Fe oxides) and the most resistant primary minerals. These minerals are largely unaffected by change to less humid or less severely leaching conditions, and hence the broad chemical characteristics of the regolith are retained, except for those due to pedochemical modification at the surface. In drier climates, continued weathering at the base of the profile does, however, result in rather different mineralogy, especially the development of 2:1 lattice clays (e.g., smectites) and, in semi-arid and arid environments, retention and accumulation of components such as alkali and alkaline earth elements and silica. Duricrusts, formed by the exposure and irreversible hardening of ferruginous laterites, or the later precipitation of Fe oxides, silica and carbonates, are important in armouring and protecting the regolith from erosion. The principal chemical modifications of the regolith due to changes from the conditions of formation are summarized in Table 2. An understanding of the geochemical significance of these modifications is essential for the correct interpretation of exploration data. Dispersion patterns associated with these later episodes are superimposed upon those inherited from the past and together give rise to the present expression of mineralization in the regolith.

In humid climates, regolith modifications are largely those related to intensified leaching of surface horizons, due either to increased rainfall, or to better drainage following uplift (Table 2). This may result in desilication and gibbsite formation, and further reductions in trace element abundances. Overall, modifications are probably greater in arid climates, where precipitation of silica and carbonates can significantly alter the bulk chemical and mineralogical composition of some horizons of the profile, and ground waters may have greatly increased total dissolved solids contents. Although geochemical dispersion in arid environments is generally considered to be dominated by mechanical processes, it is evident that, particularly where there is an extensive deep regolith, there is significant chemical (hydromorphic) mobility of many ore-related trace elements in groundwater and soil environments, including U and V (Mann and Deutscher, 1978), Cu, Pb and Zn (Mann, 1983), Au (Mann, 1984; Gray *et al.*, 1992; Gray and Lintern, 1994) and rare earth elements (Gray, 1993).

Erosional modifications and geochemical models

Tectonic activity and climatic change commonly result in partial erosion of the regolith. The resultant landforms are broadly similar across different climatic zones, so that deeply weathered landscapes in semi-arid regions have many similarities to those in the humid tropics. The genetic links between regoliths and landforms of these terrains form the basis for exploration models that describe geochemical dispersion and permit comparisons across regions and climatic zones (Butt and Smith, 1980; Butt and Zeegers, 1992). The models correspond to landform units defined and classified according to the degree of stripping, their relationship to the regolith, the presence of transported overburden and the relief (Butt and Zeegers, 1992). The most important subdivision of the models relates to the degree of preservation of the pre-existing lateritic profile, because this largely determines the importance of geochemical and mineralogical characteristics, such as enrichments of Al, Fe, Ni and Au, and depletions of Na, K, Ca, Mg, Cu and Zn, inherited from previous weathering episodes. The degree of preservation also determines the nature of the uppermost residual horizon, whether modified as soil or buried beneath transported overburden. "A" type models are those in which the profiles are fully preserved. The uppermost residual horizon is commonly the lateritic ferruginous horizon, or soils developed over or from it. "B" type models are those in which profiles are partially truncated by erosion, so that saprolite, with quite different geochemical characteristics from the ferruginous horizon, forms the uppermost horizon and the parent material of residual soils. "C" type models are those in which the earlier regolith has been entirely eroded and bedrock is buried by transported overburden, outcrops at surface or has residual soils forming directly from it.

