UNDERSTANDING THE REGOLITH IN TROPICAL AND SUB-TROPICAL TERRAINS: THE KEY TO EXPLORATION UNDER COVER.

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Regolith distribution and characteristics

Large areas of the world, especially the largely tropical to sub-tropical zone between latitudes 40º north and south, are characterized by a thick regolith cover. Much of this regolith is residual and consists of intensely weathered bedrock, but there may also be an overlying component of transported material, itself weathered to varying degrees. The regolith is most extensive in continental regions of low to moderate relief, such as the Precambrian shields, and adjacent and overlying Phanerozoic sedimentary basins, of South America, Africa, India, south east Asia and Australia. Remnants are present in some areas of stronger relief, perhaps most significantly in parts of the circum-Pacific belt, where ophiolitic rocks have weathered to form high grade nickel laterites. Commonly, such regolith is absent from tectonically active and mountainous areas. Thick residual regolith is also generally absent from very arid terrains in the tropics and sub-tropics, such as the Sahara and Arabian deserts, although transported materials, including fluvial deposits and dune sands, are widespread. Nevertheless, isolated occurrences of strongly weathered regolith are recorded from these desert regions, either exposed or buried beneath the younger sediments, indicating that it was once more widespread. There is also increasing recognition of the presence of similar regolith, mainly as thick saprolite, in North America and Europe.

Much of the residual regolith has broadly lateritic characteristics, with a thick, clay-rich saprolite, generally with an overlying iron and /or aluminium-enriched horizon, although the latter may be only patchily developed or have been removed by later erosion. Lateritic regoliths are considered to have been formed under seasonally humid tropical to sub-tropical climates, although there is evidence that similar weathering may occur under cooler conditions. The age of formation varies from Palaeozoic to present day, determined by palaeomagnetic, isotopic and stratigraphic techniques. Commonly, several validated ages may be obtained from a single profile, site or district, indicating multiple stages in development. There is considerable evidence for widespread late Mesozoic to early Tertiary deep weathering extending from equatorial regions to the present high latitudes. These dates have been obtained in S. America, Africa and Australia; the buried bauxites and nickel laterites of eastern Europe and the Balkans are Mesozoic and there is interpreted Tertiary tropical weathering in N. Ireland. (The age of other high latitude saprolite is less well constrained, with weathered Palaeozoic and older rocks buried by Mesozoic (e.g., south Urals), Oligocene (e.g., north Urals) or Pleistocene (e.g., northern USA) deposits. Subsequently, the land surface has been subjected to a variety of conditions, ranging from humid to arid and tropical to sub-arctic, consequences of climatic change and continental drift, resulting in the physical, mineralogical and/or chemical modification of the pre-existing regolith. In places, the earlier regolith has been almost fully preserved; elsewhere, it has been partially or wholly eroded, or buried by sediments that themselves may then be weathered. The outcomes are landscapes that consist of mosaics of different regolith-landform associations.

Exploration issues

The complex regolith environment presents both challenges and opportunities for mineral exploration (Table 1). The morphological, petrophysical and compositional characteristics of the residual regoliths are commonly profoundly different from those of the rocks, including ore deposits, from which they have been derived. These affect geological, geochemical and geophysical exploration procedures and constrain their use. The presence of transported overburden and basin sediments exacerbates these problems, especially for geochemical procedures based on surface or near-surface sampling. Geophysical survey methods, particularly airborne techniques, are commonly applied to "see through" this cover, but are hindered by interfering regolith-related responses. Conversely, because much of the regolith is residual, and has the potential to provide secondary dispersion targets that are broader than the primary mineralization itself. In addition, deep weathering also leads to the formation of many important secondary and supergene ores, notably bauxite, some iron ores, nickel-cobalt laterites, niobium-rare earth-phosphate deposits, lateritic and supergene gold, supergene copper, and industrial and building materials.

