Geochemical Exploration in Areas Affected by Tropical Weathering — An Industry Perspective

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ABSTRACT

The thickness and complexity of the regolith in areas affected by tropical weathering, present or past, has tended to intimidate explorationists when applying geochemical techniques. Recent industry experience in Australia, covering a wide geographic range and variety of regolith types, indicates that appropriate low cost surface geochemical techniques have been deployed effectively in such terrains. Cost-effective geochemical exploration in areas affected by tropical weathering, as everywhere else, requires the application of techniques appropriate not only to regolith constraints, but also to the stage of exploration, and which are optimised with respect to fundamental factors such as sampling density, analytical and anomaly recognition techniques.

INTRODUCTION

Ten years ago at Exploration '87, it was asserted that Australian explorers were over-cautious with regard to the complexity of the regolith in areas of deeply weathered terrain, to the extent that bedrock geochemical drilling was commonly used in many programs where surface techniques would have been more appropriate, both technically and financially (Mazzucchelli, 1989). It is pleasing to note that surface geochemistry has enjoyed a major revival in Australia and is currently also achieving great success in similar areas affected by tropical weathering, past and present, throughout the world. This paper examines the impact of deep weathering on geochemical search technology and how the mineral exploration industry has sought to meet the challenge of exploring in areas affected by tropical weathering.

AREAS AFFECTED BY TROPICAL WEATHERING

Many of the areas currently the focus of mineral exploration throughout the world are affected by tropical weathering. These include not only the present-day tropical climatic zone, but also terrains like the Yilgarn Block of Western Australia, which have undergone multiple cycles of tropical weathering through the Mesozoic and Tertiary, the imprint of which has survived the change to a more arid climate. The common characteristic of all these areas is deep weathering, modified to varying degrees by erosion and any subsequent depositional processes. This can lead to a thick and complex regolith.

Generally speaking, the regolith in areas of present-day tropical weathering is less complex, and presents fewer problems to explorers than former tropical terrains that have subsequently become arid. This can be attributed a level of precipitation sufficient to maintain a balance between weathering and erosion. The resulting regolith typically consists of "tropical red earths", a friable mixture of kaolin and iron oxides, with little differentiation, overlying variably leached saprolite extending to depths of up to 100 m (Ollier and Pain, 1996). Ferruginous duricrusts are not unknown within tropical terrains, and are usually interpreted as preserved indications of earlier weathering cycles.

With the change to aridity, drainage becomes intermittent and channels become choked with deposited sediments, impeding erosion and resulting in a buildup of transported materials over the retained products of earlier deep weathering. Loosely bound detritus may be redistributed over the landscape by wind action. The soluble products of weathering are no longer removed by the drainage system, resulting in increased groundwater salinity, the accumulation of pedogenic carbonate and gypsum in near-surface horizons, and the coating of outcrops with ferruginous and manganiferous "desert varnish".

The impact of change to an arid climate is most pronounced in areas of low topographic relief, such as the Yilgarn Block of Western Australia, which is probably unique in the complexity of its regolith. In areas of high relief, such as parts of the Arabian Peninsula, the mantle of deeply weathered rock generated by tropical weathering in the Tertiary has been stripped by erosion, due largely to tectonic uplift related to the Red Sea rifting (Salpeteur and Sabir, 1989). In Patagonia, the products of deep tropical weathering were partially stripped in the Pleistocene by glaciation, and although the present regolith is complicated locally by marine sedimentary sequences and extensive sheets of reworked glacial gravels, this is unrelated to the current arid climate.

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Understanding of landform and regolith relationships in the Yilgarn Block has been greatly enhanced by the intensive and long-term research program by Australia's CSIRO Division of Exploration and Mining, and, more recently, the Cooperative Reseach Centre for Landscape Evolution and Mineral Exploration (Smith, 1996). As part of this program, it has been confirmed that geochemical indications of bedrock mineralisation can persist through weathered residuum 50 m or more thick, and are detectable in near-surface lateritic samples (Smith, 1989). More recently, the same group has found evidence for upward dispersion of Au through transported overburden, generating anomalies in near-surface pedogenic carbonate horizons (Lintern and Butt, 1993). These are two of the dispersion mechanisms which explain the recent exploration successes achieved by industry groups in terrains which a decade ago were considered unsuitable for surface geochemical techniques.

