AGSO Journal of Australian Geology & Geophysics, 17(4), 89–96

Supergene gold deposits

C.R.M. Butt

Cooperative Research Centre for Landscape Evolution and Mineral Exploration, c/- CSIRO Exploration and Mining, Private Mail Bag, PO Wembley, Western Australia 6014, Australia

EXPLORATION MODEL

Examples

Most gold deposits in terrains dominated by deep regolith have weathered mineralisation and/or supergene enrichment zones. Deposits having significant lateritic and/or saprolitic reserves include: Boddington, Mt Gibson, Plutonic, Mt McClure, Granny Smith,Sunrise Dam, Paddington, Panglo, Mt Percy, (Western Australia); Redback, Jim's Find, (Northern Territory); Um Nabardi, (Sudan); Syama, (Mali). Supergene gold in palaeochannel sediments and underlying saprolite: Kanowna, Lady Bountiful Extended, Challenge-Swordsman, (Western Australia).

Target

- Typically small; <1.5 Mt, with grades 1.5–5.0 g/t Au. May represent the only mineable reserves over otherwise uneconomic primary mineralisation.
- Commonly only a minor proportion of total reserves of major deposits, but yield early cash-flow.
- Small supergene deposits, generally mined as satellites to larger operations, or several combined (eg., in palaeochannel systems) to make an economic group.

Mining and treatment

- Shallow enrichment (generally <100 m) allows cost-effective assessment and open-cut mining.
- Treatments include on-site CIP/CIL or, for small deposits, heap-leach cyanidisation.
- Supergene sulphides, especially As- or Cu-rich, may cause problems by lowering pH and poisoning carbon. Ore generally free-milling with high total recovery.

Climate and geomorphology

- ***Lateritic deposits***: found in present-day rainforest, savanna, Mediterranean and semi-arid climates, but formed under seasonally humid conditions, probably warm to tropical, in regions of low to moderate relief
- ***Saprolitic deposits***: found and probably formed in semi-arid climates, low relief. Laterally extensive supergene enrichment zones in saprolite (and within and beneath palaeodrainage sediments) characteristically form in axes of saline drainages.

Mineralisation features

- Lateritic and saprolitic deposits may be present in same profile, separated by a 'depletion zone' with very low Au content.
- Only lateritic deposits occur in present humid tropics.
- Saprolitic deposits may be present if a lateritic horizon is absent, 'concealed' by the depletion zone.
- ***Lateritic deposits***: contiguous with the ferruginous and mottled zones of the lateritic profile, mostly at the surface or buried by shallow sediments (<20 m).
  - –Commonly 2–10 m thick.
  - –Characterised by fine-grained Au of high fineness (Ag <0.5%) and some residual primary Au.
  - –Coarse Au as small primary nuggets and inclusions within vein quartz and pisoliths, and as euhedral secondary crystals developed with Fe oxides.
- ***Saprolitic deposits***: confined to weathered primary source or laterally dispersed in weathered wall rocks as one or more sub-horizontal zones, at or below the water-table; 10–>70 m depth.

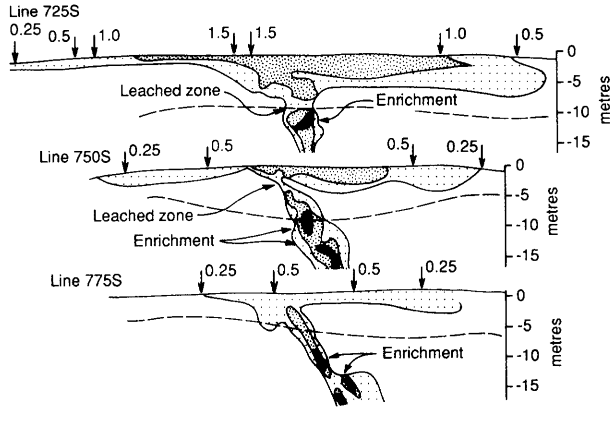

Figure 1. Lateritic gold deposit, Callion, Western Australia (after Glasson et al. 1988).

  - –Matrix commonly clay-rich; groundwaters highly saline.
  - –Gold dominantly secondary and of high fineness; residual primary grains more abundant with depth. Secondary Au as irregular grains, octohedra, dodecahedra, and flat hexagonal and triangular plates.

Regolith

- No macroscopic regolith features related to presence of mineralisation. Mature lateritic profiles commonly comprise:
  - –Lateritic residuum (ferruginous pisolitic gravels and duricrusts), 2–8 m; Go, He, Q, K, Gi, R
  - –Mottled clay zone: 0–10 m; Go, He, K, Q
  - –Unstructured plasmic clays: 0–10 m; Go, K, Q
  - –Ferruginous saprolite: 0–10 m;Go, K, Q
  - –Saprolite: 20–>50 m;K, Q, Go, P
  - –Saprock: 0–20 m; P, K, Q, Sm

(Q: quartz; K: kaolinite; Gi: gibbsite; He: hematite; Go: goethite; Sm: smectite; P: relict primary minerals; R: resistant minerals).

- Muscovite in alteration zones persists through most of profile.
- Not all horizons always present; mineralogy depends on lithology.

