

LATERITISATION AND SECONDARY GOLD DISTRIBUTION
WITH PARTICULAR REFERENCE TO
WESTERN AUSTRALIA

DISSERTATION

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ABSTRACT

Lateritisation is associated with tropical climates and geomorphic conditions of peneplanation where hydromorphic processes of weathering predominate. Laterites are products of relative (residual) and absolute (chemical) accumulation after leaching of mobile constituents. Their major element chemistry is controlled by the aluminous character of bedrock and drainage. Bauxitisation is characterised by residual gibbsite neoformation and lateritisation, by both residual accumulation and hydromorphic precipitation of goethite controlled by the redox front at the water table. The laterite forms part of a weathering profile that is underlain by saprock, saprolite, the mottled zone and overlain by a soil horizon.

The secondary gold in laterites has its source invariably with mineralised bedrock. The distribution of secondary gold is controlled by mechanical eluviation and hydromorphic processes governed by organic, thiosulphate and chloride complexing. The precipitation of secondary gold is controlled by pH conditions, stability of the complexing agent and ferrolysis. Gold-bearing laterites are Cainozoic in age and are best developed on stable Archean and Proterozoic cratons that have suffered epeirogenesis since lateritisation. Mechanical eluviation increases in influence at the expense of hydromorphic processes as a positive function of topographic slope and degradation rate. Gradients greater than 10° are not conducive for

lateritisation, with latosols forming instead. High vertical degradation rates may lead to the development of stone lines.

In the Western Australian case, post-laterite aridification has controlled the redistribution of secondary gold at levels marked by stabilisation of the receding palaeowater table. Mineable reserves of lateritic ore are located at Boddington, Westonia and Gibson toward the south-west of the Yilgarn Block. A significant controlling variable appears to be the concentration of chloride in the regolith. Based on the Boddington model, the laterite concentrates the following elements from bedrock gold lodes:

- i) Mo, Sb, W, Hg, Bi and Au as mobile constituents
- ii) As and Pb as immobile constituents.

Geochemical sampling of ferruginous lag after bedrock and laterite has provided dispersed anomalies that are easily identifiable. "Chalcophile corridors" up to 150 km in length are defined broadly by As and Sb but contain more discrete anomalies of Bi, Mo, Ag, Sn, W, Se or Au, in the Yilgarn Block. The nature of the weathered bedrock, the tabular distribution of secondary gold ore deposition and the infrastructural environment lends the lateritic regolith to low cost, open-cut mining. The Western Australian lateritic-gold model perhaps can be adapted and modified for use elsewhere in the world.

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I. INTRODUCTION

The objectives of this dissertation are to:

- i) describe lateritisation processes and the regolith in general
- ii) examine the chemical processes and the effect they have on the distribution of major and "trace" metals in the weathered profile
- iii) analyse the geochemical effects of regolith development over various primary gold lodes and the implications for exploration and mining.

Both climate and geomorphology have contributed toward laterite development and preservation over the Yilgarn Block, granite-greenstone terrane in Western Australia, respectively. The present landscape is extraordinarily flat with very little relief developed. Kalgoorlie, approximately 400 km from the nearest coastline, is at an elevation of about 300 m. Lateritisation and subsequent aridification facilitates repeated dissolution and reprecipitation of gold in a tabular fashion at the water table. Fluctuation of the water table and landscape degradation control the redistribution of gold throughout the weathering history of the primary deposit. These processes disperse gold from the primary source that is invariably vertically disposed, into a horizontal position where it is concentrated by chemical and physical degradation within the laterite.

Although the regolith masks the potential bedrock target, lateritisation provides a resistant sampling medium that contains concentrations of certain elements of economic interest. Post-lateritisation reworking in an arid climate may disperse the ferruginous crust as a lag, providing a copious "blanket" of sample material.

The behaviour of secondary gold in the Western Australian, Yilgarn Block environment has given much impetus to the gold

mining industry in that part of the world. The manner in which it distributes itself horizontally within the regolith and the physical nature of saprolitic bedrock, makes it accessible to low cost, open cut mining. The gold is free milling, is often of high fineness and supplies a readily accessible source of funds for rapid capital pay back. These secondary gold deposits invariably overlie or occur immediately adjacent to primary lodes that are more easily exploitable on the back of finance generated, at least in part, by mining of the associated secondary ore bodies.

Gold-bearing laterites of economic interest are found in Africa, Brazil, the Guianas and India and show similarities to the Western Australian lateritic profiles both physically and chemically. Their differences are a function of changing climate and geomorphological processes.

II. LATERITISATION

A. Introduction

The accumulation of laterite constituents can result either in loss of less soluble materials (relative accumulation) or in the addition of constituent material (absolute accumulation). These differential movements of material can occur on the profile scale both in a closed and open system. Realistically the laterite profile is influenced by mechanisms that are operative in both systems and interact mutually to varying degrees and at different rates (Maignien, 1966). The definition of laterite has met with little success as these various mechanisms change in relative influence with time, producing weathered profiles that can vary considerably from one another. The efficiency of these mechanisms are a function of rainfall, temperature, drainage, relief and vegetation. Hardness, colour, iron content, aluminium content, silica/alumina/ferric oxide ratios and pedology have been used to define laterites. From a pedological and field classification point of view, laterite is an intrazonal occurrence that is developed under special geomorphic, groundwater and soil water table conditions (McFarlane, 1976).

Laterites can be divided into two groups; those of aluminous and those of ferruginous and manganiferous accumulations.

Aluminous crusts (bauxite) are related to increased drainage, deionisation and desilication by warm waters. Aluminous crusts of pedogenic origin are found where precipitation is at least 1200 mm. Gibbsite is the most common constituent of aluminous crusts that form in fairly irregular relief and in very humid, tropical climates. Subjacent basic rocks with a high plagioclase content yield gibbsite most readily upon weathering. Aluminium appears to be a residual lateritic element and if mobilised from the system, this appears to be

only in small quantities. The mobility of gibbsite is seldom observed in the form of infill to cracks and the formation of pisoliths. In the case where the alumina enrichment is by the formation of boehmite, the relationship with subjacent rocks is unclear. Crystallisation does not occur after *in situ* weathering, as in the case of gibbsite but precipitates from transported solutions. Due to the relative immobility of alumina, aluminous crusts are usually products of relative accumulation (Maignien, 1966).

Ferruginous crusts (laterite) can be developed within *in situ* soils that are formed upon rocks that are both rich and poor in ferrous minerals. The soil behaves as a physically receptive medium through which chemically transported ferrous fluids may percolate and precipitate ferric oxyhydroxides. Ferruginous crusts may have derived their iron from a lateral source, whereby relief has controlled chemical transport of the iron. On the profile scale, horizons enriched in iron and/or manganese may be formed by either descending fluids enriched in metals or by ascending fluids through capillary action driven by evaporation. The relative mobility of iron and manganese allows crusts to form as products of absolute accumulation (Maignien, *op.cit.*). Much of the data analysed by McFarlane (1976) suggests that laterites are largely a function of residual accumulation. Ferruginous crusts have a variety of forms, the most common being dark brown and pisolithic. McFarlane (*op.cit.*) has recognised two broad groups of laterite containing pisoliths:

- i) those in which the pisoliths are cemented together
- ii) those in which the pisoliths are spaced and supported within an earthy matrix (both are *pisolithic laterites*).