GEOCHEMICAL EXPLORATION—INDUSTRY EXPERIENCE

Gold exploration

Table 1 summarises the gold discovery case histories presented at the recent Conference on "New Generation Gold Mines: Case Histories of Discovery" (Australian Mineral Foundation, 1995), in terms of the role played by geochemical methods, and the nature of the regolith. The locations of these and other deposits to which reference is made in this paper are shown on Figure 1. Of the 16 case histories, all but one mention geochemistry as playing a significant role, if not the crucial role in discovery, and all but two of these involved the application of surface geochemical techniques. It can be concluded from this that the intelligent

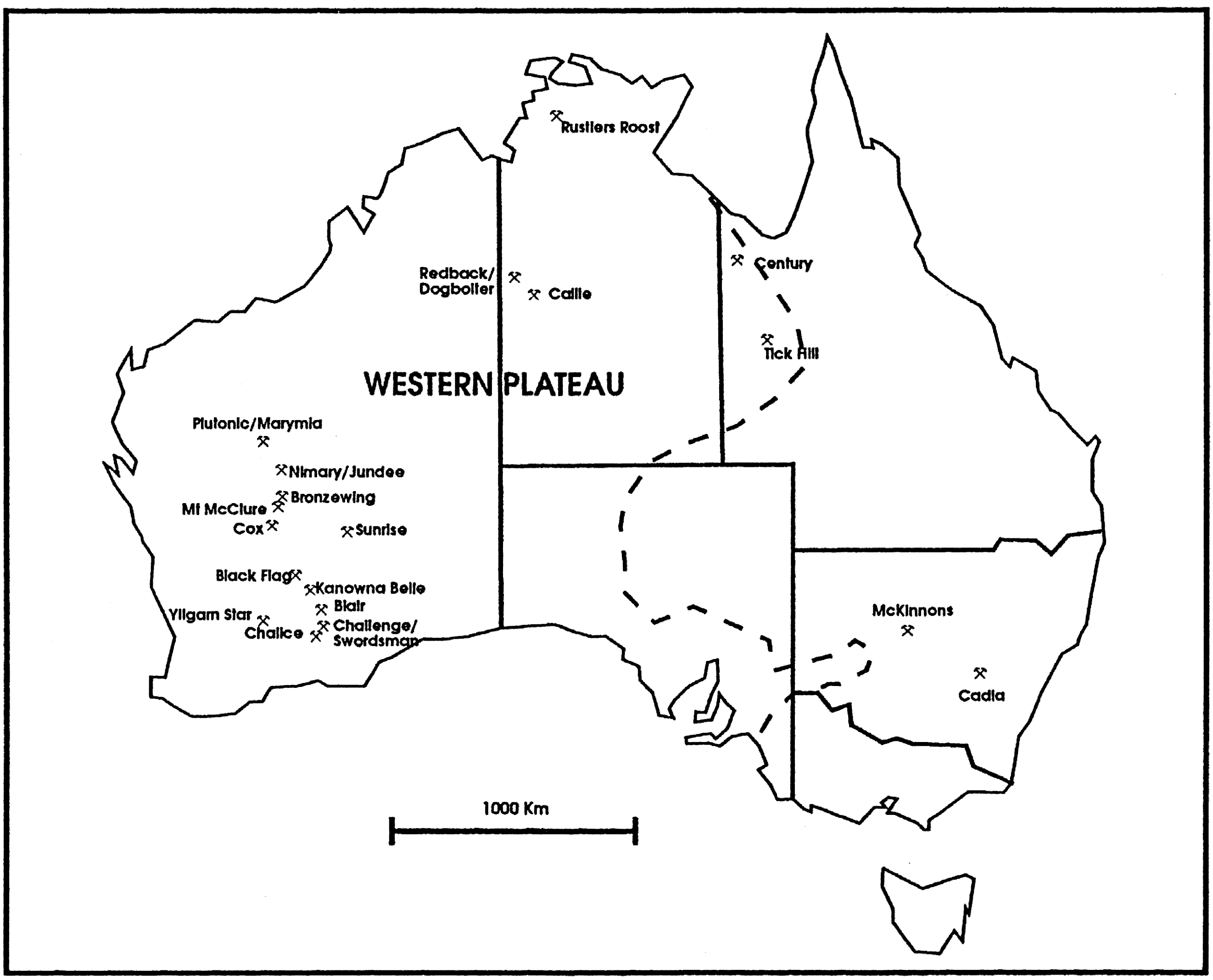

Figure 1: *Plan showing location of case histories and area of Western Plateau (after Mabbutt, 1980).*

application of simple surface techniques in prospective areas is still yielding discoveries, despite the acknowledged complexity of the regolith over a wide geographic range. This in turn implies that the surface geochemical techniques applied are very robust, an attribute that takes two forms—the ability of different geochemical techniques to show essentially the same dispersion patterns related to mineralisation; and the ability of a given technique to reflect bedrock mineralisation through a range of regolith types and thicknesses.