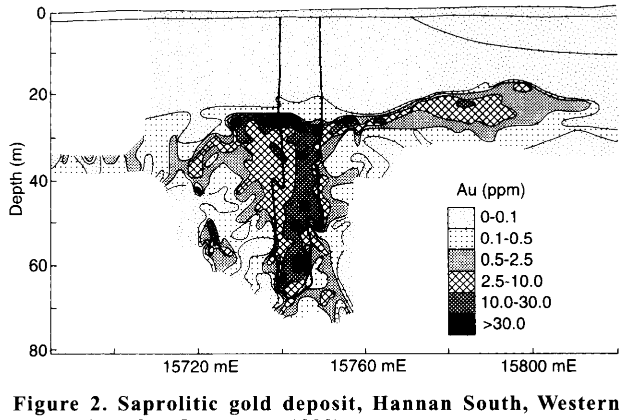

Figure 2. Saprolitic gold deposit, Hannan South, Western Australia (after Lawrance 1992).

Geochemical criteria

- ***Lateritic deposits***: widespread multi-element anomalies (Au±As±Sb±W) in lateritic residuum.
  - –Gold anomalies (>50 ppb in Yilgarn), commonly 400 ∞ width of primary source.
  - –Crop out in relict regolith-landform regimes (e.g. Mt Gibson) or buried in depositional regimes (e.g. Mt McClure, Bronzewing).
  - –Gold is leached at the surface in humid environments (e.g. Boddington and most tropical occurrences), with greater enrichment at 2–5 m).
- ***Saprolitic deposits***: laterally extensive (to 50 ∞ width of primary source), at 10 – >50 m depth, beneath barren weathered wallrocks or depleted weathered primary mineralisation.
  - –No associated enrichment of pathfinder elements, but Mn or Fe oxides may mark redox fronts. Pathfinders retained through depleted zone.
  - –Surface expression in pedogenic carbonates (Au only) in erosional regimes and where overburden is shallow (<10 m).
  - –Palaeochannel-related deposits commonly blind, with no direct surface expression.
  - –Precipitated by dilution, reduction, increased pH, e.g., at water-table, redox fronts. In some channel deposits, precipitation is on lignite.

Fluid chemistry

- ***Lateritic deposits***: formed by dilute groundwater in vadose zone. Generally, moderately oxidising, weakly acid (bicarbonate ion).
  - –Gold probably mobilised by organically derived ligands (e.g., humic and fulvic acids, CN^-, S-rich complexes).
  - –Precipitated by dilution, reduction by Fe^{2+} oxidation.
- ***Saprolitic deposits***: formed in saline groundwaters in vadose or upper phreatic zones.
  - –Gold mobilised as halide (Cl, I) complexes in highly oxidising (Eh>550 mV) and acid (pH <4.5) environments.

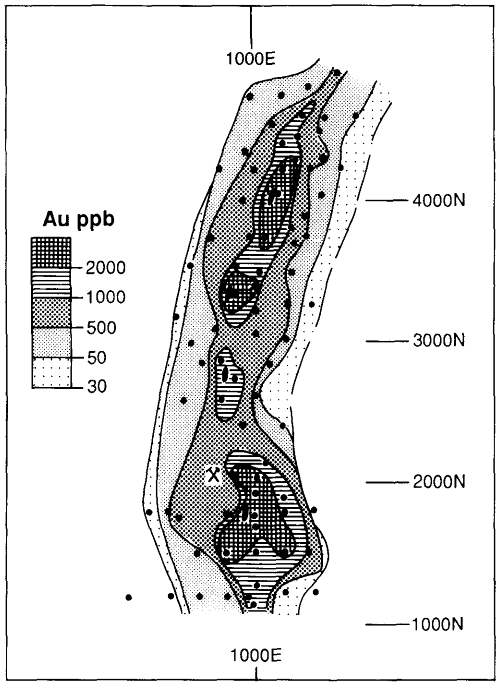

Figure 3. Gold distribution in lateritic residuum, Mt Gibson, Western Australia (Smith & Anand 1992).

References

Bowell et al. 1996, Butt 1989b, Davy & El-Ansary 1986, Freyssinet et al. 1989a, Gee 1990, Glasson et al. 1988, Gray et al. 1992, Lawrance 1992, Lecomte & Zeegers 1992, Mann 1984, 1998, Smith & Anand 1992, Stott 1994, Zeegers & Freyssinet 1993, Zeegers & Lecomte 1992.

Introduction

An understanding of the genesis of supergene Au deposits requires an appreciation of the characteristics and origin of the regolith and the genetic relationship between the regolith and the Au mineralisation it hosts. The regolith in most of Australia is the product of a long complex weathering history, under a variety of climatic conditions. Some parts of the Precambrian cratons of the Western Shield may have been exposed to sub-aerial conditions since the late Proterozoic. However, much of the land surface was subjected to glaciation in the Permian and the oldest identifiable landforms, such as the dendritic drainage pattern, probably date from the early Mesozoic.

Because the land surface of the cratons has been subjected to continuous weathering during this time, the effects of various weathering episodes are superimposed and there is little direct evidence to relate specific weathering products to particular periods or climatic environments. The regolith is commonly lateritic and, when complete, consists, from the base, of saprock, saprolite, mottled clays or ferruginous saprolite, and an uppermost lateritic residuum that includes nodular and pisolitic gravels and duricrusts. It may be overlain by a variable thickness of transported overburden.

The regolith on the more tectonically active regions of the Tasman Fold Belt is highly variable because the complex history of erosion, deposition and volcanic activity has resulted in the partial preservation of a multiplicity of older land surfaces. Many such surfaces are deeply weathered, but, in areas where relief is stronger, erosion rates are high and the regolith is thin or absent.

