Use and Implications of Paleoweathering Surfaces in Mineral Exploration

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ABSTRACT

Paleoweathering surfaces can result in thick blankets of deeply weathered residua arising from alteration of bedrock. In such terrains, ore deposits are concealed by the regolith blanket, yet significant geochemical dispersion patterns arising from ore deposits may be present. Recognisable patterns of dispersion can arise from long and intense weathering of many types of ore deposits, including gold, base metal, rare metal, iron and the kimberlitic host rocks to diamonds.

Concealed ore deposits typically give rise to geochemical dispersion haloes a kilometre or more across and some kilometres in length preserved within lateritic residuum. Gold deposits almost invariably show a dispersion halo of Au as well as some common associate elements: Cu, Pb, As, Sb, Bi, In, Mo and W. For base metal deposits Ni, Co and Cr are commonly added to the list; for rare metal deposits, Sn, Ta, Nb and rare earth elements. The exploration methods described are expected to be generally applicable to lateritic terrains across the globe.

Where a lateritic surface is exposed the preferred sampling media for geochemical exploration, in decreasing order of preference, as shown by a conceptual model, are: lateritic pisoliths or nodules, lateritic duricrust, ferruginous saprolite, ferruginous mottles, soil overlying any of the previous categories, and iron segregations within upper saprolite. Lag can also be sampled in lateritic terrain but, for effective interpretation, lag sample sites need to be directly related to mapped regolith-landform units because the characteristics of lag vary with the immediate substrate.

In terrain where a lateritic surface is buried beneath alluvial plains, the regolith stratigraphy should be established through drilling early in the exploration program. Systematic sampling is carried out using further drilling, capitalising on enlargement of target size arising from dispersion patterns likely to be preserved within the lateritic residuum. The preferred sample media, all of which are subsurface, in order of priority, as shown in a second conceptual model, are: pisolitic or nodular lateritic residuum, lateritic duricrust, basal lateritic colluvium, ferruginous saprolite, ferruginous mottles in upper saprolite, and iron segregations in upper saprolite.

A third conceptual model is proposed for a partly weathered base metal-gold deposit buried beneath sedimentary basin cover. Geochemical sampling is directed at the buried weathering surface, hydromorphic anomalies in weathered bedrock, dispersion anomalies at the unconformity between basin sediment and weathered bedrock, as well as leakage geochemical haloes in the cover sequence.

INTRODUCTION

Paleoweathering refers to weathering over long periods of time, which can be hundreds of thousands of years, or even tens of millions of years in more extreme cases of lateritic weathering. Paleoweathering surfaces include exposed weathering crusts such as lateritic duricrusts, ferricretes or cuirasse, lateritic bauxites, certain calcretes and silcretes, as well as saprolite (deeply weathered rock). Some aspects of paleoweathering are provided in Widdowson (1997).

An interpretation of the distribution of deeply weathered terrain, including lateritic terrain is shown in Figure 1. This draws from the maps of Budel (1982) and Bardossy and Aleva (1990). Deeply weathered terrains are estimated to form some one-third of the earth's land surface.

A consequence of deep weathering is that it can result in complete alteration of the mineralogical, chemical and petrographic characteristics of bedrock and mineralisation that is hosted in bedrock. However, the dispersion of ore-related elements can create larger, though commonly subtle, exploration targets that can be used to advantage in

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Table 1: ***Some gold deposit discoveries in Australia in which laterite geochemistry and regolith-landform control over sampling have been important factors.***

Year of discovery	Deposit	Company
1983	Johnston Range, WA	AGE Joint Venture
1983	Bottle Creek, WA	Electrolytic Zinc Co.
1984	Callion, WA	Metall Mining, Thyssen, Lubbock
1988	Plutonic, WA[1]	Plutonic Resources Ltd. (Great Central Mines original discoverer)
1989	Turrett, WA	Forsayth NL
1989	Waroonga-Genesis, WA	Forsayth NL
1992	Bronzewing, WA[1]	Great Central Mines
1993	Jundee, WA	Great Central Mines, Mark Creasy
1993	Nimary, WA	Hunter Resources, Eagle Mining Corporation NL
1993	Baxter (Harmony), WA	North Ltd., Plutonic Resources
1993	Stellar, WA	WMC Resources Ltd.
1993	Jim's Find, NT	Otter/Billiton
1994	Dalgaranga, WA	Hunter Resources, Newcrest, Western Reefs, Equigold

1. World-class deposits

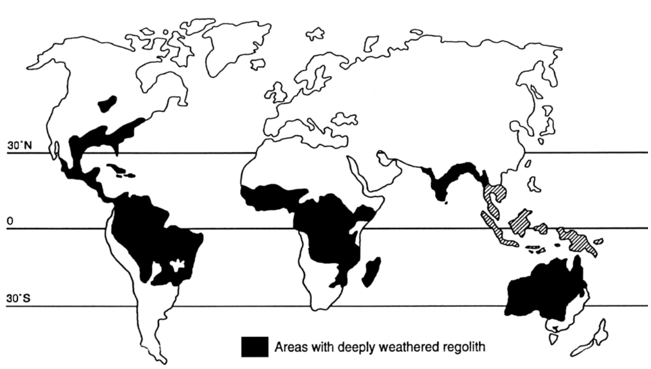


Figure 1: *The interpreted distribution of areas of deeply weathered regolith. Modified after Bardossy and Aleva (1990) and drawing from Budel (1982). Deep weathering occurs sporadically in the areas of hatching.*

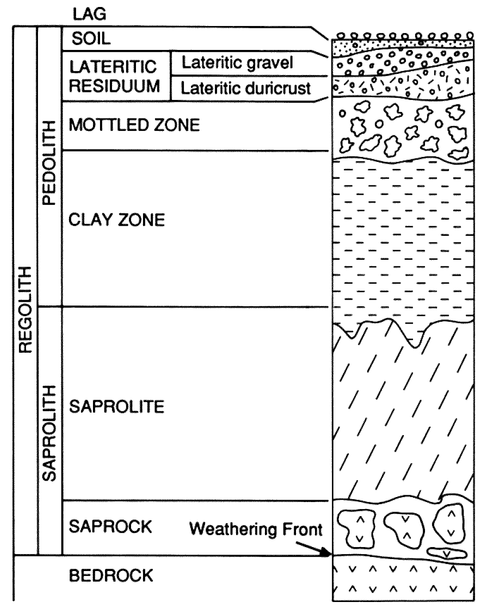


Figure 2: *Regolith terminology used for deeply weathered laterite profiles. Modified after Anand and Butt (1988).*

mineral exploration by enlarging target size as summarised by Smith (1989), Smith *et al.* (1992), and Anand *et al.* (1993).

Lateritic regions have received considerable research over the last decade. Exploration methods that were being proposed in the early work by Smith (1989) have now had extensive development, and predictive models have been refined. Application of the concepts and models in Australia have resulted in numerous exploration successes, Table 1. Furthermore, the exploration methods described in this paper are expected to be effective empirically, and the models to a large extent generically, in lateritic terrains across the globe.