According to McFarlane (*op.cit.*):

"A *pisolithic laterite* is one composed of pisoliths, not necessarily cemented into a mass or *pisolite*. A laterite composed of cemented rock-like mass of pisoliths is a *pisolite* or *pisolitic laterite*."

In the Ugandan situation this distinction is important geomorphologically as the "cemented or packed pisolithic laterites" represent detrital accumulations and the "spaced pisolithic laterites" are *in situ* products (McFarlane, *op.cit.*).

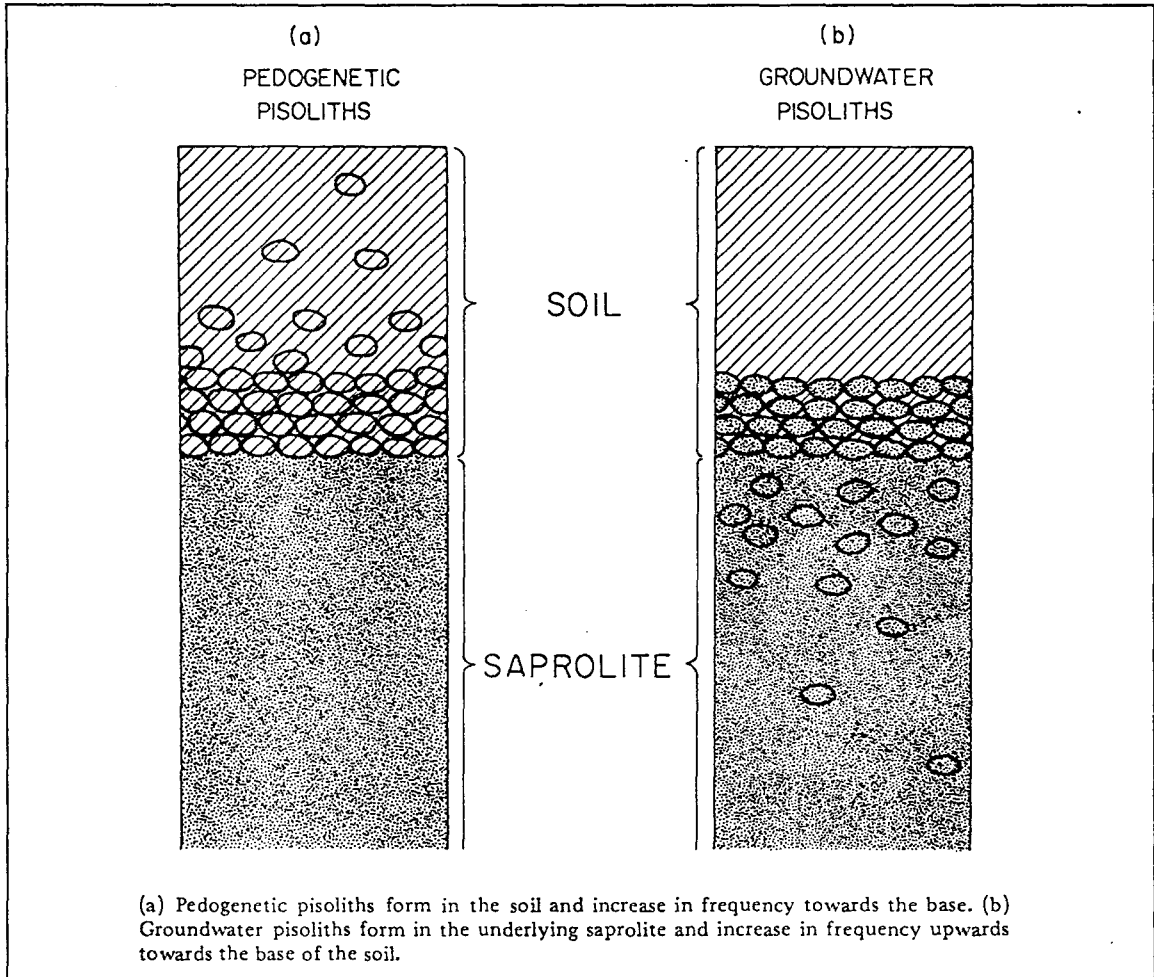


Figure 1
The use of pisolith distribution in laterite profiles for field classification purposes (after McFarlane, 1976).

A practical field classification can be made between *groundwater* and *pedogenic* laterites which have different physical properties and which form in different loci within the profiles of zonal soils (McFarlane, *op.cit.*). In the case of the former, ferruginous precipitates develop within the zone of groundwater table fluctuation. In the latter situation, they form within soil where alternating conditions

of wetting and drying occur (Fig. 1). Laterite occurs at a great variety of altitudes suggesting a multiplicity of planation surfaces. Geomorphologically, these surfaces are easier to interpret using the distribution of groundwater laterites only. Pedogenic laterites are excluded because of their apparent azonal nature. The above classification was developed in the Ugandan environment and has been found to be relevant to laterites in Kenya, Tanzania, Zaire and Central African Republic (McFarlane, *op.cit.*).

Goudie (1973) recognised that laterites (ferricretes) have many similar morphological features to calcretes and has suggested a morphological classification:

- i) vermicular ironstone at the base of the crust
- ii) vesicular lateritic ironstone
- iii) cellular ironstone
- iv) nodular, oolitic and pisolitic ferricrete at the top.

Induration is a function of desiccation, to a certain extent, iron content and its spacial arrangement with associated insoluble matter. This spacial arrangement appears to have its structural strength in a cohesive "framework" of crystallised goethite (Maignien, 1966). Fossil aluminous, ferruginous and manganiferous hardpans can provide a source for remobilisation and deposition as new indurated horizons. The secondary mobilities of aluminium, iron and manganese occur in cycles of different duration and intensity, respectively. These cycles are more or less out of phase with one another due to the different degrees of solubility of the respective elements and in the long term, redistribute lateritic constituents from higher to lower levels of relief. When oxyhydroxide liberation exceeds losses to the oceans via drainage, hardpanning is increased. If mobilisation and leaching effects predominate, then hardpans do not develop and old hardpans are removed. When a topographically elevated area is subject to leaching but drainage is deficient in low-lying areas, then hardpan accumulation ought

to migrate toward the topographically lower zones (Maignien, *op.cit.*). Mechanical degradation of laterites takes place by erosion that is hastened through physical disruption of strata by vegetation and human activity. Degradation leads to "inverted relief" and further exposes the ferruginous crust to redistribution both chemically and physically.

B. Climate

High rainfall, relatively high humidity and temperature are required for lateritisation. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is generally, less than 2 for laterite and decreases with an increase in drainage and temperature. In West Africa, basic and quartz-rich granitic rocks will undergo lateritisation at annual rainfall levels above 1100 mm and 1300 mm, respectively. There does not appear to be an upper limit to precipitation for laterite development. Leneuf (1959 in Maignien *op.cit.*) is of the opinion that the humid conditions of the Ivory Coast, require 20 000 to 80 000 years to ferrallitise (alter to Fe/Al oxyhydroxides) a calc-alkali granite to a depth of 1 m. Laterites and associated indurated horizons may be found where annual precipitation is in excess of 4000 mm (Maignien, *op.cit.*).