The distribution of gold in lateritic regoliths

Economic or near-economic supergene concentrations of Au occur in deeply weathered regolith in most climatic zones. They are mostly small (<1.5 Mt), low-grade (1.5–5.0 g/t) relative or absolute accumulations, characterised by predominantly secondary Au, with some residual primary Au and occasional nuggets (Mann 1984, 1998, Butt 1989a,b).

Lateritic supergene deposits

These are more or less flat-lying enrichment zones contiguous with the ferruginous and mottled zones of the lateritic profile. They are characterised by fine-grained Au of high fineness (Ag <0.5%) and some residual primary Au. Particles of coarse Au may be present as primary nuggets and inclusions in vein quartz and pisoliths, and as secondary crystals developed with Fe oxide segregations. Many accumulations of this type are known, but mining has been largely restricted to regions in Australia with Mediterranean and arid climates, such as the Yilgarn Craton (e.g. Boddington: Davy & El-Ansary 1986; Mt Gibson: Gee 1990, Smith & Anand 1992) and The Granites–Tanami Inlier (Redback and Dogbolter deposits). Similar deposits are being mined in West Africa (e.g. Syama: Bowell et al. 1996) and South America.

Saprolitic supergene deposits

Relative enrichment of Au, with minor secondary accumulation, is common as the result of weathering of Au-bearing lodes and shear zones. Where the regolith is thick, this may result in exploitable reserves, amenable to low-cost open-cut mining. Similar enrichment is also typical of porphyry Cu deposits, e.g., in Papua New Guinea (see Hughes 1990) and at Northparkes, NSW. Marked absolute enrichment in saprolite also occurs, commonly deep in the regolith, either mostly confined to the source unit or laterally dispersed into the weathered wall rocks, as one or more sub-horizontal zones. The Au is dominantly secondary and of high fineness, even in the weathered source unit, but residual primary grains become more abundant close to the base of the profile. Saprolitic enrichment is known and mined only from semi-arid (or once semi-arid) environments, again principally in Australia. Typical of these deposits are Paddington (Robertson & Munckton 1995), Hannan South (Schiller & Ivey 1990, Lawrance 1992) and, perhaps, McKinnons, NSW.

Palaeochannel deposits

Numerous, secondary deposits associated with palaeochannels ('deep leads') are known, mainly in Victoria (Ballarat–Bendigo–Ararat area) and in the Kalgoorlie–Norseman area of the Yilgarn Craton. In Victoria, Au is associated mainly with coarse basal sands and gravels, within 2 m of the unconformity (Swensson 1990), and is considered to be alluvial, commonly with a well-defined primary source. In the southern Yilgarn, Au occurs either in the sediments or in the saprolite immediately beneath the channel (Fig. 4). Most of these deposits are individually small (e.g. Baseline, 0.25 Mt @ 3 g/t Au), but they may occur in clusters along a particular palaeodrainage system, thereby forming a significant resource, such as at Kanowna (Gibb Maitland 1919), Lady Bountiful Extended (Devlin & Crimeen 1990), and Challenge–Swordsman at Higginsville. In some deposits, the Au in the sediments may be alluvial. However, it commonly occurs as secondary Ag-poor particles and the enrichment zones themselves may transgress sedimentary features, including the unconformity. Accordingly, it is considered that, in most deposits, the Au is probably a chemical precipitate, derived from a source up-drainage or, possibly, from immediately beneath the channel. Gold in the saprolite tends to form flat-lying enrichments 5–10 m below the unconformity; they appear to be similar in geometry and origin to the saprolitic deposits described above.

In semi-arid areas, such as the Yilgarn Craton and The Granites–Tanami Inlier, lateritic and saprolitic deposits may both be present where profiles are complete, separated by a zone 5–20 m thick that is barren of Au, (e.g. Mt Gibson, Boddington). Within the weathered lode or other source, this is commonly referred to as the 'depleted zone'. The depleted zone may be present even where the laterite has been eroded, either at the land surface or beneath transported overburden; as such, it presents a considerable hindrance to exploration for concealed supergene and primary mineralisation. However, pathfinder elements, such as As, Sb, Bi and W, appear not to be leached from the depleted zone; hence, multielement geochemistry has value where strong leaching of Au is suspected. Neither saprolitic enrichment nor a depleted zone has been reported from humid tropical climates; Au appears to be slightly leached throughout the saprolite, but there is no dispersion into wall rocks and little or no secondary Au is present.

This subdivision of supergene Au deposits is part descriptive and part genetic. There are other enrichments, some of ore grade, that do not fit easily into this classification. These include the association of Au with pedogenic carbonate, which, in some lateritic deposits (e.g. Callion: Glasson et al. 1988), locally attains higher grades than the ferruginous fractions.

Formation of supergene gold deposits

Gold mobility during weathering

Gold is chemically inert under most weathering conditions, but may be chemically very mobile where certain complexing ligands are present in soil- and ground-waters (Gray et al. 1992). The principal complexes, which are significant under different chemical conditions, are

thiosulphate: generated by pyrite oxidation under neutral to alkaline conditions;
organic: formed by the interaction of Au with organic matter under oxidising conditions;
halide: formed by oxidative solution of Au under acid saline conditions.

Precipitation usually occurs as a result of chemical changes that destroy the Au–ligand complex. Recent results, however, suggest that some complexes, probably organic, are very strong, such that they precipitate as evaporites (e.g. with pedogenic

Table 1. Conditions for gold mobilisation and precipitation during weathering (after Mann 1984, Webster & Mann 1984, Gray et al. 1992).