The Plutonic mine, found in 1988 in a poorly explored Archean basement inlier between the Yilgarn and Pilbara Cratons, is a typical Archean greenstone gold occurrence with significant lateritic and supergene components, which could have been found by any one of several geochemical techniques (Bucknell, 1995). Anomalous Au response was obtained in initial reconnaissance sampling in 1987 in stream sediment concentrates (up to 46 ppm), soil (180 ppb) and rock-chip (180 ppb) samples. Subsequent geochemical surveys included laterite pebble reconnaissance on a 1600-m by 800-m grid, which yielded up to 1.18 ppm Au, systematic lag sampling on a 240-m by 60-m grid and finally soil sampling. The dispersion pattern for Au in soil shows that peak values exceeding 700 ppb Au occur in the vicinity of ore occurrences, whilst the full extent of anomalous values (>5 ppb Au) occupies an area in excess of 3 km^2, an anomaly that would be difficult to miss in systematic geochemical reconnaissance.

The Bulk Leach Extractable Gold (BLEG) technique, sometimes called BCL for Bulk Cyanide Leach, originally developed to cope with the low concentration levels and the 'nugget' effect in drainage surveys for gold, has also been widely used in soil sampling. In many cases, results obtained using BLEG analysis are essentially comparable with results for "total" (hot aqua regia digestion) on soils or lags. Both BLEG and "total" analyses of soil samples were used in the course of exploration for the Kanowna Belle deposit, 18 km northeast of Kalgoorlie, and the results of the two methods were found to give "comparable" results (Gellatly *et al.*, 1995). Initial indications for the Mt McClure deposits in the northern Yilgarn Block came from anomalous lag samples (Au to 900 ppb and As to 840 ppm), but the main ore deposits were ultimately delineated by a BLEG soil survey using a threshold of 3 ppb (Otterman and de San Miguel, 1995). Figure 2 demonstrates the close correlation between BLEG soils and lag geochemistry as shown by two independent orientation surveys over the same grid line in an area in the northern Yilgarn Block, the samples being taken by different operators at different times and processed in different laboratories. Either technique would clearly show the same features, but the lag profile has stronger anomaly contrast and has cost and logistical advantages over BLEG. A lag survey by Wiluna Mines Ltd. based on these results, subsequently located the 500,000-ounce Cox deposit in an area previously subjected to intensive but unsuccessful RAB (Rotary Air Blast) drilling for bedrock samples.

The effectiveness of surface techniques under varying regolith conditions is exemplified by a major soil geochemistry program conducted over a 400-km^2 area at Black Flag, to the northwest of Kalgoorlie (Mazzucchelli, 1996). The same technique was applied throughout the area—near-surface soils were sampled at depths of 10–20 cm, on sampling grids varied from 400 m by 100 ms in reconnaissance, to 40 m by 40 m for detailed delineation of anomalies prior to drilling. The <2-mm fraction of soil samples was pulverised and analysed for gold to 1 ppb by graphite furnace AAS, following an aqua regia digestion. Strong response to bedrock mineralisation was recorded in a wide variety of regolith/landform situations, including complete laterite profiles, partially stripped profiles and within playa lakes, where the material sampled was essentially leached saprolite under 5 cm or so of transported lake sediment. Some areas at Black Flag that had been explored previously, allowed comparisons between geochemical dispersion patterns documented by different methods. At the Woops prospect, near-surface soil samples taken over a complete laterite profile show essentially the same anomalies over gabbro-hosted gold mineralisation as deeper (1–2 m) auger samples from within the ferricrete horizon, although Au abundances were lower. BLEG and aqua regia results on soils show comparable features over the Accord laterite/oxide deposit. The soil geochemistry provided a much more definitive indication of the Zsa Zsa mineralisation in the Black Flag area than an earlier bedrock drilling survey, despite weathering depths up to 100 m.