The purpose of the paper is to summarise some exploration approaches that use paleoweathering surfaces to advantage. Operational methods are presented, orientation studies are referred to and some exploration successes are mentioned. The purpose is also to direct attention to some more challenging exploration frontiers in areas of sedimentary cover where paleoweathering may provide insights into procedures for locating large concealed ore deposits.

PALEOWEATHERING SURFACES

From the mineral exploration perspective, to date the most intensively studied paleoweathering surfaces are lateritic. The ferruginous upper part of a lateritic weathering profile (lateritic residuum or its component layers of lateritic gravel and lateritic duricrust, Figure 2; and Butt and Smith, 1992) acquires an iron-rich, dark-brown, yellow-brown or black appearance that commonly disguises bedrock characteristics and in many situations results in an almost monotonous blanket across the landscape. This ferruginous layer or its overlying soil or sand is a common feature in lateritic terrains, covering many thousands of square kilometres in western and central Africa, parts of Australia, India and South America (Zeegers and Lecomte, 1992; and Butt and Zeegers, 1992).

Commonly underlying the ferruginous layer is a clay-rich zone, typically kaolinitic, some tens of metres thick, resulting from intensive weathering and leaching of bedrock. Where rock fabric is at least partly preserved despite intensive weathering the term saprolite is used. The term saprock applies where bedrock is only slightly weathered. Thus lateritic weathering creates two barriers to exploration—an obscuring blanket of lateritic residuum and associated soils, and a zone of intense clay-rich weathering. However, by understanding the formation and evolution of paleoweathering surfaces, geochemical dispersion patterns, which are an inherent part of weathering, can provide major advances in exploration.

Deeply weathered mantles are commonly further modified by the process of erosion, deposition and mineralogical changes in response to changes in climate. The result is a landscape in which erosional and depositional phases of various ages are set in an environment of ancient weathering.

Over the last two decades, substantial research has focused on understanding the characteristics and processes of weathering in lateritic terrain as well as establishing the patterns of geochemical dispersion from concealed mineral deposits, through orientation studies (Butt and Zeegers, 1992; and Smith, 1996). Procedures for different regolith-landform settings have been developed, using a variety of sample media including surficial or buried lateritic residuum, ferruginous saprolite, soil and ground water. Summaries are provided by Butt and Smith (1980); Zeegers and Lecomte (1992); Lecomte and Zeegers (1992); Butt and Zeegers (1992); Smith *et al.* (1992); and Anand *et al.* (1993).

In lateritic terrains specifically and deeply weathered terrains in general, it can be useful to map regolith-landform units and then interpret the landscape in terms of relict, erosional and depositional regimes. A relict regime is defined as one where a weathering surface (such as a lateritic duricrust, or silcrete) is extensively preserved. An erosional regime is where the relict weathered layer has been removed, and a depositional regime refers to areas of sediment accumulation. A generalised cross-section showing some common regolith-landform situations in lateritic terrain is given in Figure 3.

Exploration almost invariably starts in the erosional regimes because bedrock, although it may be deeply weathered, can outcrop. In terms of increasing difficulty, exploration would then tackle relict regimes, applying advances in exploration geochemistry. As the relict regimes are explored, attention tends to go to depositional regimes, for which substantial drilling is inevitably required.

Exposed lateritic surfaces

Lateritic residuum commonly forms from accumulation and modification of the saprolitic substrate. The residuum chemically is dominated by oxides of silica, iron and aluminum. Texturally, lateritic residuum can consist of loose or cemented lateritic pisoliths or nodules, or can occur as hard weathering crusts, duricrusts, commonly 1–3 m thick. Where the bedrock is Fe-rich, precipitation of Fe oxides forms a goethite-hematite-rich upper ferruginous saprolite, containing much kaolinite. Where the bedrocks are low in Fe, a mottled upper saprolite rich in kaolinite is commonly developed instead of ferruginous saprolite.

Lateritic residuum commonly evolves by partial collapse, involving both vertical and lateral movements, following chemical wasting. It is referred to as essentially residual if lateral movement is minor (a few tens of metres).

The Yilgarn Craton of Western Australia has been the focus of intensive research into the use of laterite geochemistry for mineral exploration since the mid-1970s. Some of the research effort over the last decade has been directed at selected type districts, chosen to be distributed across the present-day rainfall gradient. Field relationships for one of these, the Mt. Gibson district (location map, Figure 4), is presented in Figure 5 as a block diagram with columns showing the regolith stratigraphy (Smith *et al.*, 1992).

The diagram shows a lateritic landscape in the initial stages of erosional dismantling, in this case in a semi-arid environment (annual rainfall averaging 250 mm). The relict regimes are characterised by weathering profiles consisting (from the top) of yellow clayey sand,

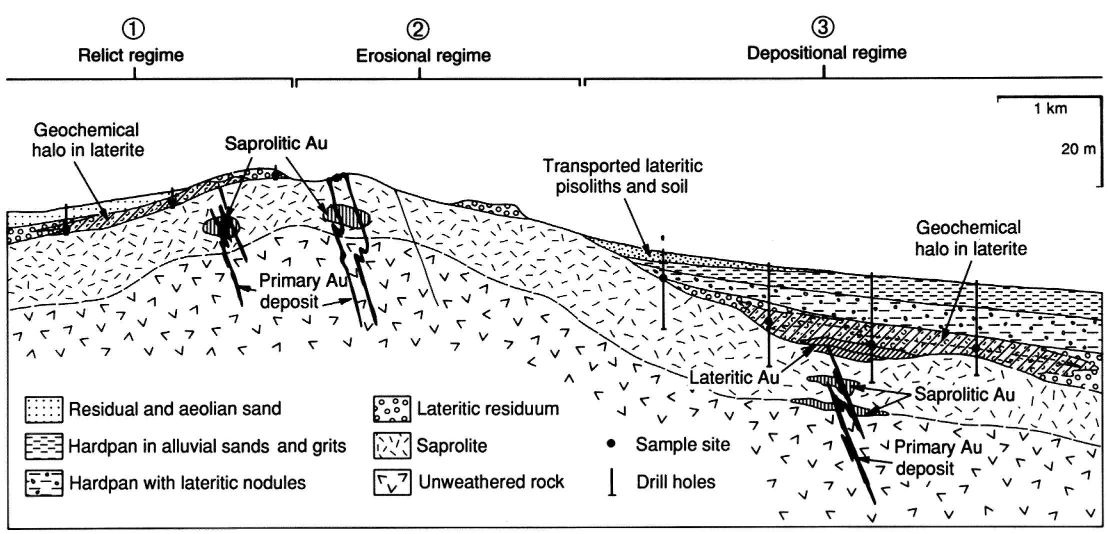


Figure 3: *Landscape section illustrating relationships between a lateritic surface that is, from left to right, exposed, eroded or buried. Dispersion of Au into the regolith is shown diagrammatically in terms of two of the dispersion models referred to in the text. Modified after Smith and Anand (1988).*