REGOLITH-LANDFORM CONTROL ON GEOCHEMICAL EXPLORATION PRACTICE

Regolith-landform mapping

The formation and modification of lateritic regoliths and the effects of erosion during and after these events results in significant regolith-landform control on sample media. This is expressed in terms of the basic models described above, hence determination of the appropriate exploration model, even at a general, informal level, is an essential prerequisite for effective exploration of these terrains. This is best achieved by regolith landform mapping. A *regolith-landform mapping unit* is defined as an area delineated on a map which occurs as a specific association of regolith materials, landform and, possibly, bedrock geology. It may consist of multiples or subdivisions of tones, textures, patterns and/or multispectral images visible in aerial photographs, satellite imagery or radiometric data. The units thus interpret landforms in terms of the nature and origin of the substrate (i.e., the regolith), and can be applied at prospect, district and regional scales. The more detailed the scale, the closer the units relate to regolith variations. The first step is always to make an objective map of the units present. Because lateritic residuum (gravels and duricrust) is an important geochemical medium, it is important to establish its presence or absence; additionally, areas of substantial transported overburden need to be established, since this will be expected to mask, or severely subdue, any surface geochemical expression of mineralization. At the simplest level of mapping, therefore, these two important boundaries need to be established and, from them, the basic regolith-landform regimes can be interpretatively mapped as relict, erosional and depositional (Anand *et al.*, 1993). The *relict* regime consists, conceptually, of relicts of an ancient weathered surface and may be characterized by widespread preservation of lateritic residuum. An *erosional* regime is one in which the pre-existing regolith profile has been truncated, so that the mottled, zone, saprolite or fresh bedrock are exposed or concealed beneath either soil developed from them or a thin (<1.0 m) mantle of locally derived sediment. A *depositional* regime is characterized by widespread sediments that may be many metres thick and which may conceal a complete or partially or wholly truncated residual weathering profile. Appropriate geochemical models can thus be deduced for the relict (A models) and erosional (B or C models) regimes, whereas in depositional areas, further information is required by drilling in order to establish the model from the degree of preservation of the concealed residual regolith. The relationship between these mappable regolith-landform regimes and geochemical models is illustrated in Figure 1. Broadly similar regimes and models apply across many deeply weathered terrains. However, due to the incompetence of the drainage in arid regions, erosion products are retained in the landscape as transported overburden, hence depositional units are much more extensive. Having established the model type, some broad characteristics of the geochemical expression of mineralization can be predicted and can be used to design sampling strategies. Many such predictions will be valid across quite diverse climatic environments and for regions in which there is little or no existing information. More detailed aspect of dispersion, however, will be regionally specific, and their description requires models based on appropriate orientation and case studies. The use of different sample media, some specific to particular regolith-landform regimes and units, is described below.

Geochemical response in different sample media

Lateritic residuum

Lateritic residuum is a collective term that refers to the uppermost ferruginous zone of the regolith where this has developed essentially *in situ* and consists of units of duricrust and/or loose gravels. The presence of lateritic residuum is an essential characteristic of landscapes represented by A-type dispersion models. Because lateritic regoliths are developed on undulating surfaces, such models may represent sites ranging from upland plateaux, and slopes to lowland plains and valleys. Lateritic residuum may occur at or close to the surface in relict landform regimes or buried in depositional regimes.

As a consequence of land-surface reduction during lateritization, a variety of relatively resistant materials are residually incorporated in lateritic residuum. These include partly weathered ferruginized and/or silicified lithorelics, resistant primary minerals, Fe oxide segregations such as those formed in the mottled zone and, possibly, gossan fragments derived from oxidized sulphides. Residual accumulation, combined with mechanical and hydromorphic dispersion, results in widespread dispersion haloes related to concealed ore deposits being contained within the lateritic residuum, merged with geochemical patterns arising from the host and country rocks. The haloes tend to be large relative to the mineralized source, typically 100–400 times larger in area than the deposits from which they have been derived (Smith *et al.*, 1997). Sampling of lateritic residuum can thus be useful for reconnaissance surveys through to early stages of prospect evaluation. *Regional sampling* should be directed at the upper pisolitic laterite, rather than at the mid- to lower duricrust, in order to utilize the maximum extent of mechanical and hydromorphic dispersion and the most homogeneous geochemical signatures. However, in humid regions, strong surface leaching may necessitate sampling at depths of 1–2 m. Sample intervals of 1 km to as much as 3 km can be used for reconnaissance surveys, particularly where large deposits are sought or expected. Sampling for *prospect evaluation* should be directed progressively to lower horizons of the duricrust to reduce the influence of mechanical dispersion, at intervals of 400 m closing, as exploration progresses, to 100 m or less for the delineation of drilling targets. In the absence of lateritic residuum,