Soil sampling has proven surprisingly effective in detecting mineralisation concealed by transported overburden. Of the case histories covered at the AMF Conference (AMF, 1995), Chalice, Sunrise and possibly Kanowna Belle are examples of the successful application of near-

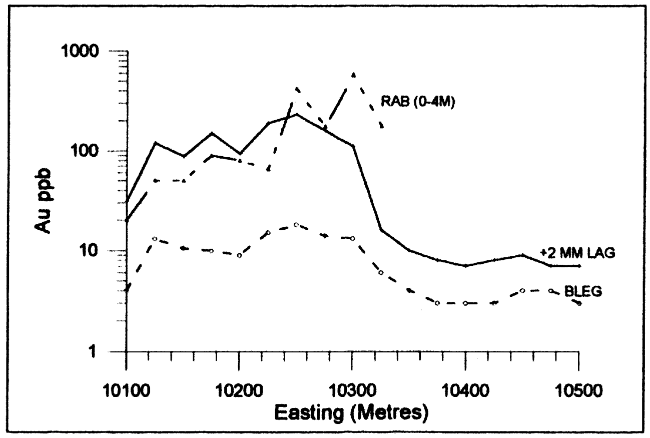

Figure 2: *Lag and BLEG orientation results—Cox deposit, northern Yilgarn Block, Western Australia.*

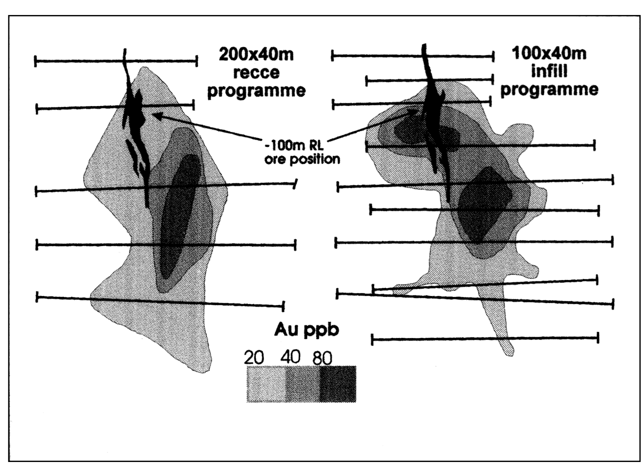

Figure 3: *Chalice gold deposit soil geochemistry (from Bonwick, 1995).*

Table 1: ***Importance of geochemistry and regolith considerations in recent Australian gold discoveries (adapted from Australian Mineral Foundation, 1996).***

Deposit	Resource (million ounces)	Upper regolith	Geochemistry Type	Geochemistry Impact[1]
Yilgarn Star	1.6	Clay 2–5 m	Soil	Definitive
Bronzewing	3.1	Transported 2–50 m	Buried Laterite	Primary
Mt. McClure	0.9+	Shallow Residual (?)	Lag, Soil	Definitive
Nimary	0.7+	Shallow Residual	Lateritic Lag	Primary
Jundee	1.3	Shallow Residual (?)	Lag	Primary
Callie	1.1	Aeolian Sand 5 m	Bedrock	Primary
Redback/ Dogbolter	0.6	Aeolian Sand/ Laterite	Soil, Laterite	Primary
Chalice	0.5	Thin Transported	Soil	Primary
Sunrise	1.25	Transported	Soil	Definitive
Cadia	8.3	Transported	Auger Soil	Definitive
Rustler's Roost	1.3	Shallow Residual (?)	Drainage	Incidental
McKinnons	0.1	Residual (?)	Drainage	Incidental
Tick Hill	0.4	Residual	Drainage, Soil	Primary
Kanowna Belle	4.0	Residual/Transported 2–5 m	Soil	Definitive
Marymia	1.0	Shallow Residual (?)	Soil	Ancillary/ Definitive
Plutonic	7.2	Shallow Residual (?)	Lateritic Lag, Soil	Primary

1. Impact classifications:
Primary: leading technique in exploration program which located ore.
Definitive: may not have been first indication but critical technique in discovery.
Ancillary: geochemistry supported data from other techniques in discovery process.
Incidental: discovery independent of geochemistry, but available data show geochemistry would have been effective if other technique had not been used

surface sampling locating mineralisation through transported overburden. The progressive definition of the soil anomaly which led to the discovery of the Chalice deposit, shown in Figure 3, illustrates how the deposit would have been missed if a follow-up sampling program had not been carried out (Bonwick, 1995). Initial drilling on the peak of the anomaly located by the reconnaissance soil survey intersected subeconomic supergene mineralisation associated with a footwall lode, some 120 m east of the main Chalice lode (Bonwick, 1995).