In the case of ferruginous and manganiferous crust development, immobilisation of cementing materials is strictly related to the redox factor. The reduced forms of the iron and manganese ionic species appear to undergo complexation with products of biological activity, proceeding into solution at the pH of solutions associated with soils. Active mobilisation of iron and manganese in a moist medium (relatively reducing) gives way to abrupt immobilisation upon encountering a dry medium (oxidising). The process of incrustation occurs only in tropical regions that have alternating relatively wetter and drier seasons. The predominance of old crusts indicates a general climatic trend toward drier conditions. In the case of Western Australia,

semi-arid conditions were requisite for the induration of the laterite (Maignien, *op.cit.* and Lawrance, 1990).

Present day lateritic soils are associated with forests as they prevent the desiccation of the regolith. According to (Goudie, 1973, p.113), lateritisation is inhibited in tropical rainforests due to the influence of probable acid solutions derived from the accumulation of decaying vegetation litter. The low pH conditions inhibit the formation of iron oxyhydroxides. McFarlane (1976, p.49) suggests that the acidification of tropical soils away from equatorial areas may be not as intense as postulated by Goudie (1973) but may be neutral to alkaline with depth in the profile. Deforestation exposes the regolith to the influence of a wetter and drier seasonal climate and appears to be responsible for the induration of groundwater laterites and the formation of pedogenic laterites (McFarlane, 1976, p.43). Where lateritic soils are developed in savannas, the savannas appear to be after forest degradation. D'Hoore (1954 and 1963 in Maignien, 1966) has demonstrated that iron can be mobilised below savannas. Processes of leaching are far more active than below forests. Soils are discoloured to yellows and iron is segregated as concretions and in some cases, as crusts below the surface soils. The leaching of silica is increased with an increase in pH of soil solutions that appears to be associated with natural decline in forestation. Incrustations are a function of mobility of iron and are developed at depths not greater than 2 m below the surface. Observations in the Ivory Coast suggest that once lateritic alteration has commenced it is in no way dependent on the vegetation above it (Claisse, 1953 in Maignien, *op.cit.*).

C. Geomorphology

The relationship between laterite formation, relief forms and their relative positions requires analysis. This analysis

must distinguish between lateritic alteration soils containing or void of aluminous crusts and all soils containing ferruginous crusts (Maignien, *op.cit.*).

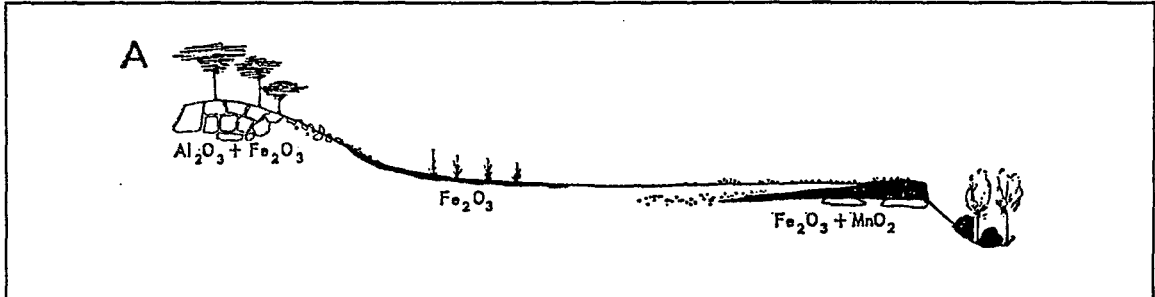


Figure 2

Distribution of aluminous and ferruginous cuirasses (crusts) on the High plateaus of Guinea (after Maignien, 1966).

Laterite occurs on either flat surfaces or gentle slopes, in general. The laterite develops with a reducing landscape that matures into a planation surface blanketed by a sheet of residual material (McFarlane, 1976). Lateritic soils are never found in their juvenile stage of development, in a low lying, poorly drained situation. High precipitation and forest vegetation that are associated with lateritic soils, affect the formation of "hill relief" and convex slope formation that facilitates run-off. Formation of hardpans may modify this geomorphology to an extent that is dependent on whether the crust is either aluminous or ferruginous. Only lateritic alteration soils can produce aluminous indurated horizons under certain circumstances. This mainly gibbsitic, incrustation is found on the best drained parts of hills, i.e., on summits and the slopes leading up to them (Fig. 2). The formation of ferruginous crusts in soils are typically related to subhorizontal topography with gradients less than 1 in 10 ($< 6^\circ$) and less than those upon which aluminous crusts are developed. Ferruginous crusts may be developed on plateaus, plains, alluvial terraces and structural ledges as a function of laterally moving soil water (Maignien, 1966).

Lateral accumulations of iron oxyhydroxides can control the development of concave topographic forms that level out and terminate as an incrustated ledge above a drainage axis. A stepped configuration can be produced by this process of incrustation (Maignien, *op.cit.*).

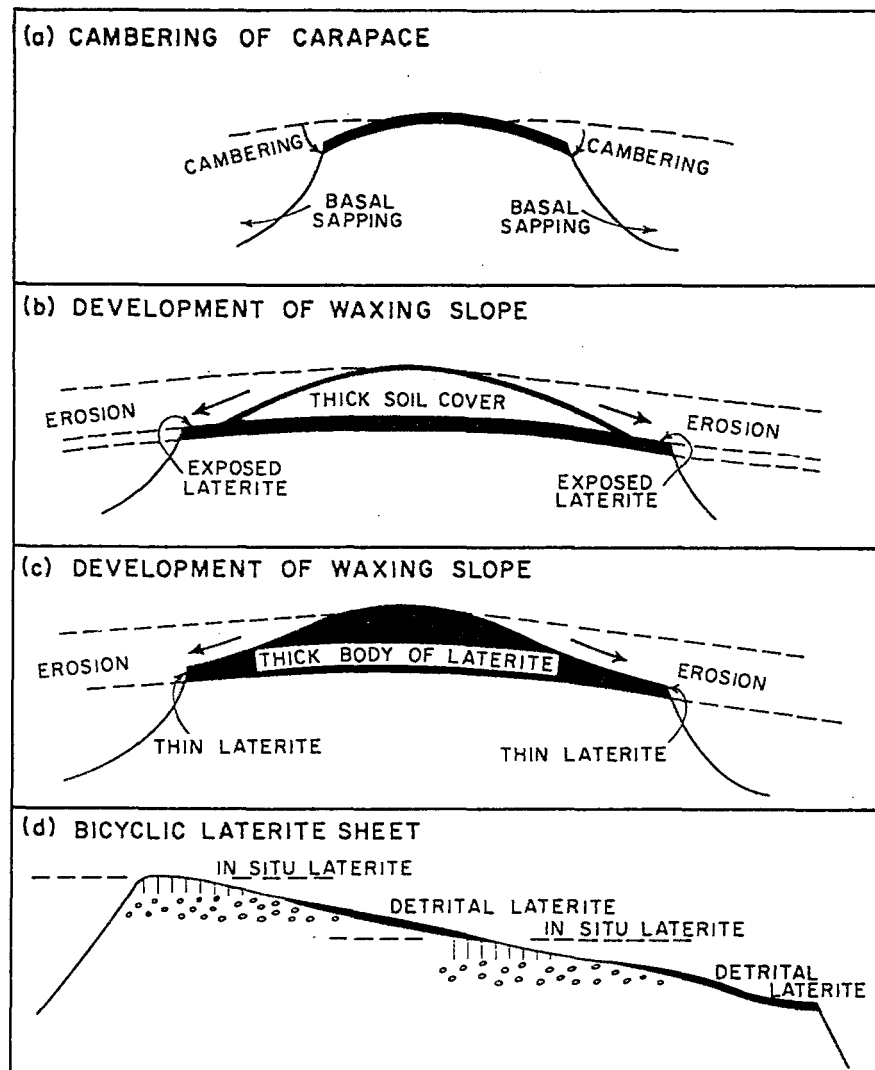


Figure 3

Postincision modifications of the relief of old laterite surfaces (after McFarlane, 1976).