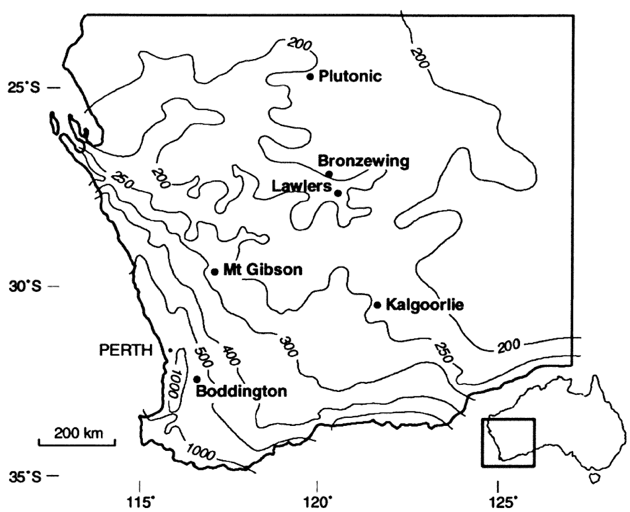


Figure 4: *Western Australian locations referred to in the text.*

pisolitic or nodular lateritic gravel, lateritic duricrust, a mottled clay zone, and typically some tens of metres of saprolite overlying fresh bedrock. In the erosional regimes, lateritic residuum has been removed, with the underlying weathered mantle being truncated down to the mottled zone or deeper. Some of the erosional detritus has been deposited locally; other detritus has been transported more distally to drainage sumps. In the Mt. Gibson study, the lateritic duricrust and the immediately overlying lateritic gravel has been shown to be a residuum through field relationships, petrography and geochemistry. Transported lateritic gravels also occur and can be recognised by their field setting.

Some of the results from the orientation geochemical study at Mt. Gibson are shown in Figure 6. The dispersion patterns arise from the concealed gold deposits and the mineralised system that led to their formation. The multi-element anomaly is up to a kilometre in width and continues for more than 7 km, following the strike of the mineralised shear zone. Within this large anomaly, discrete geochemical highs are directly related to specific ore deposits. Besides mining of saprolitic and bedrock ore, the strongest parts of the geochemical dispersion anomaly in lateritic residuum have also been mined as ore, the cut-off grade being 1 ppm (1 g/t) Au or somewhat less varying with the gold price at the time.

The geochemical dispersion patterns in Figure 6 are based on sampling lateritic gravel (the upper unit of the lateritic residuum) regardless of whether it was sampled at surface or subsurface using shallow drilling (at depths of 5–10 m) on the eastern side of the anomaly. Dispersion patterns based on the immediately underlying lateritic duricrust are similar in element associations and abundance levels, are generally narrower, and likewise show a direct relationship to the bedrock ore deposits.

Geochemical dispersion patterns for a seasonally wet climate with a moderate rainfall (850 mm per year) are provided by an orientation study of the Boddington Au deposit (Figure 7), another Yilgarn-type district (Anand *et al.*, 1993). The mineral deposit is an Archean style of porphyry Au-Cu deposit, hosted within intermediate intrusives. However, gold ore has been mined extensively from lateritic residuum, bauxite and saprolite zones as well as from bedrock.

A lateritic weathering surface, probably of Eocene age, undulates across the landscape with topographic elevation varying from 250–400 m. The location is within the Darling Range lateritic bauxite province, the general features of which are described by Anand (1994), and Bardossy and Aleva (1990).

Field relationships, petrography and geochemistry show that the lateritic duricrust and associated lateritic nodules and pisoliths are largely residual, with transported pisoliths and nodules occurring on the lower slopes. Strong multi-element geochemical anomalies occur both in the lateritic duricrust and lateritic nodules/pisoliths. The element associations in the surface and near surface materials are As, Mo, Sn, W, and Bi with more erratic Cu and Au. The abundance of Au decreases from a concentration in the bauxite zone upwards through the lateritic duricrust to the layer of loose pisoliths. It is noted that Au in pisolitic gravel at surface is relatively weak, whereas Sn, W, Mo and As are strongly anomalous at surface. However, 1 or 2 m below the surface Au is strongly anomalous in the fragmental duricrust.

It is believed at Boddington that high rainfall and soil waters rich in organic materials produced from the abundant vegetation, may result in the leaching of the Au from the loose pisoliths (Anand, 1994). The leached Au is dissolved by organic acids and reprecipitated at the base of the bauxite zone. Soil processes have been discussed for Au mobility in tropical rain forest soils of Ghana by Bowell *et al.* (1993).

An implication in exploration from the study at Boddington is that it is unwise to expect Au always to dominate a surface dispersion anomaly from a Au deposit in lateritic terrain, in this case in a seasonally wet climate. Thus, because of this leaching of the Au from the surface, anomalies defined by strong chalcophile element associations, with or without Au, seem to be the best and most reliable surface indicators of a Au deposit. Samples of the lowermost unit of lateritic residuum (here fragmental duricrust) should be collected particularly at the anomaly delineation stage, because of the reliability of the Au geochemical anomaly in that unit.

Lateritic surfaces under cover

Drilling to define regolith stratigraphy in the Lawlers district, another of the type districts in the Yilgarn Craton (annual rainfall averaging 200 mm), showed that areas of lateritic residuum commonly lie preserved under extensive alluvial and colluvial plains. Here the depth of cover commonly reaches 10–20 m, and in some places in excess of 50 m. The Lawlers district became a test case for exploration directed at buried geochemical haloes in lateritic residuum, because of the enlarged target size. Discovery of the North, Turrett and Waroonga gold deposits in the period 1988 to 1991 followed, demonstrating the effectiveness of the approach. Application of the concepts and methods developed at Lawlers contributed to the discovery by Great Central Mines of the world-class Bronzewing gold deposit in 1992. The concealed Au deposits have geochemical haloes in lateritic residuum characterised by various combinations of Au, As, Sb, Bi, Mo, Ag, Pb, and W.