Several of the important paleochannel deposits recently mined in Western Australia have been located by soil sampling, despite transported cover of 20 to 40 m. These deposits are closely associated with a major drainage network of Tertiary age now buried below the current peneplain surface. The complete Tertiary sequence, which ranges from 15 to 40 m thick, consists of basal sands and grits overlain by mottled clays and laterite (Commander *et al.*, 1991). The gold found in paleochannel deposits may have originated as placers but has been chemically redistributed, now occurring in discrete lenses, often extending into the saprolite below the gritty base to the stream channel. The surface soil anomalies associated with paleochannel deposits tend to be diffuse and of relatively low contrast. For example, the geochemical anomaly that led to the discovery of the small Palace paleochannel deposit (85,000 tonnes at 4.45 g/t Au) was a local peak of 80 ppb within an anomaly measuring 800 m by 300 m at the 30 ppb level (Mazzucchelli, 1996). The much larger Challenge-Swordsman deposits were found in the Higginsville area using similar surface soil sampling techniques (Bonwick, 1995).

Base metals

Geochemistry has played a prominent role in the few major base metal discoveries made in Australia in recent years. Basic soil geochemistry contributed substantially to the discovery of the major Century deposit (118 million tonnes averaging 10.2% Zn, 1.5% Pb and 36 g/t Ag) in northwest Queensland (Broadbent, 1995). The initial indication leading to the discovery was a soil anomaly over a width of 1600 m with Zn values ranging from 400 to 1000 ppm Zn, and erratic high Pb values, located by sampling regional geophysical traverses. Retrospective drainage sampling carried out post-discovery showed that the deposit could

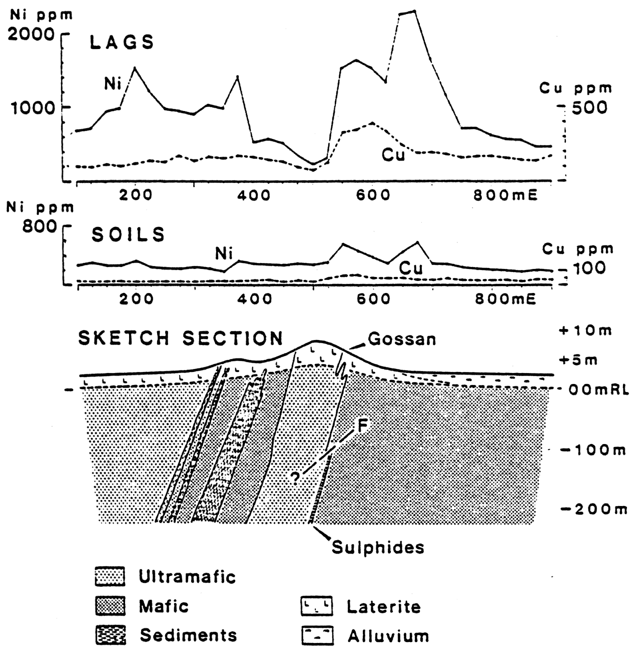

Figure 4: *Geochemical profiles for Ni and Cu in −6+2 mm lags and −200 μm soils over Ni sulphide mineralization, Blair Shoot, Yilgarn Block, Western Australia (from Carver et al., 1987).*

also have been found by sampling either the −80 mesh or −20+40 mesh fraction of stream sediments (A. Eggo, pers. comm., 1997).

Lag surveys often generate similar dispersion patterns to soils in gold exploration but provide better results in the search for base metals in areas of deep lateritic weathering. In such terrains, geochemical contrast may be much greater in lateritic lag than in soil developed over leached saprolite, as shown by profiles for Ni and Cu over the Blair nickel deposit, 30 km southeast of Kalgoorlie (Figure 4). Similar findings have been reported for VMS sulphide deposits, where the base metals Cu and Zn, which are the major components of the ore, are drastically leached from surface soils. Strong geochemical response related to the Golden Grove Cu-Zn deposits was shown in near-surface lateritic pisolites, being particularly marked for chalcophile pathfinder elements such as As, Sb, Bi, Mo and Sn (Smith and Perdrix, 1983).

COPING WITH THE TROPICAL REGOLITH

Australian explorers have clearly developed effective geochemical strategies for overcoming problems inherent to deep tropical weathering, although there is as yet no general consensus on the methods applied. Figure 5 shows geomorphology (here considered to include both regolith and landform attributes), along with theoretical factors, previous experience, and data from orientation surveys as critically important inputs to the design of a geochemical survey. In practice, geomorphology also comes under consideration during the sampling and interpretation phases.