If annual precipitation exceeds 500 mm, the oxyhydroxides can be leached from exposed and mechanically eroded crusts. Differential leaching takes place with manganese, iron and alumina mobilised in order of decreasing solubility, respectively. Laterites developed on slopes greater than 10°

are perhaps original subhorizontal forms that have undergone postincision modification (Fig. 3). Old crusts are generally erosionally resistant forming topographic tabular features that are gradually reduced in size by lateral erosional retreat. Soil erosion in an established forest environment may lead to the chemical degradation of laterite. With degradation, the upper acidic soil layer is lowered and impinges on the zone of iron oxyhydroxide development that subsequently undergoes dissolution. Soluble ferrous compounds migrate downward and are oxidised and reprecipitated at the lowered water table under neutral to slightly alkaline conditions (Fig. 4)

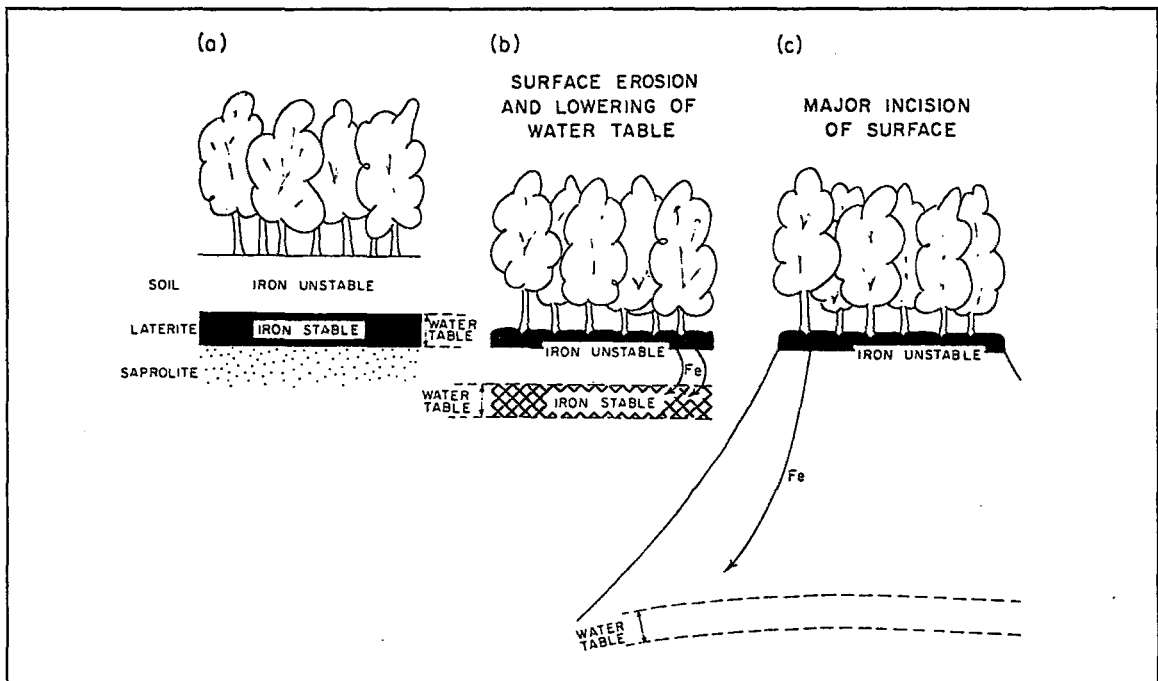


Figure 4

Dissolution of laterite under a forest cover experiencing soil degradation. (c) a substantial drop in base level may result in total loss of the laterite (after McFarlane, 1976).

Based on the influence of drainage, relief and climate, Harrison (1933 in Maignien *op.cit.*) distinguishes two types of laterites:

- i) "high-plateau" laterites consisting almost entirely of hydrated alumina and iron oxides that are formed under heavy constant rain and perfect drainage conditions

- ii) "low-plateau" laterites containing secondary hydrated alumina silicates and occasionally secondary quartz, formed under less persistent rain and under imperfect drainage conditions.

The above is similar to a classification devised by Grubb (1973) for bauxites, i.e., "high level upland" and "low level peneplain" types.

D. Primary Geology

With the possible exception of some pure quartzites, indurated laterites and lateritic soils can be found developed on all rock types that contain aluminosilicate minerals. The process of lateritisation is more intense and laterally extensive over basic rocks than on quartz-rich acid rocks. Mineral neoformation is dependent primarily on bedrock chemistry and secondarily, on water circulation that can modify pH and ionic concentration. In gabbros, syenites and diabbases, feldspars weather to gibbsite and the ferromagnesian minerals into colloidal ferruginous products. The weathering of peridotites yields ferric colloidal products and minor alumina. Mica schists, gneisses and granites yield kaolinite and colloidal alumina silicates (Lacroix, 1913 *in* Maignien, *op.cit.*). During the weathering of acid rocks, silication may produce more clayey laterites while desilication produces surficial concreted bauxite masses at relatively low and high pH, respectively (Harrison, 1933 *in* Maignien, *op.cit.*).

Readily hydrolysable basic rocks having a silica deficit yield gibbsite if the drainage is good. If the drainage is moderate and relatively high humidity permanent, then these rocks give kaolinite. If the drainage is poor, then the neoformations tend to be fine grained and micaceous (Maignien, *op.cit.*). Montmorillonite may become a product of weathering of basic rocks if the drainage is poor and

insufficient to remove magnesium from the system (Deer *et al.*, 1977). Under poor drainage conditions, acid rocks are hydrolysed more gradually and weather to kaolinite after a brief intermediate stage of montmorillonite development (Maignien, 1966). According to Deer *et al.* (1977), acid conditions are required for kaolinite formation and alkaline waters generally yield montmorillonite as a function of the availability of calcium and the paucity of potassium. Illites may be formed in potassium-rich systems. There appears to be a connection between the extent of dissolution of quartz and quantity of ferromagnesian minerals present. Dissolution features are present as "more or less" decayed quartz grains within many ferrallitic soils. Stressed quartz in gneisses, for example, undergo dissolution more readily than unstressed quartz as a consequence of increased surface area available for reaction with weathering fluids (Maignien, 1966).