Complex	*Dissolution conditions*	*Precipitation conditions*	*Product*
Thiosulphate	Alkaline, mildly oxidising	Dilution, acidification, oxidation, reduction	Electrum
Organic	Alkaline–acid, mildly oxidising	Reduction	Fine-grained Au, high fineness
Halide	Acid, oxidising	Dilution, increasing pH, reduction	Au, high fineness

carbonates) and will redissolve in water.

During the long period of development of the regolith in much of Australia, Au has been mobilised and dispersed by one or more of these complexes, leading to the formation of supergene Au deposits. The dominant reactions have varied with time, in response to the varied environments imposed by successive climatic and geomorphological changes. In addition, physical movement of Au, as fine particles or in colloidal form, is also probable, but the contribution of such processes has not been assessed. The principal environments that appear to have controlled the mobility and distribution of Au in the regolith are, firstly, those associated with the formation of the deeply weathered, lateritic, regolith under seasonally humid, temperate to warm conditions until the early Tertiary and, secondly, those that led to physical and chemical modifications to the regolith during the dominantly arid periods since the mid-Miocene.

Gold mobility during lateritic weathering

During lateritisation in seasonally humid, probably temperate to warm climates, oxidation at the weathering front, deep below the water-table, produces neutral to acid conditions, with low pH occurring particularly over felsic rocks and rocks with high sulphide content. Gold associated with tellurides or held in the lattice of the sulphides and other minerals may be released, but the free metal remains largely immobile, owing to the absence of suitable complexing ligands. Free Au (and Ag) may be mobilised if high concentrations of carbonate are present in the primary mineralisation, because the oxidation of pyrite in such an alkaline environment produces thiosulphate (Mann 1984). However, although this mechanism has been implicated in dispersion in some locations (e.g. Papua New Guinea: Webster & Mann 1984), it does not seem to have widespread significance in lateritic environments. Concentrations of chloride ions and, deep in the profile, organic matter are very low. Accordingly, although some corrosion and reduction of size occurs, primary Ag-rich Au grains persist through the saprolite and into the ferruginous zone; lateral dispersion into saprolitic wall-rocks is also minimal.

Lateral dispersion of Au is evident towards the top of the lateritic profile in the present humid tropics, particularly in the ferruginous and mottled horizons (e.g. Freyssinet et al. 1989a,b, Lecomte & Zeegers 1992, Zeegers & Lecomte 1992). The dispersion is due in part to residual concentration and surface wash during land-surface reduction and in part to mobility, either in solution or as particulates (e.g. colloids or very fine grains of free metal). Some Au may also be contributed directly to the soil in organic litter after uptake by plants. Reduction of the complexes results in the incorporation of fine-grained Au with low Ag content in Fe oxides, particularly in the lower part of the ferruginous horizon and in the mottled zone. Such mechanisms can account for the formation of lateritic Au deposits and Au anomalies, with their mixture of high and low fineness Au, that form widespread blankets over relatively narrow mineralised sources.

The relative contributions of the physical and chemical mechanisms are uncertain, during both this and subsequent climatic episodes. The presence of Ag-poor rims on residual primary grains suggests that Ag may be completely removed from small grains, whereas the Au reprecipitates immediately, yielding a product of high fineness. Downward mechanical illuviation of Au particles and colloids is also possible, and could be responsible for some of the observed distributions.

Gold mobility in arid environments

The effects of aridity on Au distribution can be determined by comparison with studies of humid lateritic environments (e.g. Freyssinet et al. 1989a,b, Gray et al. 1992, Lecomte & Zeegers 1992, Zeegers & Lecomte 1992). The most prominent differences are:

1. the development of a zone of marked depletion beneath the lateritic horizons;
2. supergene enrichment deep in the saprolite, characterised by secondary Au of high fineness;
3. in some environments, enrichment in pedogenic carbonate.

In addition, there is commonly the concomitant formation of the palaeochannel deposits.

The effects of a change to more arid climate, coupled with minor uplift, are shown in Figure 5. Lowering of the water-table results in progressive dehydration of the upper horizons, and lower rainfall leads to a general reduction in leaching. The decrease in vegetation greatly reduces the availability of humic complexes for Au mobility, although organic ligands remain important for Au mobility in soils. Alkalis and alkaline earths derived from rainfall and continued slow weathering are retained in the regolith. These changes cause the mechanisms of Au mobilisation to change also. More prevalent alkaline conditions increase the possibility of thiosulphate formation during sulphide oxidation, but the rate of weathering is mostly very slow. More significant, however, is the development of salinity, for this permits the formation of soluble Au-halide complexes.

In the present warm arid zones, the change from humid seasonal climates has taken place since the mid-Tertiary or earlier. During this long period, several reversals to humid climates have occurred, temporarily restoring conditions conducive to deep weathering. Accordingly, the lowering of the water-table has been punctuated by still-stands or temporary rises. Such events have great significance, for under these circumstances, the increased rainfall leaches precipitated salts and recreates redox conditions suitable for ferrolysis, thus producing acid and saline groundwaters. As these waters become more strongly oxidising, they can become capable of dissolving Au and Ag as halide complexes. Evidence from the Panglo deposit in Western Australia (Gray 1990) suggests that the Mn redox couple controls this oxidation step and that, there, iodide is more important than chloride as the complexing species. That such a mechanism is possible is demonstrated in the near-coastal Darling Range, where recent humidity has resulted in active ferrolysis and leaching by saline waters. Elsewhere in the region, the rise in water-table caused by clearing for agriculture has mimicked this climatic change. During humid periods, therefore, Au may be dissolved and mobilised.