Paleoweathering surfaces in areas of sedimentary basins

Where continents have been relatively stable over long periods of time, opportunities arise for sedimentary basin sequences to bury paleoweathering surfaces. Weathering profiles buried beneath Tertiary or

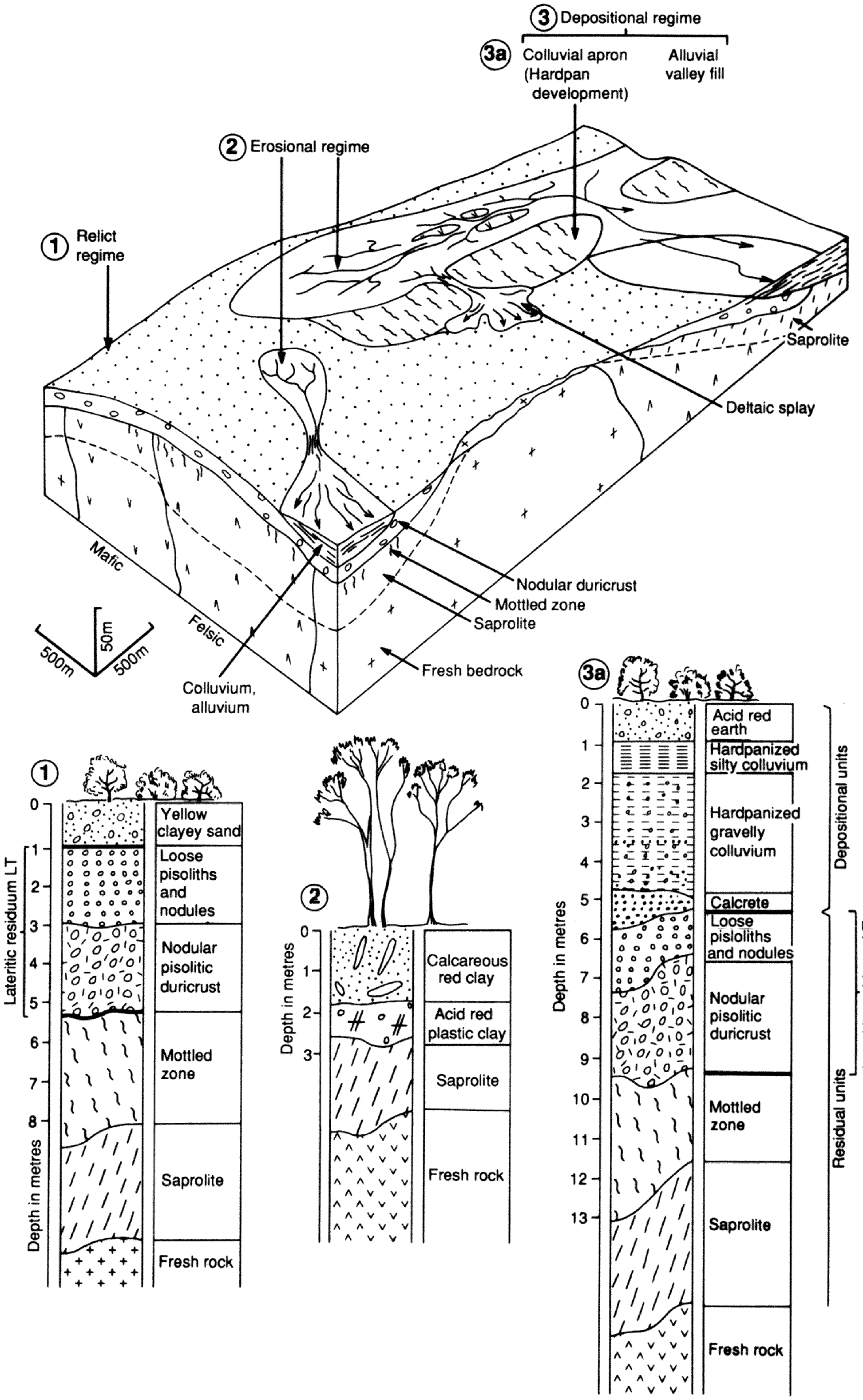


Figure 5: *Regolith-landform model for the Mt. Gibson district, Yilgarn Craton, Western Australia. Columns show units of the regolith stratigraphy for different positions in the landscape. (From Smith et al., 1992).*

Mesozoic sequences are not uncommon (Alley, in press; Alley *et al.*, in press) and, in some cases, paleoweathering beneath Paleozoic and older sequences are known.

In some situations, deep weathering has continued after deposition of the sedimentary sequence. This weathering takes place by vertical and lateral movements of ground water, which can flow through the weathered pre-cover rocks as well as through the sedimentary basin sequence. This leads to possibilities of geochemical dispersion into the cover sequence. Continued weathering of pre-cover rocks is difficult to demonstrate unequivocally, requiring careful isotopic dating.

The sedimentary formations and paleochannel sediments may carry mineralogical signatures that bear on the provenance of buried mineral deposits, but are likely to be very much complicated by sedimentary history. Thus, to understand the signatures, the history of a basin and its sedimentary pathways need to be unravelled by gaining an understanding of factors affecting deposition, such as paleoclimate, tectonism and eustasy.

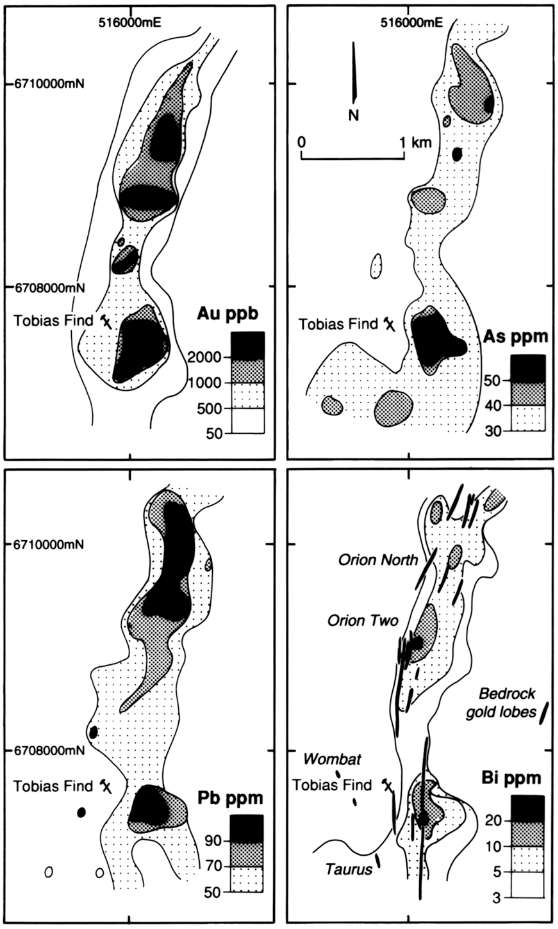
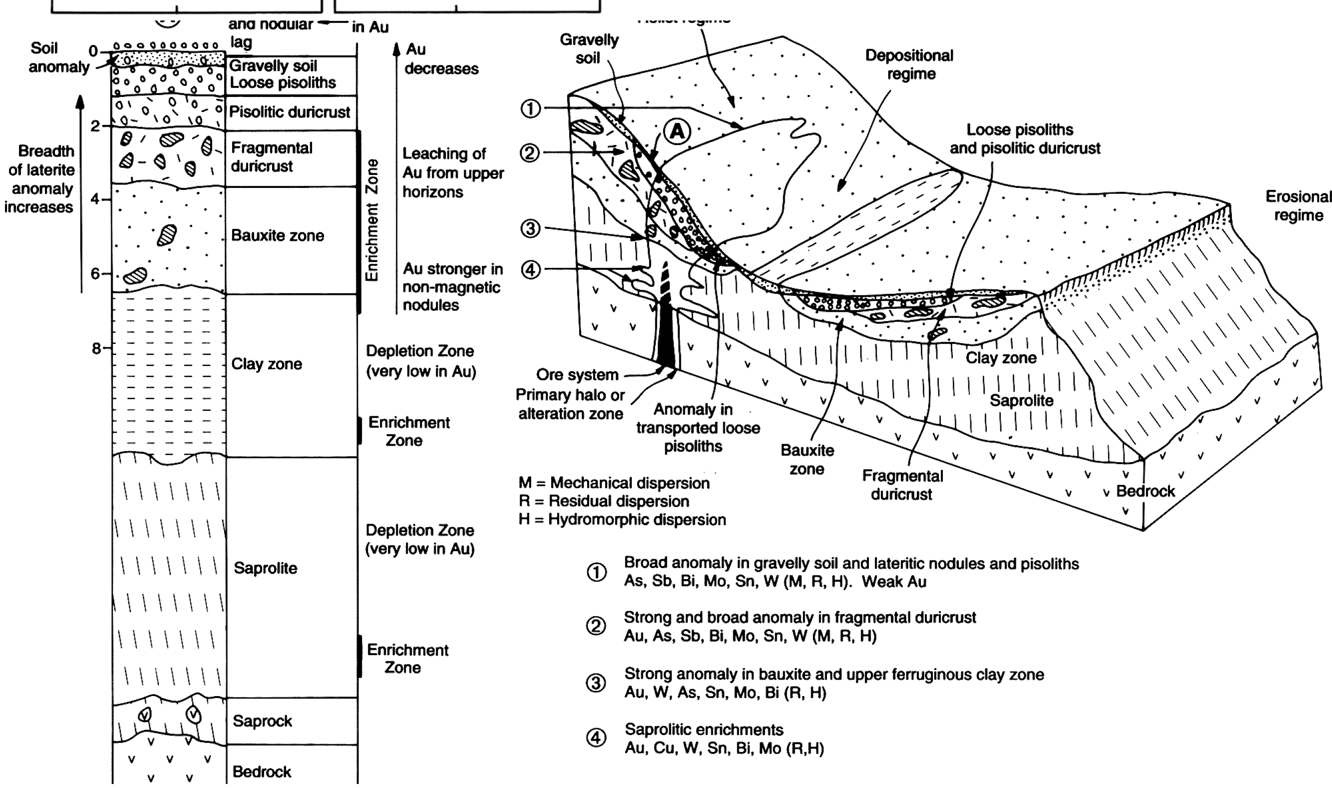