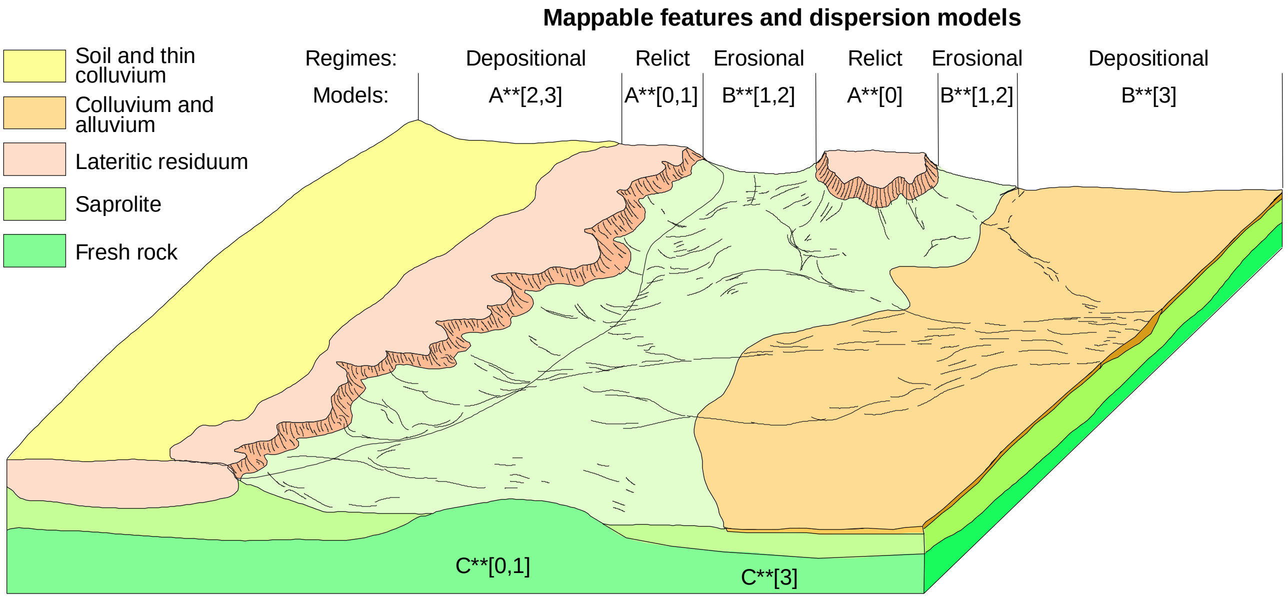

Figure 1: *The relationship between mappable regolith-landform regimes and geochemical models. Model codes (see text) refer to presence of lateritic regolith: A, preserved; B, partially truncated; C, absent. Surface: [0], outcrop; [1], residual soil; [2], semi-residual soil; [3], transported overburden (after Butt and Zeegers, 1992).*

in areas represented by B-type models, ferruginous saprolite is an alternative sample medium, particularly for prospect evaluation.

Laterite geochemistry has been applied successfully in the Yilgarn Craton of Western Australia in exploration for base metals (Smith and Perdrix, 1983), Au (e.g., Smith and Anand, 1992) and for detecting metallogenic provinces (Smith *et al.*, 1989). The lateritic residuum may be at surface, in relict regimes, or buried by 20 m or more of transported overburden, in depositional regimes. Abundances of mobile chalcophile elements, such as Cu, Ni and Zn, may be low relative to those in the primary mineralization, and recognition of anomalies derived from base metal deposits may depend on the presence of pathfinder elements such as Sn and Bi. Gold mineralization generally yields strong anomalies in lateritic residuum, commonly of ore grade, supplemented by patterns in elements such as As, W and Sb. Broadly similar approaches are appropriate to equivalent terrains elsewhere. Equivalent, widespread, Au anomalies have been reported in lateritic residuum, or soils developed from it, in, for example, Mali (Freyssinet, 1993), Gabon (Lecomte and Colin, 1989) and Brazil (Lima da Costa *et al.*, 1993); Freyssinet *et al.* (1989) reported a similar multi-element anomaly in Cameroun. The use of lateritic residuum in exploration is discussed fully by Smith *et al.*, 1997.