Design

The geomorphology of an area is probably the major factor determining the types of geochemical techniques applicable in exploration. Depending on a broad assessment of geomorphology it is possible to develop a strategy for application of techniques in a logical sequence, flowing from reconnaissance of large areas, with different techniques as the area of interest is reduced and the search becomes more detailed. An example of such a flowsheet developed for the Western Plateau of Australia (shown in Figure 1), which includes the Yilgarn Block, is shown in Figure 6. Over large parts of the world, irrespective of climate, the basic sequence is stream sediment, soil, weathered bedrock, fresh bedrock. This sequence is exemplified by the discovery of the Tick Hill deposit in northwest Queensland, which was found during a regional reconnaissance survey targeted at both base metals and gold (Forrestal *et al.*, 1995). The deposit was initially detected as a BLEG drainage anomaly, the source of which was delineated by a BLEG soil survey, and then tested by trenching and ultimately drilling to prove the resource. A successful case history resulting from the use of a similar staged geochemical exploration program outside Australia was the discovery of the Jenipapo gold deposit in Brazil (Taufen and Morrow, 1994).

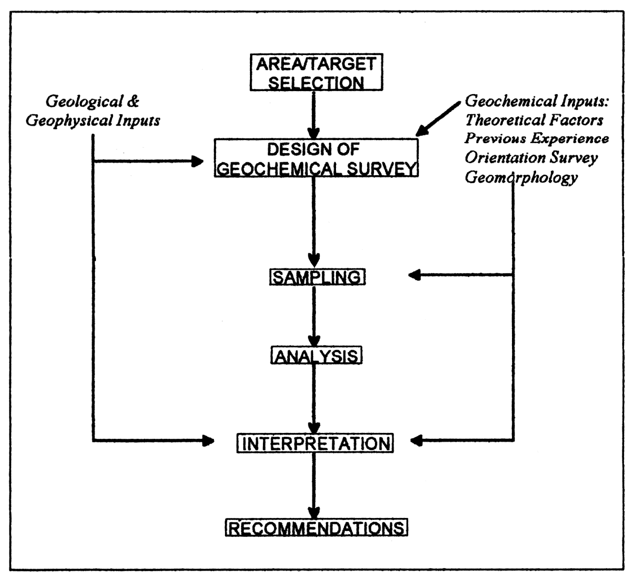

Figure 5: *Elements of a geochemical survey.*

The low relief in many parts of the Western Plateau of Australia generally precludes the application of stream sediment geochemistry, and the exploration sequence may need to include playa lake sediments, groundwater, lag and bedrock sampling. The major Bronzewing and Callie discoveries resulted from a more detailed analysis of geomorphology, indicating the likely concealment of prospective terrain by transported overburden, and hence the need for drilling for deep samples. In the case of Bronzewing the initial discovery was made by sampling a buried laterite under some 35 m of transported overburden (Eshuys *et al.*, 1995). The Callie discovery was made by drilling through aeolian