Figure 6: *Geochemical maps showing the distribution of Au, As, Pb and Bi in nodular lateritic gravel (the upper part of lateritic residuum) in the Mt Gibson gold mining district, Yilgarn Craton. Samples are distributed each 200 m along east-west lines that are 200 m apart, with some fill-in sampling.*

Figure 7: *Geochemical dispersion model for the Boddington gold deposit, Western Australia. The column shows the stratigraphy through the regolith for the upland part of the model. (From Anand, 1994).*



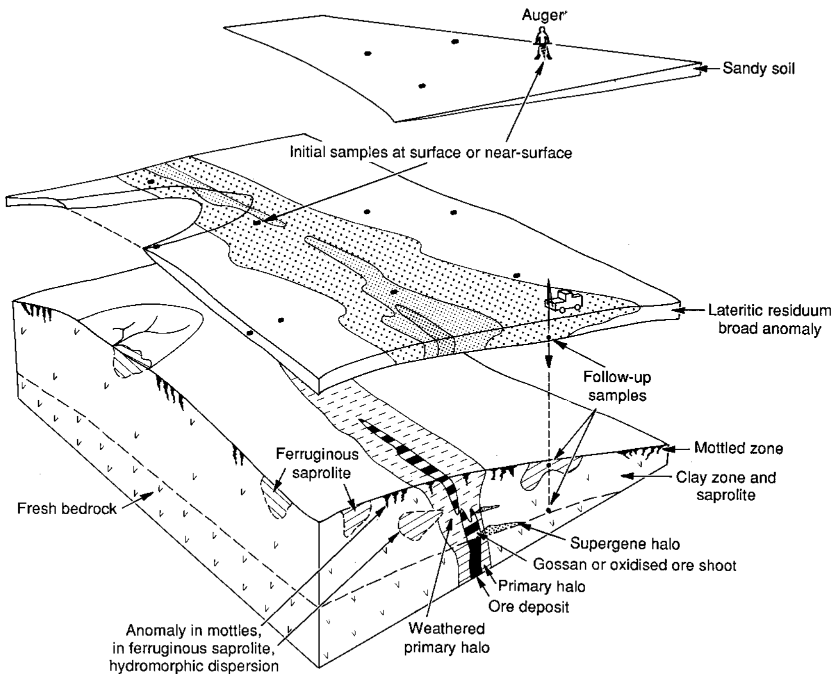


Figure 8: *Block diagram showing dispersion model where the full lateritic profile is essentially preserved and occurs at or near surface. (From Smith et al., 1992).*

EXPLORATION MODELS AND THEIR PRACTICAL APPLICATIONS

Exploration model for exposed lateritic weathering surfaces

A generalised model recognised in orientation studies which incorporates weathering processes and the inherent geochemical dispersion is shown in Figure 8. The shape, size and type of an ore deposit target will vary from case to case and this will influence the characteristics of the dispersion haloes. The most ideal situation is where the lateritic residuum has formed directly from a high-contrast ore deposit. However, weathering of a primary halo in many cases can be sufficient to provide a recognisable halo in lateritic residuum. The model and various derivatives have been applied with considerable success, notably in gold exploration.

Several weathering processes are involved. Residual accumulations of resistate minerals and of Fe-oxyhydroxides has occurred as leachable elements were removed during weathering culminating in physical collapse of the upper saprolite and ferruginous zones in some of the weathering situations. Hydromorphic dispersion has also commonly taken place during lateritisation (which may or may not be continuing under present-day conditions). Hydromorphic dispersion also can continue post-lateritisation. Mechanical dispersion affects elements (such as Sn, Au, Cr, W and Zr) held in resistant mineral grains. Mechanical dispersion of ferruginous blocks, cobbles, nodules and pisoliths can carry elements such as As, Sb, Cu, Pb and Au, that have an affinity for the Fe-oxyhydroxides.

Orientation studies and exploration campaigns have shown that anomaly size is enlarged over the size of the source ore deposit, commonly being 100 to 400 times greater in area (Smith *et al.*, 1992). Many anomaly targets are a kilometre or more across; some, such as for the Boddington gold deposit (Anand, 1994), or the Greenbushes rare metal pegmatite deposit, being several kilometres in dimension (Smith *et al.*, 1987).