Soil

Soil sampling is very widely employed in exploration in deeply weathered terrain. Soils are developed from the underlying substrate, in response to present-day climatic and drainage conditions. The geochemical response, and the success of the technique, thus strongly depend upon the composition of the substrate which, in turn, is determined by the regolith-landform setting. In relict regimes, the soil composition reflects that of the lateritic residuum, and dispersion patterns will be very similar. However, contrasts may be strongly reduced due to further leaching during soil formation and/or to dilution by transported material (e.g., aeolian dust). Accordingly, it is probably more appropriate to sample lateritic residuum, rather than the soil. Alternatively, the coarse fraction of the soil may be a suitable compromise, since it commonly consists of lateritic debris. In rainforest environments, where such debris is absent, leaching results in smoothed, homogeneous anomalies of very low contrast (Lecomte and Zeegers, 1992).

In erosional regimes, which are represented by B- and C-type dispersion models, or residual areas where lateritic residuum has not developed, soils are derived from saprolite and fresh rock, respectively. Dispersion haloes are generally limited to a few metres or tens of metres from the subcrop. This dispersion is greater than in the saprolite itself and, depending upon the degree of truncation of the profile and extent of past and present leaching, contrasts tend to be greater than in lateritic residuum. Soil sampling is thus very effective in erosional areas, particularly for prospect evaluation. Although regional sampling at intervals of 1600 × 500 m has been successful, particularly in the humid tropics, the restricted dispersion commonly requires sampling at 20–40 m intervals on lines 100–200 m apart. The requirement to confirm optimum sampling horizons, size fractions and intervals by orientation cannot be overemphasized.

Inadequate understanding and mapping of deeply weathered terrains has resulted in extensive soil sampling in depositional regimes. Here, transported overburden forms the soil parent material, so that, in the absence of effective hydromorphic or mechanical (e.g., bioturbation) dispersion, there is little chance of a surface expression of buried mineralization, whether the underlying residual lateritic regolith is complete or partially or wholly truncated. Where the cover is thin (<2–5 m), there may be some expression of concealed mineralization (see calcrete sampling, below), but in general, soil sampling is inappropriate in depositional regimes. A range of partial extraction analyses have been promoted to detect subtle hydromorphic anomalies in soils in such areas, but these generally show similar patterns to total analysis and/or give false positive anomalies and have yet to demonstrate significant results except in very specific environments.

Lag sampling

Lag is the residual accumulation of coarse, usually hard, fragments that accumulate at the surface in semi-arid terrains and some dry savannas. They have been left as a residue after the physical and chemical dismantling of the upper horizons of the regolith and the removal of fine materials in solution or by sheetwash or wind, supplemented by particles moving upwards, e.g., by churning. It is most useful as a sample medium when the fragments are lateritic in origin, and consist of pisoliths, nodules, hardened mottles or fragments of ferruginous saprolite. Lag sampling is most appropriately employed in erosional areas, especially where the pre-existing regolith has not been deeply truncated and there is an abundance of ferruginous fragments. Here, lag may give broader anomalies than the soils due to mechanical dispersion at the surface. Thus, Carver *et al.* (1987) found that lag (2–6 mm) collected on a 400 × 50 m grid gave a Au anomaly of 1.7 km^2, compared to 0.5 km^2 in soil (minus 6 mm), both defined by the 5 ppb contour.

Lag (1 kg sample) may be swept from the surface and is best sieved to reject both fine transported material and coarse fragments. Generally, finer materials (2–6 mm) are used than for lateritic gravel sampling, but they tend to be less homogeneous so that data may need to be normalized for Fe content. Alternatively, greater homogeneity may be obtained by collecting the magnetic fraction of the lag, preferentially concentrating maghemite-rich nodules and resistant magnetite. However, this eliminates non-magnetic, hematitic and goethitic materials, including gossan fragments, which may be the principal hosts for trace metals (Robertson, 1997).

Except for ease of sampling, lag sampling offers little or no advantage over laterite or (coarse fraction) soil sampling in relict areas and, indeed, may be much less satisfactory if the lag is derived from a veneer of transported material. As for soil, lag is generally an inappropriate sample medium in depositional areas, except where the transported cover is thin (<2 m) and bioturbation has brought fragments of lateritic residuum to the surface. The compositions of lag, soil and overburden reflect that of their provenance, not the underlying bedrock. Where the provenance can be established, lag may be useful for regional sampling, equivalent to drainage sediments.