Gold precipitation will take place in response to a rise in pH or dilution of the halide concentration, both of which may occur when solutions percolating through the unsaturated zone reach the water-table. Precipitation is also caused by the reduction of the Au chloride by dissolved ferrous iron. This reaction may occur at the water-table or, probably more commonly, at the interface between an upper oxidised aquifer and a lower reduced aquifer. Such double aquifer systems have been commonly observed in the Yilgarn Craton, and precipitation at their interfaces has resulted in enrichment parallel to, but below, the

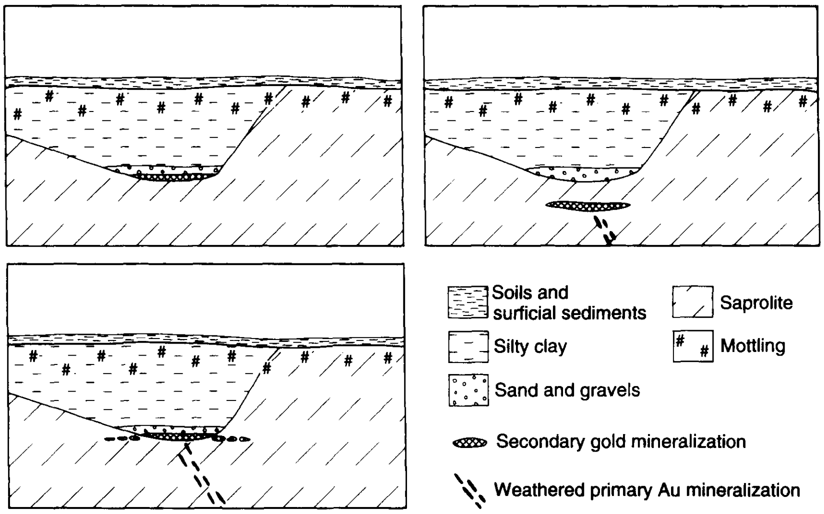

Figure 4. Location of secondary gold enrichment associated with palaeochannels (deep leads), Yilgarn Craton, Western Australia. Similar enrichment of basal sands in palaeochannels in the Ballarat region, Victoria, is thought to be alluvial.

water-table. These mobilisation and precipitation events, occurring during the general lowering of the water-table and post-lateritic evolution of the regolith, account for supergene enrichment within the weathered mineralisation and in adjacent saprolitic wall rocks. Because electrum may be more soluble than pure Au, primary Au could be preferentially dissolved during this process, thus assisting the preservation of pre-existing lateritic secondary enrichment. Additionally, the repeated strong leaching of the upper saprolite leads to the formation of the depletion zone between the lateritic and saprolitic enrichment zones. Mobilisation of Au by plants under present-day conditions may also cause depletion, but is also implicated in the association of Au with pedogenic carbonates. The latter is an important phenomenon in the southern Yilgarn Craton and the Gawler Craton, where calcrete and calcareous soil are the preferred hosts for Au in the surface horizons of the regolith and are important exploration sample media (Lintern & Butt 1993, 1997).

Minor dispersion of Au as a thiosulphate complex is also suspected at some locations. This complex may account for high Au concentration in both saline and non-saline groundwaters in the Yilgarn Craton, and the presence of secondary electrum in some deposits. It does not, however, appear to have been a significant mechanism in the formation of supergene mineralisation.

Where the profile is truncated, any lateritic enrichment will have been destroyed; the depleted zone thus becomes the uppermost residual material and either forms the parent material for the soils or immediately underlies the transported cover. Leaching of the upper horizons can still occur, so the near-surface expression of mineralisation is minimal. Gold enrichment in the pedogenic carbonates is particularly significant in such circumstances and may give rise to a surface expression of the mineralisation. Where there are no carbonates, however, Au concentrations may be lower by an order of magnitude. The high solubility of Au in surficial materials demonstrates dispersion is active, although it is probable that the amount and, especially, the proportion of soluble Au may relate more to surficial environmental conditions than to the proximity of mineralisation.

The Au deposits in palaeochannels in southern Western Australia appear to be products of the later, arid phases of regolith evolution. Stratigraphic relationships suggest that the channels were incised into a deeply weathered landscape. Subsequently, they were infilled by erosion products from that landscape and, commonly, they have a sequence that consists of basal sands overlain by clay-rich sediments. The latter are apparently lacustrine or, in places, estuarine, and may include reduced, commonly sulphidic, units, including lignites of late Eocene age. These sequences have been weathered, initially with strong mottling and pisolith development with lateritic affinities, and later under arid conditions. Gold enrichment in the sediments is dominantly associated with oxidised facies, but is also present in lignites, for example in the Officer Basin (Mulga Rock: Douglas et al. 1992) and the Kambalda–Norseman region. It is not known whether such enrichment is syngenetic or epigenetic with respect to the sediments. Gold in flat-lying enrichment zones in saprolite beneath the channels is commonly associated with an underlying primary source. The zone geometry, occurrence in highly saline environments, and hydrogeochemistry suggest formation under conditions similar to those currently prevailing.