The development of laterites can be anomalous, with lateritisation favoured by a particular lithology in one instance but apparently, inhibited by the same lithology in another. Variations in the nature of laterite with lithology may occur on an interregional scale (McFarlane, 1976). For example, Goldman and Tracy (1946) have observed that bauxite can develop from kaolinitic parent material suggesting that any primary lithology that produces kaolinitic clay on weathering, may prove a potential source for bauxite development. Variations in lithology may influence topography and the dependent, distribution of laterites/bauxites (McFarlane, 1976). Other factors that effect lateritisation are porosity and permeability of the bedrock, the free circulation of water, movements of the water table, pH and the chemical activity of the environment. As the physical properties of the bedrock, the geohydrology and geomorphology dominate control of the lateritisation process, the more obscure the aluminium/iron chemical relationship between the laterite and subjacent rocks

becomes. In the above situation, trace elements or heavy minerals may be used to trace the relationship between bedrock and the regolith (McFarlane, *op.cit.*).

III. CHEMISTRY OF MOBILITY

A. The leached host rock

1. Introduction

The main components of the laterite are:

- i) iron oxyhydroxides
- ii) aluminium oxyhydroxides
- iii) clays
- iv) aluminous and aluminoferruginous amorphous products

Lateritisation is a process of decomposition of bedrock with the concentration of iron, aluminium oxides and hydroxides after the leaching of alkali, alkali earth metals, ferrous iron and silica. Lateritic hardpan formation processes are shown schematically in Fig. 5.

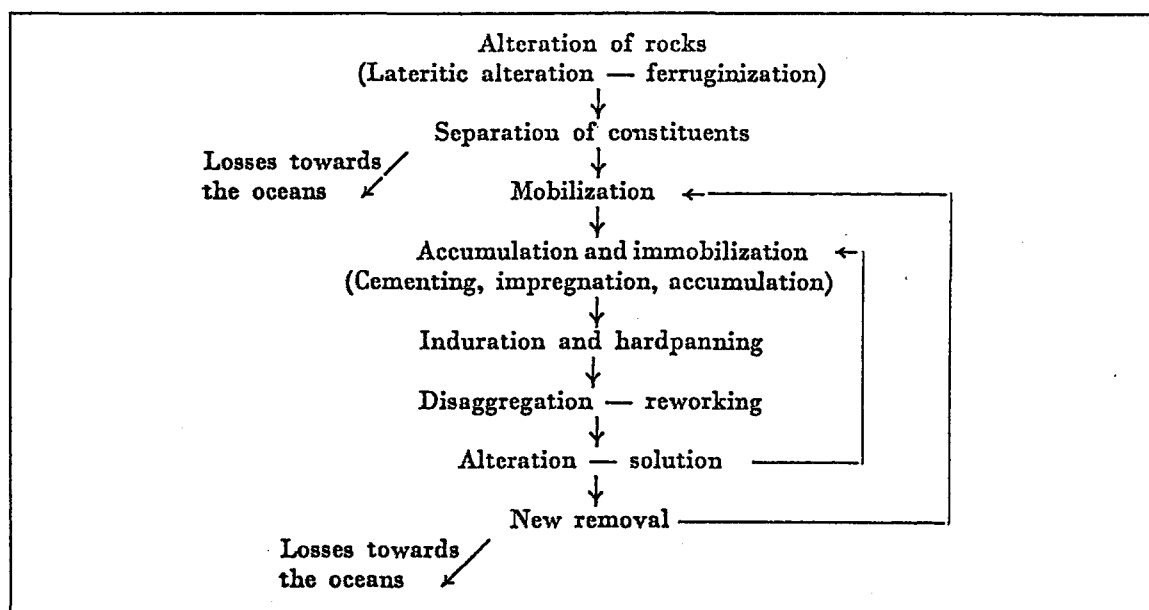


Figure 5
Schematic representation of hardpan formation processes (after Magnien, 1966).

The major element chemistry of selected rock-forming mineral phases was plotted on ternary diagrams in order to illustrate the general change in rock composition with progressive

weathering (Fig. 6). For bauxite development, plot A suggests that leaching of the alkali and alkali earth elements drives the resultant composition of the weathered bedrock towards kaolinite. Gibbsite may be formed by either desilication of kaolinite or primary neoformation through leaching of silica prior to the stabilisation of kaolinite. In certain instances, kaolinite appears to be after silication of bauxite minerals (Krauskopf, 1979, p.155). Plot B depicts the change in composition of bedrock with laterite formation. Initial leaching of alkali, alkali earth metals and the ferrous ion produces the clays. Subsequent oxidation of ferrous iron precipitates goethite at the capillary fringe.

The different forms of iron in soils are not all favourable for mobilisation and transport into an illuvial horizon (Maignien, 1966):

- i) the ferric ion is almost insoluble at the pH of tropical soils
- ii) the ferrous ion is appreciably soluble but stable only in a reducing medium
- iii) iron in its colloid form can be displaced but is very sensitive to electrolytes
- iv) the iron ion vigorously attaches to clay and can be leached together with it
- v) ferric and ferrous ions are able to associate with certain substances passing through soils producing electronegative complex ions which do not attach to clay and are less sensitive to electrolytes. Silicic acids and organic products form pseudosoluble complexes with iron
- vi) under certain conditions iron can migrate in the form of carbonates.

The mobilisation of ferric iron may be enhanced through reduction to ferrous iron by micro-organisms, chelation and/or complexation with organic compounds. Precipitation of