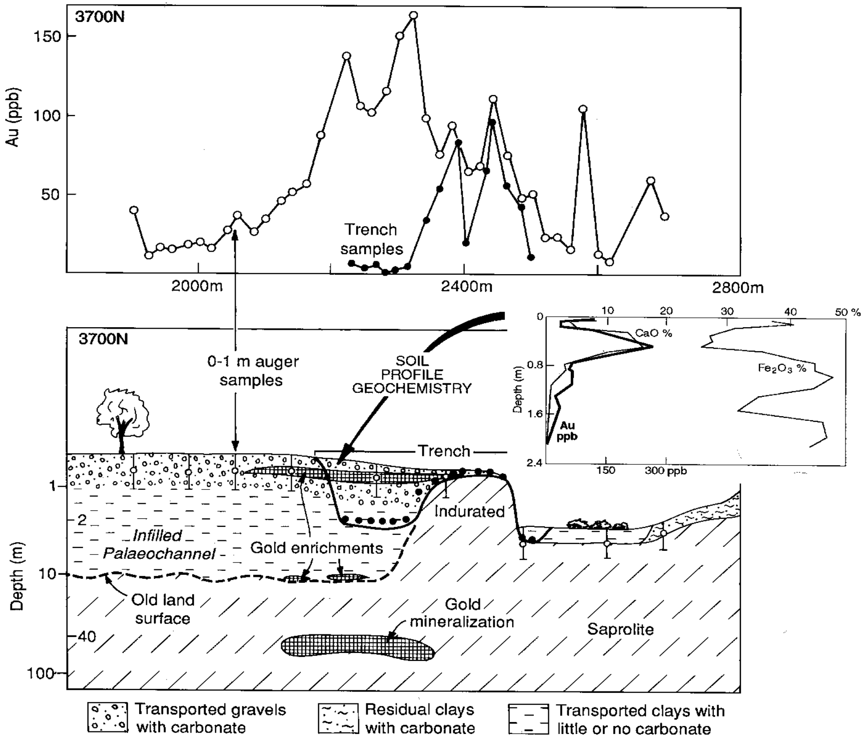

Figure 2: *The association between Au and pedogenic Ca (and Ca-Mg) carbonates, Panglo, Western Australia. Shallow carbonate-rich samples (0–1 m) give a significant response to mineralization, whereas deeper, non-calcareous samples (1–2 m) have background Au contents (after Lintern and Scott, 1990).*

Calcrete (pedogenic carbonate, caliche)

The presence of pedogenic carbonates (calcite, dolomite) is a common feature in many semi-arid regions, whether these are juvenile terrains having soils developed from fresh rocks, or ancient landscapes with deep regoliths. The carbonates occur as coatings, friable powders, nodules or massive accumulations. They have generally been avoided as sample media because, as late stage precipitates, they tend to dilute the concentrations of other elements (Garnett *et al.*, 1982). Exceptions are sites having strong pH contrasts, in which elements mobile in deep, acid ground waters precipitate in the alkaline environment of the carbonate horizon. More strikingly, however, is the specific association between Au and pedogenic carbonates, first documented in the southern Yilgarn Craton of Western Australia (Lintern, 1989; Lintern *et al.*, 1992; Lintern and Butt, 1993). The distributions of Au and Ca (and Ca-Mg) carbonates are very closely correlated, commonly in the top 1-2 m of the soil profile (Figure 2), locally as deep as 5 m. The soil carbonate horizon is thus the preferred surface sample medium in these environments, except where lateritic residuum is present. No other ore-related elements show this association—indeed most are diluted by the carbonate. A high proportion of the Au is highly soluble, even in water, and it is concluded that both the Au and the Ca(-Mg) carbonates act as evaporites (Gray and Lintern, 1994). The Au-carbonate association is also apparent in the hitherto poorly explored Gawler Craton of South Australia, and calcrete sampling has become the predominant geochemical exploration tool for the region, with a number of new discoveries attributed to this technique (e.g., Edgecombe, 1997; Kennedy, 1996; Martin, 1996; Parker, 1996). Whereas in the Yilgarn Craton, calcrete sampling is generally used for prospect evaluation, in the Gawler Craton it is employed at all stages of exploration, from regional appraisal, using sample grids as wide as 1.6 × 1.6 km, to definition of drill targets at 100 × 40 m intervals. Gold anomalies generally range from 5–300 ppb, against a background of 2 ppb. In the Yilgarn, calcretes are commonly sampled using truck-mounted power augers, collecting the whole calcareous horizon where possible. In the Gawler, the carbonates are generally thicker and many are strongly indurated, so that a range of sampling procedures are used.