Exploration criteria

The present distribution of Au in the regolith is a product of a long history of weathering under changing climatic and tectonic conditions. A number of physical and chemical dispersion mechanisms have been involved, their activity and relative importance changing during this time with the prevailing environmental conditions. Various features of the distribution patterns can be related to various stages of regolith evolution by consideration of the probable mechanisms involved and by analogy with related terrains with different weathering histories. At the simplest level, recognition of the nature of supergene deposits, the regolith materials in which they occur and their relationship both to the weathering history of the region and the specific geomorphological setting of the prospective area will benefit exploration by aiding the selection of sample media, choice of a suitable multielement analytical suite, and the interpretation of geological and geochemical data. The same approach and procedures apply to exploration for the primary mineralisation, since the supergene deposits are essentially the near-surface geochemical expression of such a source. Geomorphological control for the prospective areas can be achieved by regolith-landform mapping, which, coupled with existing data and/or new orientation surveys, can be used to develop landform-based geochemical dispersion models to optimise sampling, analytical and interpretational procedures.

Lateritic deposits and anomalies

These occur in areas where the laterite profile is preserved, even if buried, so that sampling of lateritic residuum is the most appropriate procedure. Other elements associated with the primary mineralisation may also be present (e.g. As, Sb, B, Bi, Hg, Mo, W), giving larger, confirmatory or more readily detectable haloes, 100–400 times broader than the primary source (Smith et al. 1989). Sampling of lateritic residuum has been successfully used at intervals as wide as 3 km on triangular grids to reveal regional trends, closing to 100 m during follow-up. Broad, multielement anomalies of this type are present at Boddington and Mt Gibson (Smith et al. 1989, Butt & Smith 1992, Smith & Anand 1992) and similar deposits elsewhere, e.g. Callion (Glasson et al. 1988); Jim's Find, Tanami (Stott 1994). Duricrusts, nodules or pisoliths are the ideal sample media and may be collected from the surface or near surface in relict landform regimes and by drilling in depositional regimes, where they may be buried by a considerable thickness of transported overburden. In the latter case, it essential to be able to distinguish lateritic residuum from transported lateritic debris (Anand & Smith 1993).

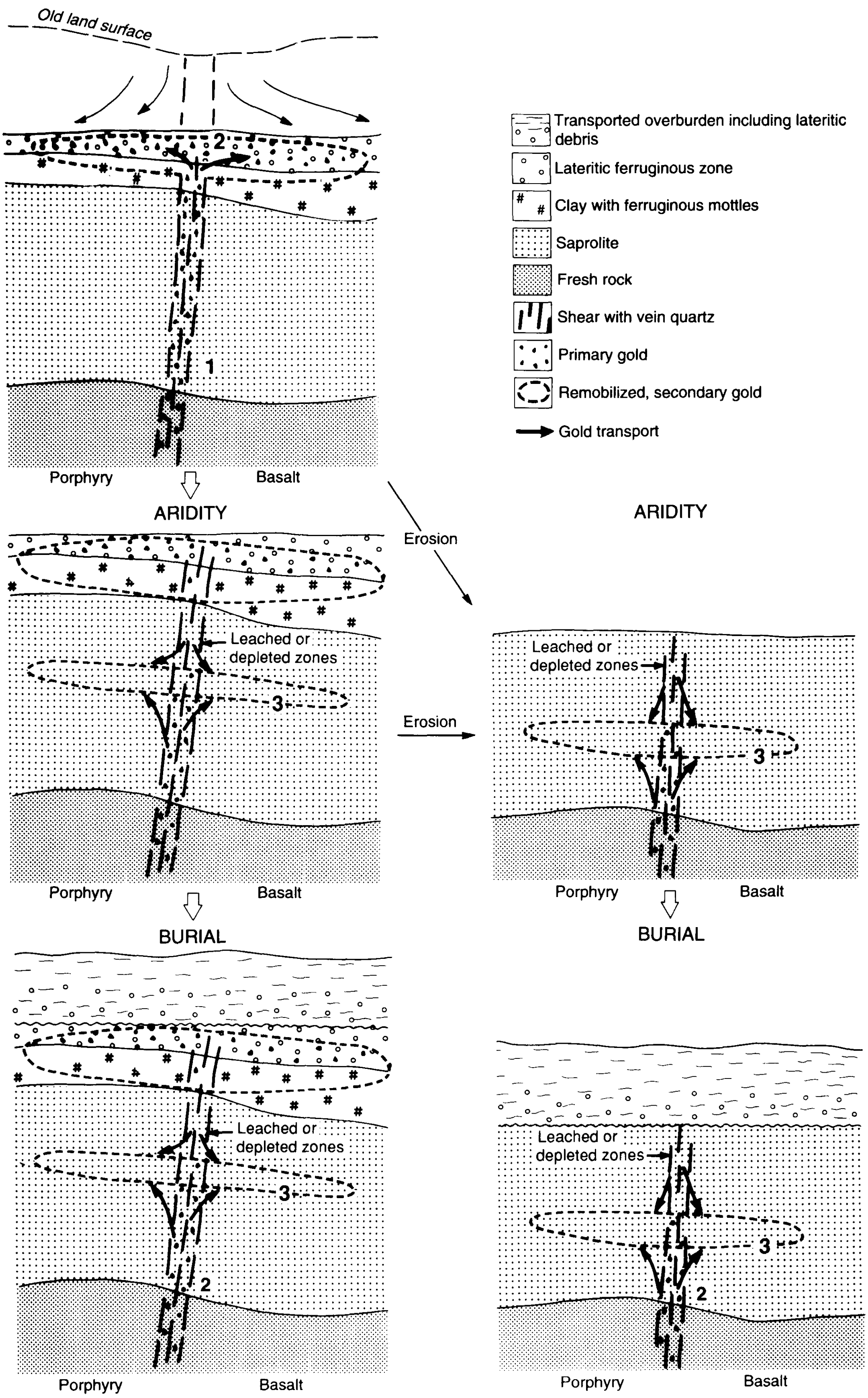

Figure 5. Formation of lateritic and saprolitic gold deposits during successive humid and arid climatic episodes (after Butt 1989b). Numerals indicate possible ligands responsible for complexing and mobilising gold: 1, thiosulphate; 2, organic; 3, halide. The deposits may be exposed at the surface or buried beneath a variable thickness of transported overburden.