The formation of lateritic regoliths, their modification under changed climatic settings and the effects of erosion during and after these events result in significant regolith-landform control on sample media. Knowledge of the distribution and properties of regolith components is essential for successful exploration in regolith-dominated terrains, whether for deposits concealed by the regolith or for those hosted by it. Regolith-landform mapping is an essential first step, followed by characterization of the regolith materials themselves. From a geochemical perspective, regolith-landform maps can be interpreted in terms of models that describe the geochemical pathways followed by ore-related elements as they disperse during weathering and, therefore, not only indicate the most appropriate sample media but assist in data interpretation (Bradshaw, 1975, Butt and Smith, 1980; Butt and Zeegers, 1992). From a geophysical perspective, these maps, particularly at district to prospect scales, may indicate the applicability of specific procedures and provide a basis for distinguishing between regolith- and basement-related responses. Accordingly, there is increasing emphasis on regolith-landform mapping, using a combination of remote sensing procedures, followed by field checking, including drilling. Satellite imagery and conventional aerial photography remain the basic approaches to mapping, but are routinely supplemented by multispectral Landsat and airborne data for mineralogical information and airborne radiometric surveys for geochemical data (e.g., to indicate provenance). However, whilst these procedures indicate the nature and distribution of surface materials, they are poor indicators of the underlying regolith, especially in areas of transported overburden and basin cover. New electromagnetic systems, in particular, can map spatial variability of physical properties and conductivity structure in the third dimension, yielding information including total thickness of transported and residual regolith, presence of palaeochannels and an outline stratigraphy.

Integration of these data can rapidly deliver inventories of surface materials, interpretable in terms of weathering styles and geomorphological processes, but require field inspection prior to providing definitive exploration guides. Geochemical methods have been developed for relict and erosional terrains in many deeply weathered environments, but surface techniques appear to be generally ineffective in most depositional regimes. Preliminary field work should include drilling or deep pitting – ideally in all regolith landform regimes but essential where there is transported cover – to provide a basis for selecting sample media and interpreting data. Accurate logging, however, may not be easy even in good field exposure and can be very difficult from drill cuttings. Unfortunately, this task is commonly delegated to some of the most inexperienced geologists, yet correct identification of significant regolith profile units and boundaries is of considerable importance. As an example, ferruginous lateritic residuum is an important sample medium, yet may be readily confused with sedimentary units that have different relationships with bedrock and mineralization and little or no value for sampling. Similarly, despite claims to the contrary, there are very few instances where significant geochemical anomalies in transported overburden can be successfully related to underlying mineralization, even using special analytical techniques. Exceptions include gold anomalies in calcrete, which may penetrate 5-10 m of cover (Lintern, 2002), and some base metal anomalies in basin sediments (e.g., at Osborne, Queensland), although these may have formed during diagenesis rather than weathering (Lawrance, 1999). Accordingly, recognition of the presence and thickness of transported units of any type is crucial. It is expected that the development of instrumental procedures for routine logging will be of great value in overcoming many of these problems.

Regolith-landform based exploration models

General

Due to the common aspects of their formation and evolution, lateritic landscapes and regoliths are broadly similar across a range of different climatic zones. This genetic link extends to chemical and physical weathering processes and allows comparison across regions through the use of some generalized dispersion and exploration models (Butt and Zeegers 1992). These models are based on the degree of preservation from erosion of the pre-existing lateritic profile, which determines the nature of the uppermost residual horizon, and the presence of transported overburden. 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 aspects of dispersion, however, are specific to particular regions and commodities, and their description requires models based on appropriate orientation and case studies.

Gold deposits

During lateritic weathering of lode deposits, there is little dispersion of gold except in the upper horizons (Freyssinet and Itard, 1997). Lateral detrital and chemical dispersion has occurred in the lateritic residuum, commonly with leaching and depletion in the top 1 to 3 m and enrichment below. This provides a very broad, multi-element, near-surface exploration target. However, if this material has been eroded, the target in saprolite is similar in dimensions to that in bedrock, which has an immediate impact on selecting appropriate sampling density. This gold distribution is found not only in the present savannas, but in both more humid and more arid regions. In rainforest environments, leaching is stronger, decreasing the surface expression, but giving widespread drainage anomalies. Conversely, in arid regions, gold enrichment in lateritic residuum continues to the surface, increasing its accessibility to surface sampling. Even where buried, lateritic residuum is a valuable sample medium, but accurate logging is necessary to distinguish it, in drill cuttings, from detrital ferruginous gravels. In all environments, analysis for appropriate pathfinder elements (e.g., As, Sb, W, Cu, Bi), can assist in the definition and prioritization of anomalies for further exploration.