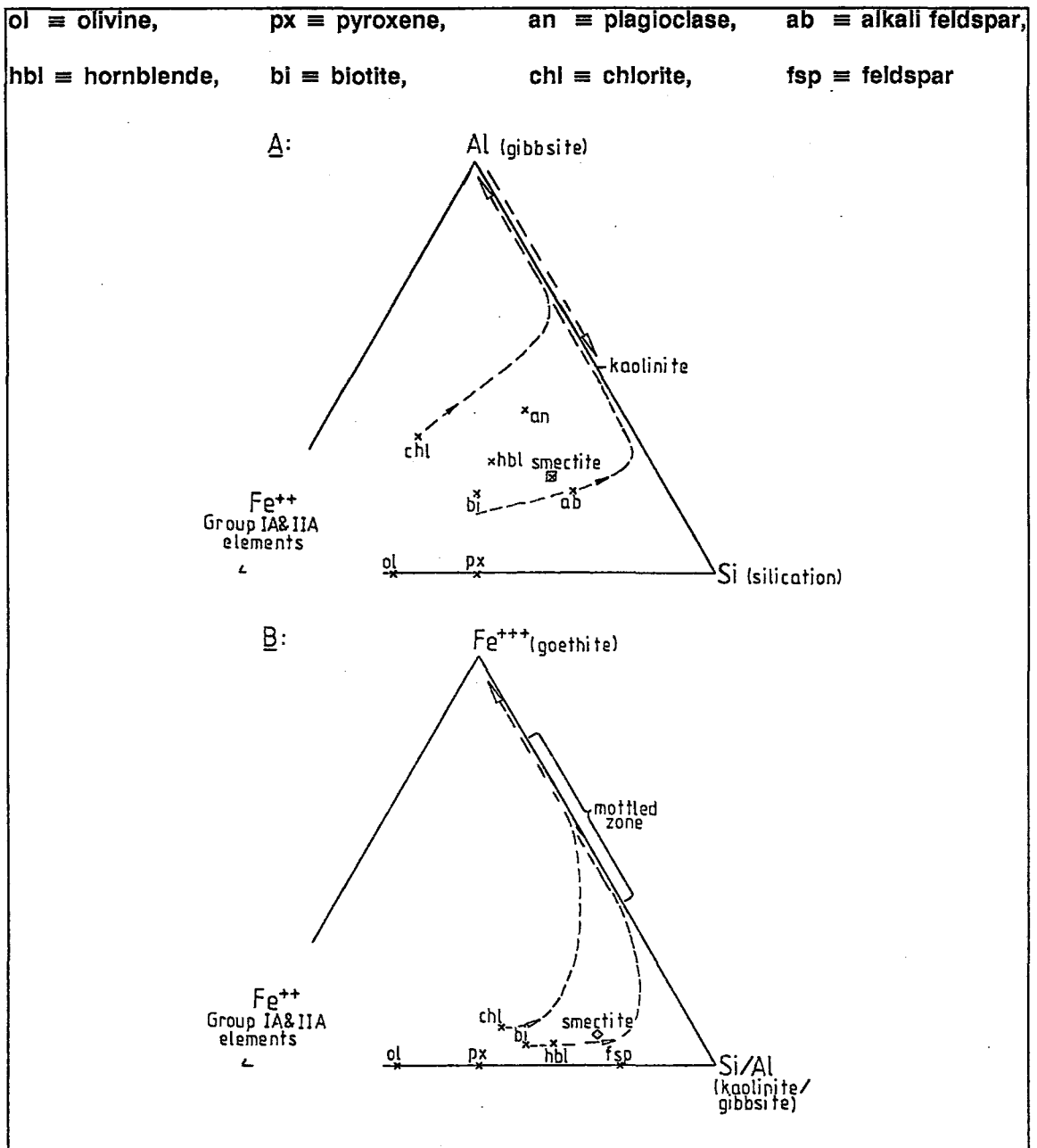


Figure 6
 Ternary diagrams illustrating the change in major element composition of the lateritic regolith with increase in weathering. (A: bauxite, B: laterite).

iron occurs either upon destabilisation of complexes by an increase in pH or Eh. A reduction of organic matter content and of biological activity in the soil promotes immobilisation. This can be induced by the onset of the dry season and the consequent decline in biological activity (Maignien, *op.cit.*). Laterite enrichment is achieved

apparently by precipitation from a fluctuating water table. Campbell (1917 *in* Maignien, *op.cit.*) has defined three zones in the regolith profile:

- i) a zone of non-saturation, above the reach of vadose water
- ii) a zone of intermittent saturation from the maximum upper limit of the capillary fringe to the lower limit at which atmospheric air can penetrate
- iii) a zone of permanent saturation from the lowest level of the water table to the capillary fringe.

The zone of intermittent saturation is enriched by iron carried by solutions rich in organic acids and by ferrous compounds rising from the zone of permanent saturation. The extent and depth of ferruginous induration is controlled by the incapacity of atmospheric air to penetrate the profile. Hence, different laterites are not able to form one under another but may develop on different forms of the relief where the receding water table lay near the soil surface.

Mottled clay horizons appear to be attributable to mechanisms of segregation given by precipitation and differential dissolution of certain components. The ferruginous mottles are of goethite and the nodules that constitute the base of the ferruginous crust are generally, of haematite (Tardy and Nahon, 1985). Manganese occurs in laterite in various mineralogical forms as black nodules, concretions, veins, coatings, linings and stains. Manganese behaves similarly to iron in soils but from the theoretical Eh-pH diagrams of Sato (1960), a greater oxidation potential (at pH = 7) is required for the precipitation of manganic manganese than for ferric iron. Consequently, the manganese content in untruncated profiles increases towards the surface and in some cases, economic concentrations of manganese may develop in the laterite environment (McFarlane, 1976).

2. Primary mineral alteration

Olivine is the least stable mineral that alters to a yellow product (isotropic). A brown product is developed along the margins and the cleavage of the grains. The olivine probably alters to a montmorillonitic product (yellow) before altering to goethite (brown) (Maignien, *op.cit.*). Antigorite develops into yellow to brown-yellow ferruginous products that give rise to cryptocrystalline goethite.

Pyroxenes and amphiboles rapidly weather to amorphous ferruginous substances which subsequently develop into goethite. Biotite also alters rapidly with loss of iron and potassium to produce chlorite which, in turn, alters to a kaolinitic powder mixed with powdery goethite (Fig. 7).

Two types of alteration of plagioclase are evident, one that gives a product rich in aluminium and the other, a product that is a mixture of aluminous and ferruginous materials. In the case of the former, the plagioclase grain is replaced by a web or skeleton of crystalline gibbsite. In the case of the latter, a mass of isotropic ferruginous material and minor gibbsite are produced. This mass is then converted to goethite and kaolinite (Maignien, *op.cit.*).

Magnetite is resistant to lateritic alteration, however margins to grains may alter to rusty-brown oxides that may crystallise into haematite and goethite. Ilmenite, zircon and chromite are extremely resistant to alteration.

Alkali feldspars alter to kaolinite while albitised orthoclase may alter to gibbsite. Nepheline alters rapidly to yellowish "confused" bands which might be halloysite. Sericitic rocks weather either into kaolinitic or gibbsitic rocks. Muscovite is resistant to weathering agents and can be found in the surface horizons to deeply weathered ferrallitic soils. The illites often found in African soils may well be cryptocrystalline muscovite (Maignien, *op.cit.*).