Saprolitic deposits and anomalies

Where a complete laterite profile is preserved, whether at the surface or buried, a lateritic deposit or anomaly will indicate a possible site of saprolitic enrichment. However, if the lateritic horizon has been eroded (or never formed), such anomalies may be absent or much reduced, particularly if there is a marked depletion zone. In erosional areas with residual soils or saprolite at surface, sampling of ferruginous lag, soil, or a specific soil fraction or component, as determined by orientation surveys, is an effective exploration procedure. Lag samples may include lateritic pisoliths and nodules; hence, widespread anomalies associated with these materials may be expected. Anomalies in soils, however, may be much more restricted in area.

In semi-arid parts of southern Australia, pedogenic carbonates should be sampled, if present, since these materials concentrate Au, even in some areas of shallow cover and/or strong depletion, and give a superjacent anomaly to concealed mineralisation. Where carbonates are absent, surface anomalies may be restricted and of low concentration and contrast. Surface anomalies and specific targets are followed up by closely spaced drilling; the possibility of laterally dispersed saprolitic Au enrichment and depletion zones more than 40 m deep, especially in saline areas, must be considered, both in planning hole spacing and depth and in the interpretation of data. For example, at Hannan South, the Au enrichment in saprolite at about 20 m depth is 200 m across, compared to the 3 m wide primary source (Schiller & Ivey 1990). Multielement analysis is recommended, because elements such as As, Sb, Bi, K, Pb, Rb and W, commonly associated with the primary mineralisation or alteration halo, are not leached in the depletion zone, even where these are highly saline, as at Hannan South (Lawrance 1992). In depositional areas, where truncated profiles are buried by transported overburden, all sampling has to be by drilling. The most widespread anomalies are found at or close to the unconformity, particularly in basal sediments and mottled or ferruginous saprolite, or in the saprolitic enrichment zone itself.

Palaeochannel deposits

Similar procedures to those used for buried saprolitic deposits are suitable for exploration for channel deposits, namely drilling to seek sub-horizontal zones of Au enrichment in the sediments or underlying saprolite. Multielement analysis, however, is probably of little value in oxidised sediments.

Acknowledgements

The concepts discussed in this article have evolved over a number of years and include ideas based on discussions with numerous colleagues and associates. These contributions are gratefully acknowledged. This manuscript greatly benefited from comments by Alison Britt. The figures were drafted by Angelo Vartesi. The Cooperative Research Centre for Landscape Evolution and Mineral Exploration is supported by the Australian Cooperative Research Centres Program.

References

Anand, R.R. & Smith R.E., 1993. Regolith distribution, stratigraphy and evolution in the Yilgarn Craton—implications for exploration. In: Williams, P.R. & Haldane, J.A. (compilers), An international conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields. Australian Geological Survey Organisation, Record 1993/53, 187–193

Bowell, R.J., Afreh, E.O., Laffoley, D.d'A., Hanssen. E., Abe, S., Yao, R.K. & Pohl, D., 1996. Geochemical exploration for gold in tropical soils—four case studies from West Africa. Transactions of the Institution of Mining and Metallurgy, 105, B12–B33.

Butt, C.R.M., 1989a. Geomorphology and climatic history—keys to understanding geochemical dispersion in deeply weathered terrain. In: Garland, G.D. (editor), Proceedings of Exploration '87. Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater. Special Volume 3, 323–334, Ontario Geological Survey, Toronto.

Butt, C.R.M., 1989b. Genesis of supergene gold deposits in the lateritic regolith of the Yilgarn Block, Western Australia. In: Keays, R.R., Ramsay, W.R.H. & Groves, D.I. (editors), The geology of gold deposits: the perspective in 1988. Economic Geology Monograph 6, 460–470, Economic Geology, New Haven.

Butt, C.R.M. & Smith, R.E., 1992. A-type models: pre-existing profile essentially preserved. In: Butt, C.R.M. & Zeegers, H. (editors), Regolith exploration geochemistry in tropical and sub-tropical terrains. Handbook of Exploration geochemistry, 4, 304–331, Elsevier, Amsterdam.

Davy, R. & El-Ansary, M., 1986. Geochemical patterns in the laterite profile at the Boddington gold deposit, Western Australia. Journal of Geochemical Exploration, 26, 119–144.

Devlin, S.P. & Crimeen, J.D., 1990. Lady Bountiful extended gold deposit. In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 405–410.

Douglas, G.B., Gray, D.J. & Butt, C.R.M., 1993. Geochemistry mineralogy and hydrogeochemistry of the Ambassador multielement lignite deposit, Western Australia. Minerals and Energy Research Institute of Western Australia, Report No. 106.

Freyssinet, P., Zeegers, H. & Tardy, Y., 1989a. Morphology and geochemistry of gold grains in lateritic profiles of southern Mali. In: Jenness, S.E. (editor), Geochemical exploration 1987. Journal of Geochemical Exploration, 32, 17–31.

Freyssinet, P, Lecomte, P. & Edimo, A., 1989b. Dispersion of gold and base metals in the Mborguene lateritic profile, east Cameroun. In: Jenness, S.E. (editor), Geochemical exploration 1987, Journal of Geochemical Exploration, 32, 99–116.