Laterite geochemistry is most powerful when multi-element analyses are carried out. This enables multi-commodity exploration, optimum target recognition, as well as providing information in terms of host rocks and possible alteration zones. In Au exploration, Au is the most direct element to use and analysing for Au alone may be adequate to locate and define dispersion anomalies. However, the precaution applies that Au can be leached from the immediate surface in high rainfall regions, mentioned above for Boddington. Other elements such as As, Sb, Bi, Mo, In, Ag, Sn, Ge, and W increase the effectiveness of anomaly recognition, and allow delineation of the source of anomalies, at the same time broadening the commodity types. For base metal exploration combinations of Cu, Pb, Zn, As, Sb, Bi, Mo, Sn, W, Ag and Au or Ni, Cu, Co, Cr are used, and in some cases REE; for rare metals Sn, Nb, Ta, Y, As, Sb, Bi, Mo, W and REE. Diamond exploration can use Cr, Ni, Nb, As, and rare earth elements for host rock identification, followed up by mineralogical studies either of anomalous samples or of follow-up samples collected for mineralogical purposes.

Exploration successes in Australia include the world-class Plutonic Au deposit, which has resources of some 9.3 million ounces of Au (296 tonnes of Au), as well as the Nimary, Johnston Range and Dalgaranga Au deposits.

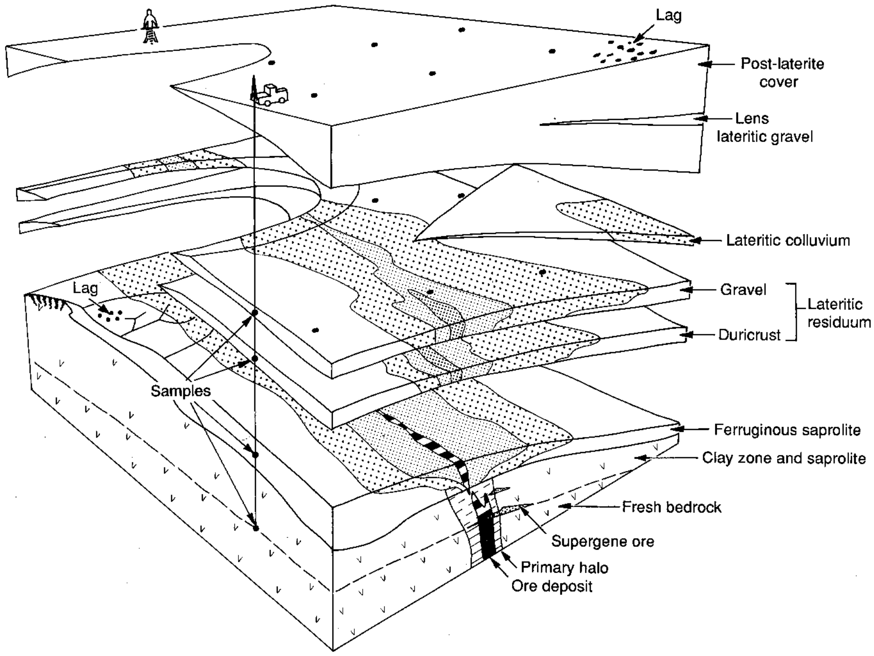


Figure 9: *Block diagram of a geochemical dispersion model where a lateritic paleosurface is buried beneath alluvium. Residual and transported regolith subdivisions are shown. (From Anand et al., 1993).*

Exploration model applicable where a lateritic surface is buried

It has now been recognised in Australia (and in parts of Mali) that alluvial plains in lateritic regions can have near-complete lateritic weathering profiles preserved at depth. Figure 9 shows the pronounced size of the dispersion halo preserved within buried lateritic residuum relative to the ore deposit source. In this diagram the lateritic residuum is subdivided into lateritic duricrust and the overlying lateritic gravel, which is a common situation. The dispersion haloes in both these units generally have similar element associations to each other, associations for different commodity targets being the same as where lateritic residuum is exposed.

However, lateritic residuum will not always be present beneath alluvial plains: it may not originally have formed everywhere, prior to burial, or it may not be uniformly preserved due to pre-burial erosion. An important early step in exploration of areas of transported cover is therefore to establish the regolith stratigraphy. This includes drilling to first detect, and then determine the extent of areas where the full laterite profile is preserved. In drilling to sample buried laterite, it is important to be able to recognise, then distinguish transported lateritic debris from residual laterite, bearing in mind that the unconformity at the base of transported cover may not be conspicuous. A degree of sophistication can be applied to exploration in areas of cover, and advanced methods are now routine with many exploration companies.

The approaches summarised in Figure 9 have contributed to discovery of several important ore deposits in Australia, including the world-class Bronzewing Au deposit in 1992, which has resources of some 3.3 million ounces of gold (103 tonnes of Au), as well as the smaller North, Turrett and Waroonga Au deposits in the Lawlers district in the period 1988–1991.

Application and sampling guidelines

In all of the approaches to exploration in lateritic terrain, it is important to establish regolith-landform control early in the program, preferably at the planning stage. This involves regolith-landform mapping (from air photography, satellite imagery, airborne radiometrics, radar, ground traverses, and from previous work), establishing regolith stratigraphy, and generating some knowledge of the characteristics of the different weathering zones or depositional units. Where exploration is focused on a district (say of 100–500 km^2) rather than on a large region, carrying out reconnaissance drilling specifically to establish regolith stratigraphy in areas of sedimentary cover, provides valuable data that should benefit planning.

Once the regolith-landform relationships for an area are understood, the details of a geochemical sampling program can be properly designed. Regolith-landform control is essential for proper interpretation of geochemical surveys, an example being discovery of the Jundee gold deposit (Wright and Herbison, 1995). This control is also important to the planning and interpretation of geophysical surveys.

The applicability of the models described above depends on the duricrust or lateritic nodules/pisoliths being a residuum, and this needs to be established for the terrain being explored. Transported lateritic pisoliths and nodules can also be used effectively provided they are recognised as such, e.g., as at Jundee.

The preferred choices of sample media are shown in Figure 10a for lateritic residuum at or near the surface, and in Figure 10b where it is likely to occur subsurface. Sampling of lateritic residuum is the first choice in both the situations. This is generally straight forward for the situations shown in A. The buried situations, B, clearly require skill in recognising the different regolith units.