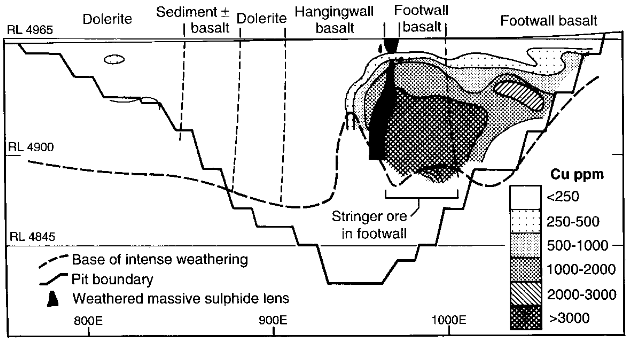

Figure 3: *Copper distribution, Teutonic Bore Cu-Zn deposit, illustrating surface leaching and the restricted dispersion of Cu in saprolite (after Greig, 1983). Copper in saprolite in the footwall derived from chalcopyrite stringers.*

Despite their widespread occurrence, the carbonates do not provide equivalent samples across the landscape. As for 'conventional' soil samples, background and threshold values vary according to the substrate, as determined by the regolith-landform regimes, and the effectiveness of carbonate sampling in depositional areas is open to question, particularly where the sediments exceed 510 m. Similarly, the response of different types of carbonate have not been fully evaluated. Regolith geochemistry investigations in the Gawler, in particular, are at a very early stage, but nevertheless, calcrete sampling has had considerable initial success, and application of the technique will be refined by ongoing research. There has been very little testing of pedogenic carbonate/calcrete/caliche sampling outside Australia, although it is anticipated that it should have widespread application. Preliminary testing in Nevada shows promise (B.W. Smee, pers. comm., 1997), and testing in semi-arid regions in other continents is strongly recommended.

Saprolite

Saprolite forms the lower zones of deep weathering profiles. In lateritic regoliths, it may be overlain by upper horizons (mottled zone, lateritic residuum) where most of the pre-existing profile is preserved (A dispersion models) or exposed or obscured by residual soils or transported overburden in truncated situations (B dispersion models). Despite the initial weathering and any subsequent modification, saprolite is characterized by the preservation of rock fabrics. It is the most commonly sampled material in prospect evaluation, usually obtained by drilling. Accurate logging of drill material is essential for the correct selection of analytical samples and for data interpretation, but this important aspect of saprolite sampling is often neglected. The distinction between saprolite and transported overburden may be unclear in drill cuttings, and identification of the bedrock from which it has been derived may be very difficult, although this may be deduced by careful examination of preserved primary fabrics (Robertson and Butt, 1993). Geochemical anomalies in saprolite are mostly residual, and hydromorphic dispersion haloes rarely extend for more than a few tens of metres from the oxidized mineralization (Figure 3), although they may exceed 100 m (e.g., for Pb in some semi-arid and dry savanna environments: Butt and Zeegers, 1992). Drill spacing and depth are thus critical. Where samples are collected deep in the saprolite, dispersion may be so restricted that the anomaly is much the same width as the primary mineralization itself. For narrow targets, such as massive sulphide shoots or Au mineralization in humid environments, where there is little lateral dispersion, vertical drilling on centres of 20 m or less across strike may be used. Rather wider intervals may be adequate if overlapping angle drilling is used, but care must be taken to allow for the effects of zones of strong leaching.