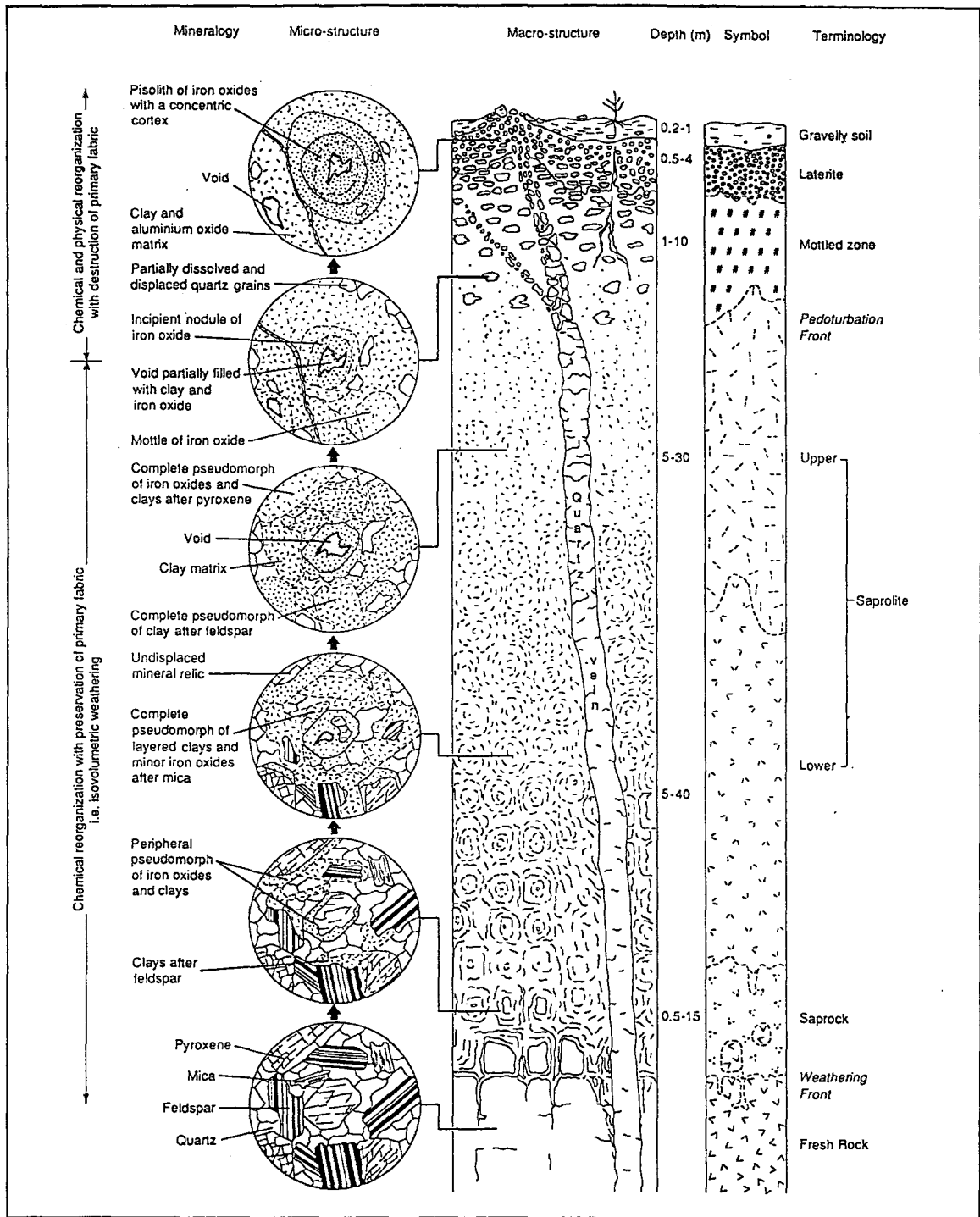


Figure 7
Schematic representation of a complete lateritic weathering profile (after Lawrance, 1990).

The alteration of quartz is minimal. The weathering of quartz appears to be a function of both physical and chemical processes. A greater surface area of the quartz is exposed

to corrosion by the impregnation of ferruginous solutions along fractures. Within the cuirasse, quartz veins may become quite fragmented (Maignien, *op.cit.* and Freyssinet *et al.*, 1989a).

Clay minerals like halloysite and montmorillonite, are observed in the early stages of alteration and are assumed to be the intermediate reactants that produce the final products of gibbsite, goethite and kaolinite (Maignien, 1966).

3. *Secondary minerals*

Gibbsite [$\text{Al}(\text{OH})_3$] can form in both alkaline and acid natural media. Whatever the pH of formation, alumina gels that develop in a de-ionised medium, crystallise into trihydrates. The de-ionisation is accelerated by intensive leaching and by relatively higher temperatures of the percolating water (Maignien, *op.cit.*).

Boehmite [$\text{AlO}(\text{OH})$] is sometimes associated with gibbsite in hardpans. Boehmite appears to crystallise from transported solutions that do not require the extent of de-ionisation that gibbsite does for precipitation. Boehmite precipitates from a slightly acidic solution, is fine grained and is readily taken up into solution again, in some cases (Maignien, *op.cit.*). Diaspore is a dimorph of boehmite and occurs as an important constituent of bauxite deposits in certain instances (Deer *et al.*, 1977).

Goethite [$\text{FeO}(\text{OH})$] is the main constituent of ferruginous hardpans. There appears to be no chemical difficulty in the transformation of a ferric hydroxide gel into goethite under the conditions of a lateritic medium. Haematite is a minor constituent of ferruginous hardpans that may be produced by either dehydration of goethite, by alteration of magnetite, chromite and ilmenite and/or by contamination (Maignien, 1966). Goethite forms commonly in young bauxitic profiles

and coexists with gibbsite. In old bauxites, boehmite may replace gibbsite and with dehydration, haematite forms instead of goethite. Goethite also coexists with kaolinite in clay-rich red or yellow latosols. Goethite only predominates in downslope profiles that are wet much of the time. Goethites may contain up to 30 mole% diasporite as a function of available alumina in solution and silica activity (Tardy and Nahon, 1985). Haematite replaces kaolinite and becomes aluminous as a function of the instability of kaolinite in the "unsaturated" zone. Pisolites tend to contain haematite rather than goethite at Mt. Gibson, Western Australia (Davy *et al.*, 1988).

Quartz can be produced from siliceous accumulations by crystallisation from a gel on aging. Crystallisation of quartz will also occur apparently from solutions that are relatively pure and not heavily charged with cations and silica. If solutions are impure and heavily charged with silica, chalcedony will precipitate instead (Maignien, 1966).

Anatase is often found associated with lateritic alteration products. It can be derived from the weathering of titaniferous silicates, ilmenite and titanomagnetites. Chlorite is not a constituent of lateritic hardpans but occurs as a transitional alteration product after biotite and possibly, pyroxene. Sericite, like chlorite is another transitional, secondary mineral after the weathering of plagioclase. Sericitisation is accelerated by a relatively high temperature and favourable conditions of humidity (Maignien, *op.cit.*).

Kaolinite is probably derived from fluids that are acid, moderately silica rich, de-ionised and generated under a permanently humid environment. Kaolinite may form from a precipitated gel and from particles in solution where alumina is stabilised as an organocomplex (Maignien, *op.cit.*).

4. *The lateritic weathering profile*

The entire lateritic weathering profile can be divided into a number of zones that include the hardpans (Fig. 7). Overlying bedrock and at the base of the profile is saprock. This is the first horizon developed in the weathering process and consists of partially weathered bedrock immediately above the weathering front. Partial weathering implies alteration of minerals most susceptible to corrosion (eg., olivine and pyroxene), with preservation of grain shape and primary rock fabric. The saprock remains compact and indurated (Lawrance, 1990). Saprock is overlain by saprolite that is divided into an upper and lower unit in well developed profiles. Saprolite is defined as a clay-rich rock formed by the near total decomposition of bedrock through chemical weathering. The lower saprolite displays progressive alteration from the base upward, preserving an arbitrary minimum of 20% of primary rock fabric. Volume changes are negligible with the original positions of resistant primary minerals like quartz, chromite, rutile and zircon, preserved. The intense weathering/leaching of the upper saprolite is manifested in its porous fabric and associated volume loss. Microsubsidence and consequent destruction of primary structures, marks the top of the saprolite and the position of the pedoturbation front (Lawrance, *op.cit.*). The pedoturbation front marks the change from the saprolith to the pedolith where smectites are replaced by kandites and the remaining mobile elements are leached from the system. Under seasonally tropical humid conditions, water table levels fluctuate in this part of the profile. Ferrous-bearing fluids precipitate iron oxyhydroxides upon oxidation at this aqueous fringe. The initial precipitation of iron oxyhydroxides occurs as spots, irregular patches and streaks that ultimately produce a mottled zone within a predominantly clay rich horizon (Fig. 8). The iron concentrations increase in size upward as concretions, until they eventually coalesce to produce a crust of pisolithic ironstone. With continued

leaching and the removal of silica, gibbsite may replace any remaining kaolinite in this upper zone (Lawrance, *op.cit.*). The depth of weathering is controlled by the grain size of the bedrock material and local structural features, particularly fault and shear zones.