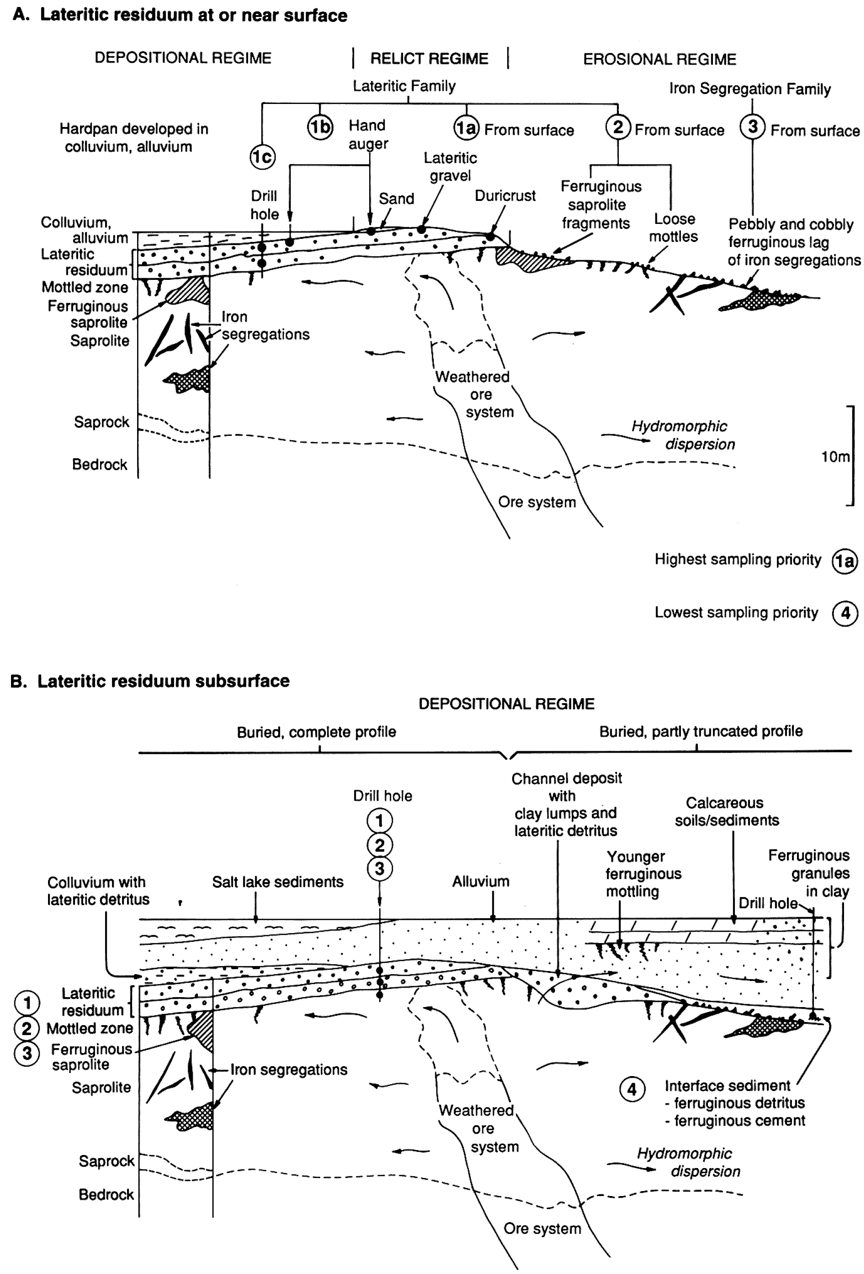


Figure 10: *Cross-section showing sampling preferences, (a) for an exposed lateritic surface; (b) for a buried lateritic surface. (From Smith et al., 1992).*

Recommended sampling guidelines for an exposed lateritic weathering surface

Select the sample site preferably using a regolith-landform map designed to provide control, otherwise use sketches or diagrams showing typical field settings, e.g., Figure 10a. Sample spacing will depend on factors such as the size and shape of expected anomalies, the likely shape and attitude of expected ore deposits, the dip of the bedrock succession, the known ore potential of an area and whether this is the first exploration program in a district or region. For reconnaissance, 3-km sampling can be appropriate for a first pass, particularly in unexplored regions. However, spacings of say 1 km on a regular grid are more appropriate for Au and base metal exploration where some previous exploration has been carried out. Spacings of 800 m and 400 m closing to 200 m, are commonly effective in Au exploration. Have a suitably trained geologist work closely with the sampling team(s). Mark the sample site so that re-visiting is possible. Take two samples, each of 1 kg; one for crushing and analysis, the other for future reference. Collect a sample over a 5–10 m radius to even out possible local variation. In choosing the actual sample site, be prepared to vary its position if this is necessary, even by some hundreds of metres in reconnaissance sampling in order to obtain the preferred sample medium. If sampling a duricrust, break off 10 to 20 pieces, again over a 5–10 m radius, rather than base the sample on just one piece. Where sampling lateritic pisoliths and nodules preferably take material in the 1–2 cm size range. This guards against the possibility of a particularly large nodule skewing the results in a sample. Sieving can be useful; however, hand-picking can be very effective. Research to date has shown that there is no geochemical advantage in sampling magnetic pisoliths or nodules. In several cases studied, the magnetic fraction is worse. Some surveys sample lag, commonly using the 2–6-mm size fraction swept from the ground surface. In relict regimes this collects the finer lateritic pisoliths and nodules. Where lateritic residuum is missing, ferruginous mottles or ferruginous saprolite may be sampled, both of which can form a coarse lag.

Non-metallic milling is preferred, using alumina, agate or zirconia. However, milling in hardened Mn-steel has also been used successfully and provides a higher sample throughput.

In laterite geochemistry, analytical methods that give the total amount of an element present should be used. This will commonly involve more than one method to give coverage of the elements required, e.g., combinations of instrumental neutron activation analysis (INAA), inductively coupled plasma with fusion for digestion (ICP), ICP mass spectrometry (ICP-MS), and atomic absorption spectrophotometry (AAS).

It is important to apply consistent terminology to samples and to have a classification scheme linked to that terminology. A code that provides the sample type for each sample needs to be entered into the geochemical database. Broad groups can be defined for compatible sample types (e.g., lateritic duricrust, lateritic nodules, lateritic pisoliths, and ferruginous saprolite being compatible in reconnaissance). Smith *et al.* (1991) provide a discussion of such concepts as applied to lateritic terrains.

Many methods can be used for anomaly ranking. The most important criteria are: the strength of key elements (e.g., Au, Cu, As), the element association, the consistency of the anomaly in terms of follow-up sampling, the regolith-landform setting (e.g., whether in situ or transported), the geological setting, and supporting geophysical information.

Systematically sampling a buried lateritic surface

The recommended steps are:

Drill to establish the stratigraphy (e.g., Figure 10b) through the transported and in situ regolith units on a scout basis using aircore, reverse circulation percussion or rotary air blast drilling. Diamond drilling is rarely done to establish stratigraphy because of cost. Ground geophysical methods can be useful in delineating regolith stratigraphy. Systematic drilling then follows using expectations of likely anomaly size. Drill holes may be widely spaced, such as 1 km on a regular grid, or may be irregularly spaced along access tracks. Where the mineral potential of an area is known to be high, drilling on a grid basis with spacings of 800 m or as close as 200 m may be appropriate. Initial drill holes should be logged from fresh rock upwards until the regolith stratigraphy becomes familiar. Be aware that more than one period of intense weathering may have affected the area and that deeply weathered alluvium can have ferruginous mottling. This must be recognised and not mistaken as in situ ferruginous weathering of basement.

A sample from the bottom of the hole, preferably unweathered rock, should be analysed as well as samples from the lateritic surface. In some drilling programs, systematic samples through the saprolite zone will also be analysed. At the stage of anomaly testing, bedrock and saprolite samples will give information on any direct intersections of mineralisation, while the lateritic surface will be providing a sample of a greater area of influence. An anomalous lateritic sample can indicate proximity to a substantial ore deposit assisting in discriminating against an insignificant occurrence of mineralisation. Deep diamond drilling beneath highly ranked anomalies is essential.