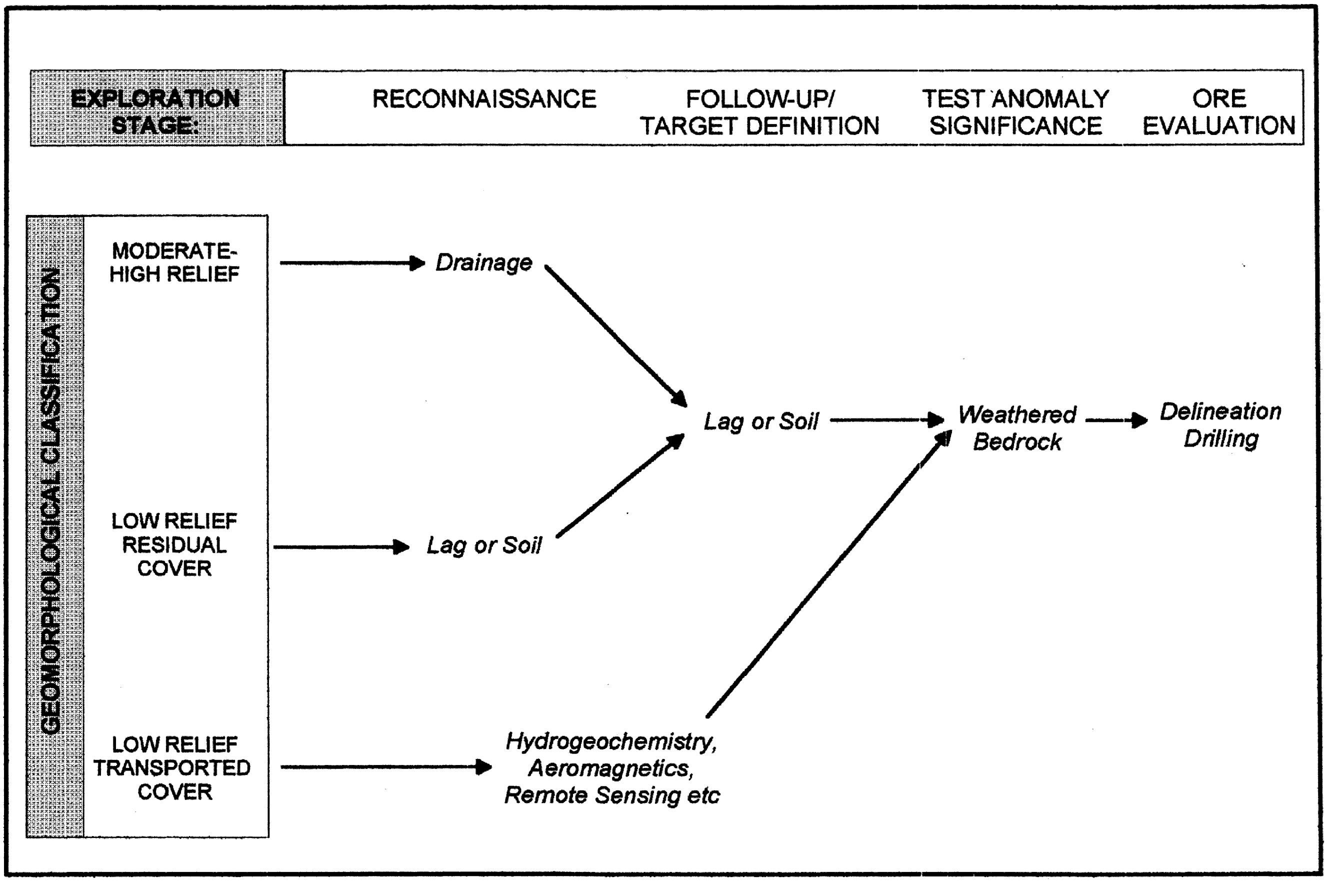

Figure 6: *Flowsheet for geochemical exploration, Western Plateau.*

sands and laterite for bedrock samples (Ireland, 1995). Both of these discoveries could be considered as examples of detailed exploration of concealed target zones within a highly prospective area, indicated by the presence of known mineralisation or other indications from surface geochemistry.

Sampling

No matter how detailed the pre-survey geomorphological mapping, it is never adequate to record all significant variations in the regolith, which can change dramatically over distances of tens of metres. It is therefore customary to record observations on geomorphology and regolith at sampling sites during geochemical surveys, to assist in the interpretation of the resulting analytical information. The level of detail for such descriptive schemes varies widely. Government research and geological survey organisations usually record detailed geomorphological and geological observations on the environment and sample characteristics at each sample site. A variety of schemes for describing regolith/landform characteristics have been proposed. The Geological Survey of Western Australia has developed a coding sytem based on the classification of the area into relict, erosional and depositional regimes for its Regolith Geochemistry Programme (Crawford *et al.*, 1996). The dispersion models proposed for tropically weathered terrains by Butt and Zeegers (1992) suggest a descriptive scheme based primarily on the degree of truncation of the deep weathering profile, with subcodes covering subsequent alteration to, and overburden deposition on the pre-existing profile.

Industry schemes tend to be more modest in their aims. Mazzucchelli (1996) describes such a scheme, which uses a code made up of three alphabet characters to describe the mechanical composition, distinguishing characteristics and interpreted genetic relationship to bedrock of soil samples.

Interpretation

The use of geomorphological data, either formally or informally, to qualify geochemical response in the interpretation stage is well documented in several of the case histories. The discovery of the Sunrise Deposit was due in part to recognizing the significance of subtle anomalies (10 to 50 ppb) in transported soils, after drilling of stronger response in residual soils had located marginally economic ore. The Jundee deposit was delineated by lag sampling, but careful interpretation of the dispersion patterns was required to discriminate bedrock-related anomalies from those of alluvial origin (Wright and Herbison, 1995). Statistical data from the Black Flag project implies the need for weighting of anomalies according to regolith type, i.e., according higher significance to weak anomalies in transported soils or soils over leached saprolite relative to skeletal or lateritic soils (Mazzucchelli, 1996).