Leaching and dispersion appear to occur dominantly during the initial phase of weathering under humid conditions (Table 1). However, some elements are mobilized during later phases, such as Au and Pb under arid conditions. Thus, although 20–50% of the total Au is leached during lateritic weathering, particularly from upper horizons (Freyssinet and Itard, 1997), Au concentrations remain at, or close to, ore grade throughout the regolith. In comparison, in semi-arid environments there may be strong Au depletion, to 100 ppb or lower, from the upper saprolite to depths of 40–50 m, commonly with an underlying, subhorizontal zone of supergene enrichment (Butt, 1989b), a consequence of Au mobilization in acid, oxidizing saline ground waters. This is an important distinction between humid and arid terrains, with important implications for sampling, analysis and data interpretation. In the former, anomalies in saprolite are always present, but very restricted, with no 'blanket' of supergene enrichment, whereas in the latter, the possibility of depletion implies a requirement for deep drilling, although the supergene enrichment may give a broad target. However, the common pathfinder elements, such as As, Sb, Bi and W, are retained through the depletion zone even in highly saline environments, hence multi-element analysis can assist in the recognition of leached mineralization. This is illustrated by the Au and As distributions at Mt. Percy, Western Australia, although here the depletion zone is mostly less than 10 m thick (Figure 4). Some of the most technically challenging situations for exploration are posed in depositional areas, where transported overburden rests directly on saprolite. If present, ferruginous saprolite close to the unconformity may provide the most suitable sample medium but, otherwise, carefully targeted, deep drilling, coupled with multi-element analysis, is the best option.

CONCLUSIONS

Geochemistry is an efficient tool for mineral exploration in regolith-dominated terrains, particularly when it is considered that many geophysical techniques have limited application. The geomorphology and regolith of a region are the products of its weathering history and hence of the past and present processes of weathering and geochemical dispersion. They are thus fundamental in determining the geochemical expression of mineralization, so that an understanding of the evolution of the landscape is essential for effective exploration. It is important to establish the dispersion characteristics of the principal ore elements and possible pathfinders at each stage of the evolution and, even at an informal level, to derive generalized dispersion models based on the particular regolith-landform characteristics (Butt and Zeegers, 1992). The most important features of lateritic regoliths include the strong leaching of most ore elements, the restricted dispersion of most elements in the saprolite and the broad, multi-element haloes in lateritic residuum.