The preferred sample choice is: pisolitic or nodular lateritic residuum (can be lateritic gravel or lateritic duricrust), basal pisolitic colluvium (useful in near-miss situations), ferruginous saprolite, ferruginous mottles in upper saprolite, or iron segregations in upper saprolite. Where practical, aim for 1 kg of sample. Generally each 1 m internal through a lateritic surface will be sampled and analysed separately. Analysing basal lateritic duricrust or ferruginous saprolite will give information most closely related to the saprolitic or bedrock substrates.

The analytical suite can be the same as for samples from exposed laterite, and the sample preparation is the same. Care is required, however, in interpretation of W anomalies since tungsten carbide is commonly used on wearing surfaces of drilling bits and inevitably introduces some contamination of W.

Exploration in areas of sedimentary basin cover

Exploration in areas where a widespread sedimentary sequence overlies deeply weathered bedrock presents unique problems. Delineating geochemical anomalies in buried weathered bedrock can only be achieved by drilling. Whilst geochemical haloes may extend into the overlying cover sediments, these haloes may well have very different configurations to the underlying bedrock, due to sediment transport and differing ground water regimes. Mineralogical signatures within the cover sediment (a valuable clue to provenance) reflect mechanical transport pathways which are strongly influenced by regional factors such as tectonism, climate and eustasy.

Figure 11 shows a model incorporating the ingredients seen as being particularly important. The model shows a gold-bearing, base metal deposit in the basement. It is weathered over its uppermost 100 m, resulting in strong gossan formation and a lower supergene zone characterised by native Cu, bornite, chalcocite, overlain by a supergene zone for Au. The weathered ore deposit has been buried beneath some 150 m of basin cover. At the base is a locally derived sediment that can contain detritus arising from the weathered ore system. In addition, weathering has continued after deposition of the cover sequence. From the water table downwards the cover sequence and weathered bedrock are saturated with ground water. A hydromorphic leakage anomaly is shown extending laterally in the weathered bedrock and through the cover sequence, the latter a result of concordant aquifer flow. Upward leakage of ground water, through evaporation and evapotranspiration, fault-controlled conduits and mound springs, has added to the hydromorphic dispersion.

Exploration of regions for which the model proposed in Figure 11 applies, would begin with airborne geophysical methods and would also involve ground geophysical follow-up as described by Craske (1995).

Geochemical exploration would start by seeking ore deposit expression in any sporadic areas of basement outcrop or subcrop. This would be followed by reconnaissance drilling to establish regolith stratigraphy and for geochemical screening of geophysical anomalies. Drilling then would allow systematic sampling through buried weathering profiles, seeking in particular, any supergene zones, realising that these may only

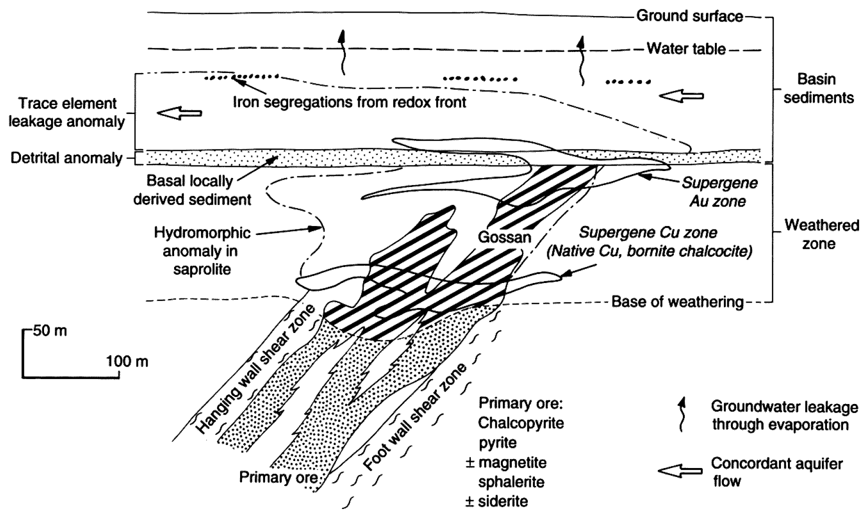


Figure 11: *Conceptual model for areas where sedimentary basin cover sediments lie on a paleoweathering surface. Weathering has continued after burial, providing opportunities for geochemical anomalies to form in the basin sediments, such as in the iron segregations, formation waters, and basal sediments.*

be detected chemically. The basal sediments would also be sampled. However, there should also be some systematic sampling of the cover sequence to detect any substantial geochemical leakage anomaly. Possibilities of anomalous mobile metal ions at surface should also be tested.

The analytical suite of elements for Au and base metal exploration, using the model in Figure 11, would be some combinations of: Au, Cu, Pb, Zn, Ni, Co, As, Sb, Bu, In, Mo, Sn, W, and Ge. In addition, elements including Fe, Mn, Ca will give some of the required information on the nature of the material being sampled.

CONCLUSIONS AND RECOMMENDATIONS

The exploration methods described in this paper are expected to be effective empirically, and the models to a large extent generically, in lateritic terrains across the globe, emphasis initially being on areas of exposed lateritic surfaces. Application is likely to be particularly fertile in frontier regions such as western and central Africa, and Brazil besides the established use in Australia. There is a critical need for comprehensive orientation studies in the new regions being explored, even though studies in Australia can provide some initial guides to expectations. Knowledge of thresholds and variations for elements of interest also need to be established in the regions being explored. As knowledge of regolith-landscape evolution becomes better understood in each of the continents, sophisticated variations of the exploration methods presented here can be expected. It is known, for example, that there have been major global changes in climate through the Cenozoic. Also the position of Australia and India have changed substantially from polar latitudes 250 million years ago to low latitudes during their northward drift, whereas Africa and South America have remained at about their present latitudes over that period. The implications of these changes to exploration geochemistry need to be established.

Exploration directed at lateritic surfaces under cover should be carried out in areas where high exploration potential has been shown from exploration of the adjacent outcropping areas or from exploration of areas where laterite is at surface.

Exploration of areas of sedimentary basin cover will continue to focus where the cover is relatively thin. The first wave of exploration in such areas almost invariably is heavily dependent on airborne geophysical surveys, typically airborne magnetics, perhaps airborne electromagnetics, with ground geophysical follow-up. Hence, initial targeting based on geophysical parameters is to be expected. After the most prominent geophysical anomalies have been tested there commonly are too many subsidiary anomalies for all to be drilled, thus the need for soundly based screening methods. Exploration models which take into account paleoweathering surfaces and inherent geochemical dispersion, should be applied. Sophisticated models should draw upon hydrogeology, geochemistry, landscape evolution and sedimentary pathways analysis. Increasing use should be made of hydrogeochemistry using isotopes as well as abundance levels of individual elements.

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