In arid regions with acid, saline groundwaters, the enrichment in lateritic residuum is preserved. However, strong leaching and depletion of gold may occur in the top 10 to 40 m of saprolite, but with absolute, supergene enrichment below. The latter may form an important resource, but commonly shows no greater dispersion target than the underlying lode and primary alteration zone (Gray et al., 2001). If the lateritic residuum has been eroded, or never formed, the depleted zone outcrops at surface or subcrops immediately beneath transported overburden, hence except where there are pedogenic carbonates, pathfinder elements will give a better expression of mineralization than gold. Pedogenic carbonates will concentrate any gold, even where there has been considerable leaching and depletion, and are the preferred sample medium in residual soils or where the cover is less than 10 m thick. The concentrations and contrasts are low, targets small and usually gold only. These variations in surface expression demonstrate the importance of regolith-landform mapping, accurate logging and knowledge of the weathering history and its impacts on element dispersion for effective exploration.

Volcanic-hosted base metal deposits

Few volcanic-hosted base metal sulphide (VHMS) deposits are known in deeply weathered shield areas of S. America, W. Africa or Australia, despite their apparent prospectivity through comparison with equivalent terrane in Canada. Most of the few discoveries (and of other massive sulphide deposits, including nickel sulphides), have been made by gossan search or, latterly, by improved electromagnetic and other geophysical techniques. Most gossan discoveries have been in erosional terrain, in arid environments; this is true for Australia, where deep weathering is widespread, and other areas such as in southern Africa and the Arabian Shield, where deep weathering is absent or vestigial. There is a poor record of discovery in arid areas with intact lateritic regoliths, in depositional areas and in the humid tropics in general. Gossan profiles are commonly described as being formed of iron oxides with variable, and commonly low, base metal contents in the upper portion, underlain by secondary enrichment zones, including native metals, carbonates and sulphates, with supergene sulphides as a transition to the primary sulphide ore. These descriptions are dominantly from arid environments, and these lower zones may have formed under the contemporary climate. Observation also indicates that gossans thin and become attenuated towards the surface. The assumption that lateritic weathering of base metal sulphides always forms gossans at surface is thus questioned, as too must be the effectiveness of many geochemical techniques that are directed at gossan search.

Lateritic weathering of VHMS deposits results in the extensive leaching of copper and zinc, leaving a gossan formed by iron oxides principally derived from chalcopyrite, pyrite and pyrrhotite. It is possible that high in the regolith, the iron oxides forming the gossan themselves dissolve, hence the near-surface expression of the deposit may be represented by a range of less mobile elements hosted by resistant minerals. In lateritic residuum at Golden Grove in Western Australia, for example, the dispersion halo is extensive, but defined by Bi, As, Sb and Sn, in addition to Cu, Zn and Au (Smith and Perdrix, 1983). There is little evidence for a widespread dispersion halo in saprolite of any of the ore elements, so that where the profile is truncated, in the absence of significant gossan, there may be little trace of the mineralization. The situation will be more complex if there is burial by transported overburden. Because VHMS deposits are major sources of labile metals, specific targeting by selective extraction analysis is a possibility in depositional areas, but is likely to be successful only if the depth to sulphides is shallow and the sulphides are actively weathering.

Interest in exploring for VHMS deposits in deeply weathered shield areas has recently increased, after a lull over much of the past two decades. Because of the uncertainties of their surface expression, very careful attention needs to be paid to geochemical procedures. Tailoring procedures to the regolith setting and understanding the potential signature has proved effective to guide sampling strategies for gold exploration and a similar approach is recommended for base metals.

Nickel deposits

Exploration for nickel sulphides has similar issues to those for VHMS deposits related to gossan formation and preservation in lateritic environments, with the added complexity that they occur in nickel-rich host rocks. Many early discoveries of massive nickel sulphides in Western Australia were through the discovery of gossans, by ‘ironstone’ sampling or soil surveys, and the majority of these were in erosional terrain. At the original discovery sites at Kambalda, for example, although the sulphides are weathered to 150 m or more, some of the wall-rocks are essentially fresh at surface. Elsewhere, some gossans are very attenuated near the surface (e.g., Redross) and, at Harmony, it is possible that the gossan may have entirely dissolved (N.W. Brand, personal communication, 2000). Petrographic examination for boxwork textures after sulphides, multi-element geochemical analysis and statistical techniques have been widely used to discriminate gossans from other ironstones.