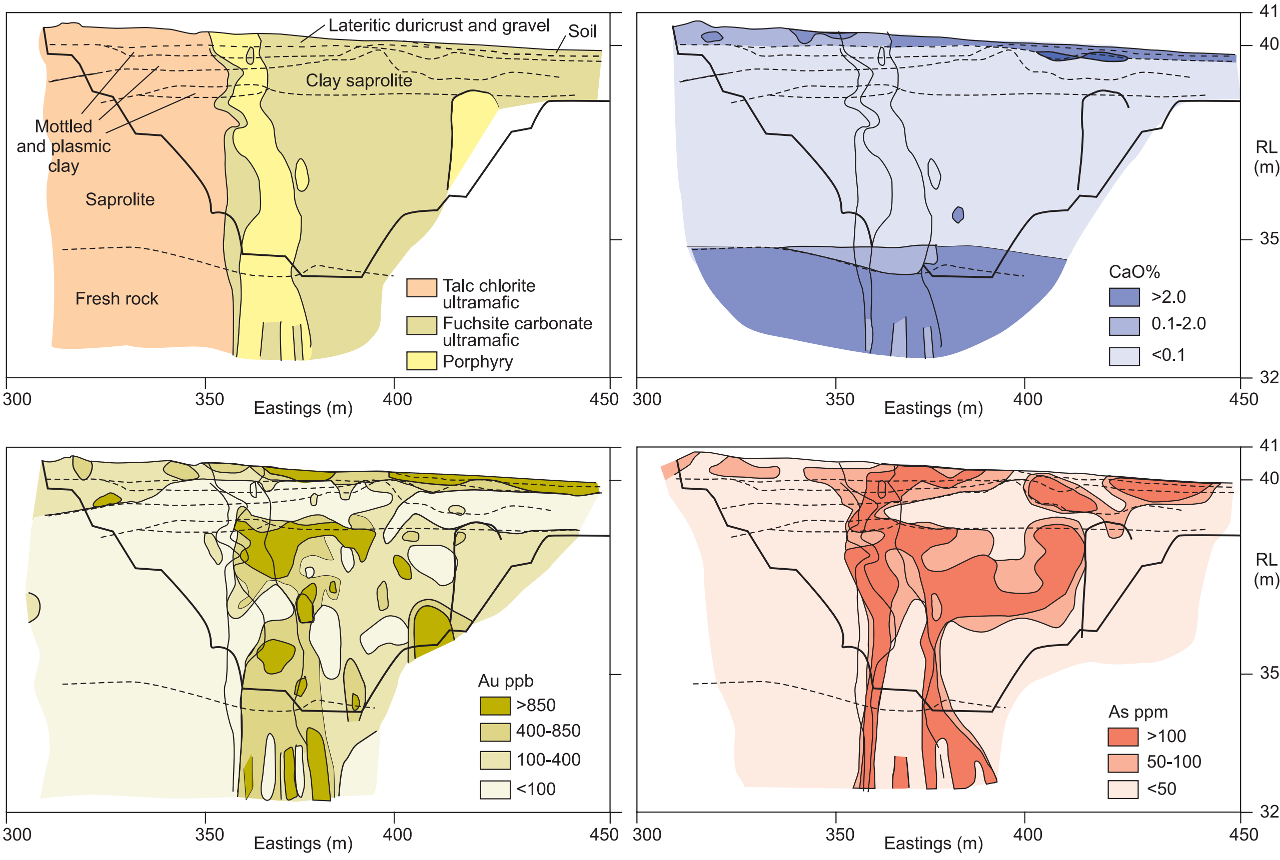

Figure 4: *Geological and regolith section, with CaO, Au and As distributions, Mystery Zone, Mt. Percy. Arsenic persists through the Au-depletion zone. Note relationship between Au and CaO in soil and lateritic residuum (Butt et al., 1991).*

Erosion during and following deep weathering, coupled with modifications due to environmental change, result in a mosaic of landforms in which the pre-existing regolith may be preserved or partly or wholly truncated, and either exposed or buried beneath transported overburden. The nature of the geochemical expression of mineralization, and the availability and usefulness of specific surface and subsurface sample media, thus vary across the landscape.

Regolith-landform mapping is an important first step to determining the appropriate geochemical exploration procedures in a region. Such mapping may initially be supplemented by stratigraphic drilling and should be revised as exploration proceeds. Principal objectives include identification of the main regolith-landform regimes and determination of the degree of preservation of the deep weathering profile—particularly of the ferruginous lateritic horizon. This procedure assists in identifying probable dispersion models and the most appropriate methods, including sample selection and procedures, sample interval and analysis, and data interpretation.

In relict landform regimes, lateritic residuum is generally the best sample medium for reconnaissance and initial anomaly delineation, giving broad, multi-element anomalies, detectable at sample intervals ranging from 3 km to 100 m or less. Soils (coarse fraction) and ferruginous lag are, in effect, equivalent, but may be less useful due to dilution or leaching. In erosional regimes, or residual areas where lateritic residuum has not developed, the surface expression of mineralization is generally restricted and some elements may be strongly leached. Lag sampling and various size fractions of the soil are generally effective, but the small dispersion halo commonly demands close sample intervals (e.g., 100–200 × 20–40 m). In depositional areas, stratigraphic drilling is necessary to establish whether the overburden overlies buried lateritic horizon or an erosion surface cut in saprolite. Lag and surface soil sampling are generally inappropriate, unless the overburden is very thin. Lateritic residuum remains an excellent sample medium if present, again with widespread haloes, but where it is absent, leaching and the restricted haloes in upper saprolite present formidable problems. Ferruginous saprolite or composites across the unconformity may be effective, but otherwise carefully targeted drilling and sampling through saprolite and saprock may be necessary. Partial extraction analyses have yet to demonstrate useful results except in very specific environments.

In arid regions, pedogenic carbonate is a valuable sample medium for Au exploration, principally in non-lateritic and erosional regimes, and in depositional areas where the overburden is shallow. Sample intervals range from 1 km for regional surveys in poorly explored areas, through to 100–200 × 20–40 m in prospect evaluation.

Saprolite is an essential sample medium in all landform environments, but the restricted haloes and possibility of leaching requires close interval drilling and sampling. Costs can be reduced by compositing samples, but particular note should be taken where these cross obvious regolith or lithological boundaries.

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