DISCUSSION

The case history information presented above shows that the complex regolith in areas affected by tropical weathering is not an impediment to the use of surface geochemical techniques. A broad appreciation of the regolith/landform relationships is required initially to plan an appropriate geochemical strategy. Additional observations made during the sampling program can alert the geochemist to local departures from the dominant regolith profile, which can then be applied in the interpretation, either to qualify the anomalies located or to indicate the need for coverage by another search technique.

The surface geochemical techniques that have been developed in Australian exploration for gold take advantage of one or more of the dispersion processes by which geochemical evidence of bedrock gold mineralisation is brought to the surface (or retained at the surface), despite the frequently transported nature of some components of the regolith. These dispersion processes include:

- normal clastic dispersion processes (downslope movement, sheetwash, etc.);
- concentration of gold and associated pathfinder elements in lateritic sesquioxide particles, which are retained in the near-surface soils and lag pavements following degradation of the original lateritic profiles due to climate change;
- upward movement of gold-bearing groundwater and concentration by evaporative processes, usually with accumulations of pedogenic carbonate formed by a similar mechanism;
- uptake of anomalous gold from depth and deposition in surface soils through the vegetation cycle;
- bioturbation by burrowing animals such as termites, lizards and mammals.

The dispersion mechanisms responsible for anomalies in surface soils over paleochannel gold deposits are not yet known with any certainty. Evapotranspiration, vegetation cycling and the relict imprint from earlier clastic processes could all be important. However, the occurrence of geochemical anomalies over paleochannel deposits is sufficiently common to warrant the application of soil geochemistry, purely on empirical grounds, in the search for this type of ore body.

In areas affected by tropical weathering, as in other areas, an appropriate allowance for the regolith is just one of the factors that need to be taken into account to achieve success in geochemical exploration. Other equally important factors that are frequently neglected in industry programs include appropriate sampling patterns, analytical techniques and criteria for anomaly recognition.

A problem commonly encountered is the lack of adequate anomaly definition prior to drilling. The Chalice discovery cited earlier (Figure 3) is a classic example of the need for adequate follow-up prior to final drilling. This deposit would have been missed if the follow-up sampling program had not been carried out. Even the largest of gold deposits, particularly in the Archean, are groupings of small oreshoots often individually 100 to 200 m in strike length. It would be hypothetically possible to find such deposits by sampling soils on a 2000-m by 100-m grid, but still miss the ore body by drilling between shoots, unless follow-up sampling is adequate to define anomaly peaks.

Problems with the application of geochemical methods are frequently due to using analytical methods with inadequate sensitivity. Many geochemical surveys and even some research investigations purport to document dispersion patterns for Au using techniques with a detection limit of 5 to 20 ppb Au. An analytical technique sufficiently sensitive to characterise the background population is a fundamental requirement for anomaly recognition. Given that the average crustal abundance of Au is about 2 ppb and any given analytical method only achieves acceptable levels of precision at abundances 5 to 10 times the lower limit of detection, a method with sensitivity of 1 ppb is the minimum required for the adequate documentation of geochemical dispersion patterns for Au.

Another common failing of industry surveys is poor interpretation. Thresholds are still established by using inappropriate statistical criteria, often based on composite data sets that include samples associated with known mineralisation. This usually results in consideration of only the uppermost slice of anomalous dispersion patterns and the elimination of potentially significant lower order anomalies.

Exploration geochemistry seems very prone to look to fads and panaceas to solve perceived problems, whereas most shortcomings of geochemical surveys are found, on detailed investigation, to be due to poor application of geochemical fundamentals. In some cases, the reason for an unexpected dispersion pattern or lack thereof may not emerge for many years, when sufficient drilling has been completed to explain the geometry, size and grade of the bedrock source of a geochemical response.

CONCLUSIONS

Geochemical methods are currently enjoying unprecedented success and have gained a high level of acceptance by the mining and exploration industry in Australia and in many other countries with similar deep weathering profiles. This success has been achieved despite the diversity of methods employed and views held by different practitioners, indicating the robust nature of geochemical techniques. Near-surface techniques are still proving the most cost-effective geochemical exploration methods in industry programs. Provided these are applied judiciously with due regard to the selection of survey parameters to suit the landform/regolith constraints of the area to be explored, they will continue to generate discoveries both in Australia and elsewhere. Considerable progress has been made in recent times in understanding and mapping regolith complexity and the constraints it places on geochemical exploration techniques. There remains a need for the involvement of more specialist geochemists, with a strong background in the scope and fundamentals of geochemical prospecting, to minimise the detrimental impact of the periodic misuse of new developments in geochemical search technology.

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