It is also important to understand the nature of nickel enrichment in lateritic regoliths, which may form deposits in their own right. The genesis of nickel laterites depends upon a variety of geological, geomorphological and climatic factors (Table 2). There are three types of deposit, based on the ore mineralogy (Brand *et al.,*1998):

- **Oxide deposits,** mean grades 1.0-1.6% Ni**:** dominated by Fe oxyhydroxides, principally goethite, forming the mid- to upper saprolite and extending to the pedolith. Manganese oxides may host reserves of Co. Deposits developed over dunites (adcumulates) may contain abundant secondary silica. There is an oxide component to all deposits, but because this requires a different metallurgical process, it is commonly either discarded or stockpiled when silicates are the principal resource.
- **Hydrous Mg silicate deposits,** mean grades 1.8-2.5% Ni**:** dominated by hydrous Mg-Ni silicates (e.g., “garnierite”; nickeloan serpentine and talc;) in the lower saprolite. The majority of producing nickel laterites are of this type.
- **Clay silicate deposits.** mean grades 1.0-1.5% Ni**:** dominated by Ni-rich smectites such as nontronite and saponite, commonly in the mid to upper saprolite and pedolith.

The high nickel content of the weathered host rocks presents considerable difficulties in the recognition of the signature of sulphides, whether at surface or deep in the regolith. Lateritic nickel enrichments may follow steeply-dipping structural elements such as shears, potentially emulating the distribution expected from the oxidation of sulphide-rich rocks. Commonly, high concentrations of copper and/or platinum group elements (PGE) can confirm a sulphide signature, although over disseminated deposits (e.g., Mt. Keith), the nickel, copper and PGE enrichment may occur in different units of the regolith profile (Brand and Butt, 2001). Similarly, although dispersion into weathered wall-rocks and surface media such as soil, lateritic residuum and transported overburden is possible, distinguishing between sulphide and silicate sources is commonly very difficult.

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Table 1: Some exploration problems and opportunities in deeply weathered terrain

Problem	Cause
Difficulty in recognizing parent lithology	Mineralogical, chemical and morphological change
Variable regolith thickness; soils derived from many different parent materials	Differential weathering and partial erosion
Subtle surface expression	Strong leaching
Spurious secondary enrichment and numerous 'false positive' anomalies	Mobility and re-concentration during weathering, erosion and deposition
Complex geochemical signatures	Superimposition of multiple weathering events
Masking by transported overburden and basin sediments, themselves possibly weathered	Ineffective chemical dispersion during post-depositional weathering and diagenesis
Attenuation or masking of geophysical responses	Increased distance between sensor and target Highly conductive surface layers
Development of false geophysical anomalies/responses:	
• Magnetics	Concentration of magnetite, maghemite
• Electromagnetics, induced polarization	Low resistivity and marked resistivity contrasts
• Radiometrics	Presence of transported anomalies; disequilibrium due to chemical mobility
• Remote sensing (e.g., spectral imaging); radiometrics	Surface response – cannot penetrate transported cover
Low contrast seismic and gravity response	Zonation, transitional contacts, density contrast

Opportunities	Cause
Presence of supergene ore deposits	Residual or absolute accumulations, e.g., bauxite, N-Co laterite; Au, Nb, P, U deposits; Fe and Mn ores. Industrial minerals.
Largely residual regolith as sample medium.	Tectonic stability; long exposure; little erosion
Widespread geochemical anomalies in a variety of regolith horizons and materials, e.g., soil, lateritic residuum, lag, pedogenic carbonates	Physical and chemical dispersion over long periods

Table 2: Summary of controls on nickel laterite formation

	Hydrous Mg silicate	**Clay silicate**	**Oxide**
Climate	Humid savanna – rainforest	Humid savanna; possibly formed or modified in semi-arid climates	Savanna; modified in semi-arid climates
Relief	Moderate	Moderate to low	Moderate to low
Drainage	Free	Impeded	Free or impeded
Tectonism	Promoted by uplift	Inhibited by uplift.	Promoted by uplift
Primary structure	Promoted by increased weathering and Ni enrichment along open fractures	Enrichment on some fractures. Possibly promoted where faults impede drainage.	Promoted by increased weathering and Ni enrichment along open fractures
Primary lithology (only on ultramafic rocks; rare or absent on talc carbonates)	Peridotite>>dunite. Only thin where there is little or no serpentinization	Peridotite>>dunite	Dunites dominantly yield oxide deposits; also form on peridotite