Gee, R.D, 1990. The Gibson lateritic gold deposit. In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 259–264.

Gibb Maitland, A., 1919. The gold deposits of Western Australia. The Mining Handbook. Geological Survey of Western Australia, Memoir 1, (reprinted by Hesperian Press, Perth, 1984, 92pp).

Glasson, M.J., Lehne, R.W. & Wellmer, F.W., 1988. Gold exploration in the Callion area, Eastern Goldfields, Western Australia. Journal of Geochemical Exploration. 31, 1–19.

Gray, D.J., 1990. Hydrogeochemistry of the Panglo gold deposit. CSIRO Australia, Division of Exploration Geoscience. Restricted Report 125R, 74 pp. (unpublished).

Gray, D.J., Butt, C.R.M. & Lawrance, L.M., 1992. The geochemistry of gold in lateritic environments. In: Butt, C.R.M. & Zeegers, H. (editors), Regolith exploration geochemistry in tropical and sub-tropical terrains. Handbook of Exploration Geochemistry, 4, 461–482, Elsevier, Amsterdam.

Glasson, M.J., Lehne, R.W. & Wellmer, F.W., 1988. Gold exploration in the Callion area, Eastern Goldfields, Western Australia. Journal of Geochemical Exploration. 31, 1–19.

Hughes, F.E., (editor), 1990. Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 1828 pp.

Lawrance, L.M., 1992. Distribution of gold and associated elements within lateritic weathering profiles of the Yilgarn Block, Western Australia. University of Western Australia, Ph.D. thesis (unpublished).

Lawrance, L.M. & Butt, C.R.M., 1992. Mt Pleasant gold deposit, Western Australia. In: Butt, C.R.M. & Zeegers, H.

(editors), Regolith exploration geochemistry in tropical and sub-tropical terrains. Handbook of Exploration Geochemistry, 4, 365–367, Elsevier, Amsterdam.

Lecomte, P. & Zeegers, H., 1992. Humid tropical terrains (rainforests). In: Butt, C.R.M. & Zeegers, H. (editors), Regolith exploration geochemistry in tropical and sub-tropical terrains. Handbook of exploration geochemistry, 4, 241–294, Elsevier, Amsterdam.

Lintern, M.J. & Butt, C.R.M., 1993. Pedogenic carbonate: an important sampling medium for gold exploration in semi-arid areas. CSIRO Australia, Division of Exploration Geoscience. Exploration Research News 7, 7–11.

Lintern, M.J. & Butt, C.R.M., 1997. Calcrete sampling for gold exploration. In: Resourcing the 21st century. Proceedings of the AusIMM 1997 Annual Conference. Australasian Institute of Mining and Metallurgy, Publication 1/97, 145–149.

Mann, A.W., 1984. Redistribution of gold in the oxidised zone of some Western Australian deposits. In: Gold-mining, Metallurgy and Geology. Proceedings of the Regional Conference on Mining and Metallurgy, Perth and Kalgoorlie, October 1984, Australasian Institute of Mining and Metallurgy, Melbourne, pp 1–12.

Mann, A.W., 1998. Oxidised gold deposits: relationships between oxidation and relative position of the water-table. Australian Journal of Earth Sciences, 45, 97–108.

Robertson, I.G. & Munckton, A.M., 1995. The Paddington gold deposit. In: Butt, C.R.M., Anand, R.R. & Smith, R.E. (editors), Regolith geology and exploration geochemistry in the Yilgarn Craton, Western Australia. Excursion 3 Guide. 17th International Geochemical Exploration Symposium. EGRU, James Cook University, Townsville, 111–118.

Schiller, J.C. & Ivey, M.E., 1990. Hannan South gold deposit. In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 443–447.

Smith, R.E. & Anand, R.R., 1992. Mount Gibson Au deposit, Western Australia. In: Butt, C.R.M. & Zeegers, H. (editors), Regolith exploration geochemistry in tropical and sub-tropical terrains. Handbook of Exploration Geochemistry, 4, 313–318, Elsevier, Amsterdam.

Smith, R.E., Birrell, R.D. & Brigden, J.F., 1989. The implications to exploration of chalcophile corridors in the Archaean Yilgarn Block, Western Australia, as revealed by laterite geochemistry. In: Jenness, S.E. (editor), Geochemical exploration 1987. Journal of Geochemical Exploration, 32, 169–184.

Stott, C.L., 1994. A regolith study of the Jim's South gold anomaly, Tanami Desert, Northern Territory. Centre for Ore Deposit and Exploration Studies, University of Tasmania, Honours thesis, 137 pp. (unpublished).

Swensson, C.G., 1990. Early Tertiary deep lead deposits of Victoria. In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 1637–1641.

Webster, J.G. & Mann, A.W., 1984. The influence of climate, geomorphology and primary geology on the supergene migration of gold and silver. Journal of Geochemical Exploration, 22, 21–42.

Zeegers, H. & Freyssinet, P., 1993. A quantitative approach gold signal evolution in different lateritic environments. 16th International Geochemical Exploration Symposium, Beijing, Abstracts, part 1, 187–188.

Zeegers, H. & Lecomte, P., 1992. Seasonally humid tropical terrains (savannas). In: Butt, C.R.M. & Zeegers, H. (editors), Regolith exploration geochemistry in tropical and sub-tropical terrains. Handbook of Exploration Geochemistry, 4, 203–240. Elsevier, Amsterdam.

Received 15 October 1996; accepted 30 September 1997