Figure 8

The mottled zone and ferruginous laterite at the South Junction Mine, Murchison Province, Western Australia. (the pale green clays are possibly nontronitic and Cr bearing).

In the Western Australian environment, the lateritic profile is modified by aridification that lowered the water table, exposed the upper portion of the regolith to greater oxidising conditions, induced further leaching and hardened the laterite through desiccation (Butt, 1987 and Lawrance, 1990). The profile became a relatively closed system that retained soluble weathering products including chloride derived largely from rainfall (Hingston and Gailitis, 1976). In 1973, the input of Cl^- into Western Australian soil ranged from 2 to $180 \text{ kg}\cdot\text{ha}^{-1}$ as a function of distance from the coast. Increased groundwater salinity with the lowering of

the water table caused bleaching of the upper part of the saprolite to produce the pallid zone or the bleached upper saprolite. From investigations of lateritic profiles in the Darling Range, Western Australia, the storage of salts within the pallid zone increases with a decrease in rainfall (Dimmock *et al.*, 1974). At positions of stabilisation of the receding water table, relict primary textures may be destroyed by dissolution of secondary minerals and the precipitation of iron as pseudomorphs, concretions and as massive aggregates in pore spaces. The levels of stabilisation are marked by the accumulation of iron oxides precipitated at the successive, new redox fronts within the lower saprolite (Fig. 9) (Lawrance, 1990).

With continued aridity, increased groundwater salinity has promoted the formation of caliches, gypsiferous soils, silcretes and playa deposits within the vadose zone of the profile and in valleys, respectively. In areas overlying granites, various forms of silica and aluminosilicates have been introduced into the lateritic profile (Butt, 1983 and 1985). The above salts have introduced mobile elements into the leached profile that have "re-organised" supergene minerals and enhanced crystal growth in a stable porous highly saline environment (Lawrance, 1990).

In the case of tropical conditions, the development of the pallid zone requires a lowering of the base level, reduction of the water table, physical erosion, incision and contemporaneous deforestation (McFarlane, 1976, p.60).

5. Soils

As in the case of laterite development, the soil profile is a function of climate, relief and bedrock geology. Biological activity and time also control soil development and have a considerable impact on the geochemical distribution of elements in the profile (Levinson, 1980).

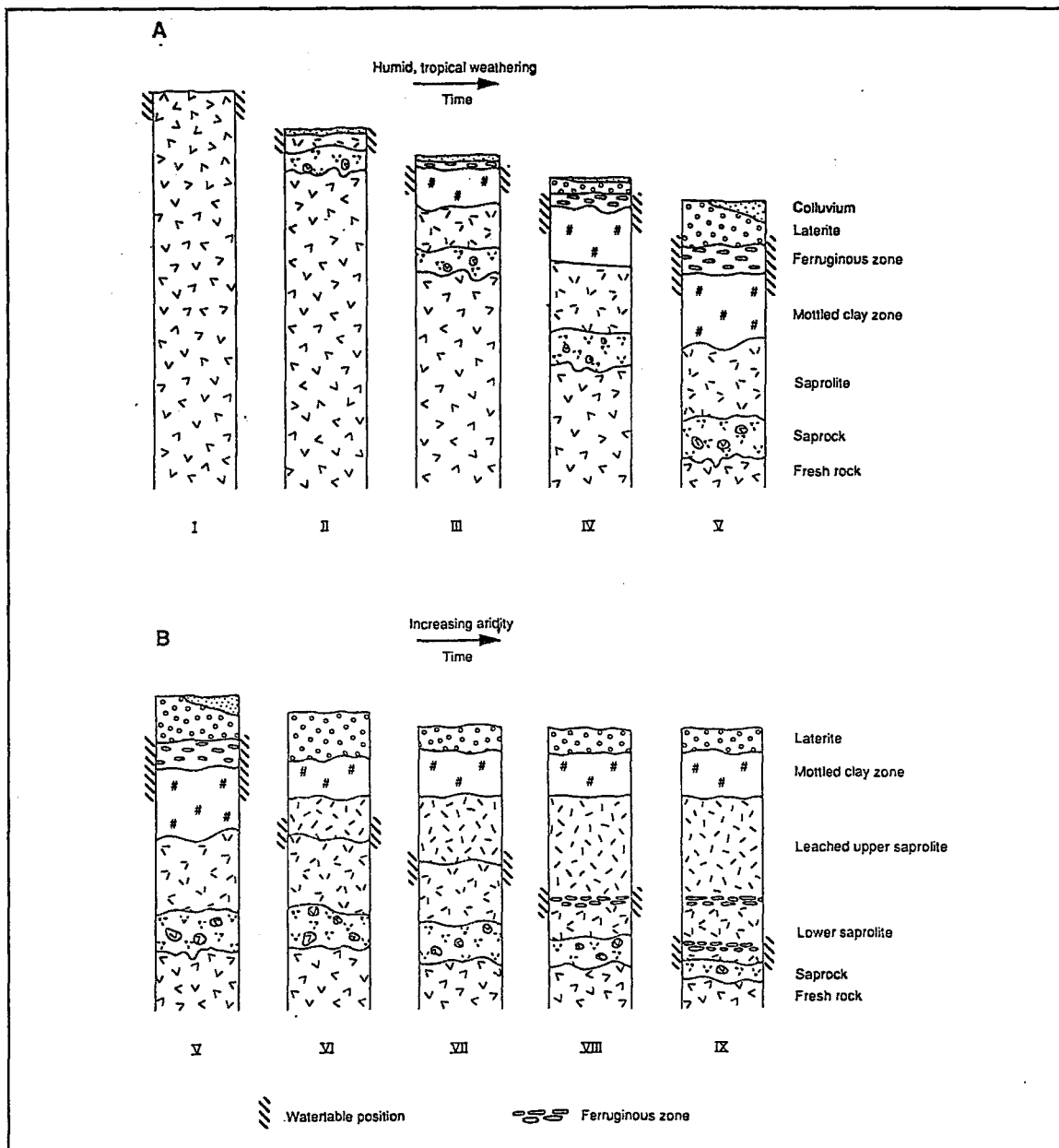


Figure 9
A schematic representation of the weathering processes, A: humid tropical weathering, B: weathering with increasing aridity (after Lawrance, 1990).

Soils are best developed in humid, temperate climates and suffer relatively less leaching than the lateritic profile that is unique to the tropics (McFarlane, 1976). The profile becomes progressively truncated with an increase in aridity and topography (Fig. 10). The soil profile is divided into three zones, C, B and A, from the base to the top, respectively and is similar to the lateritic section in the

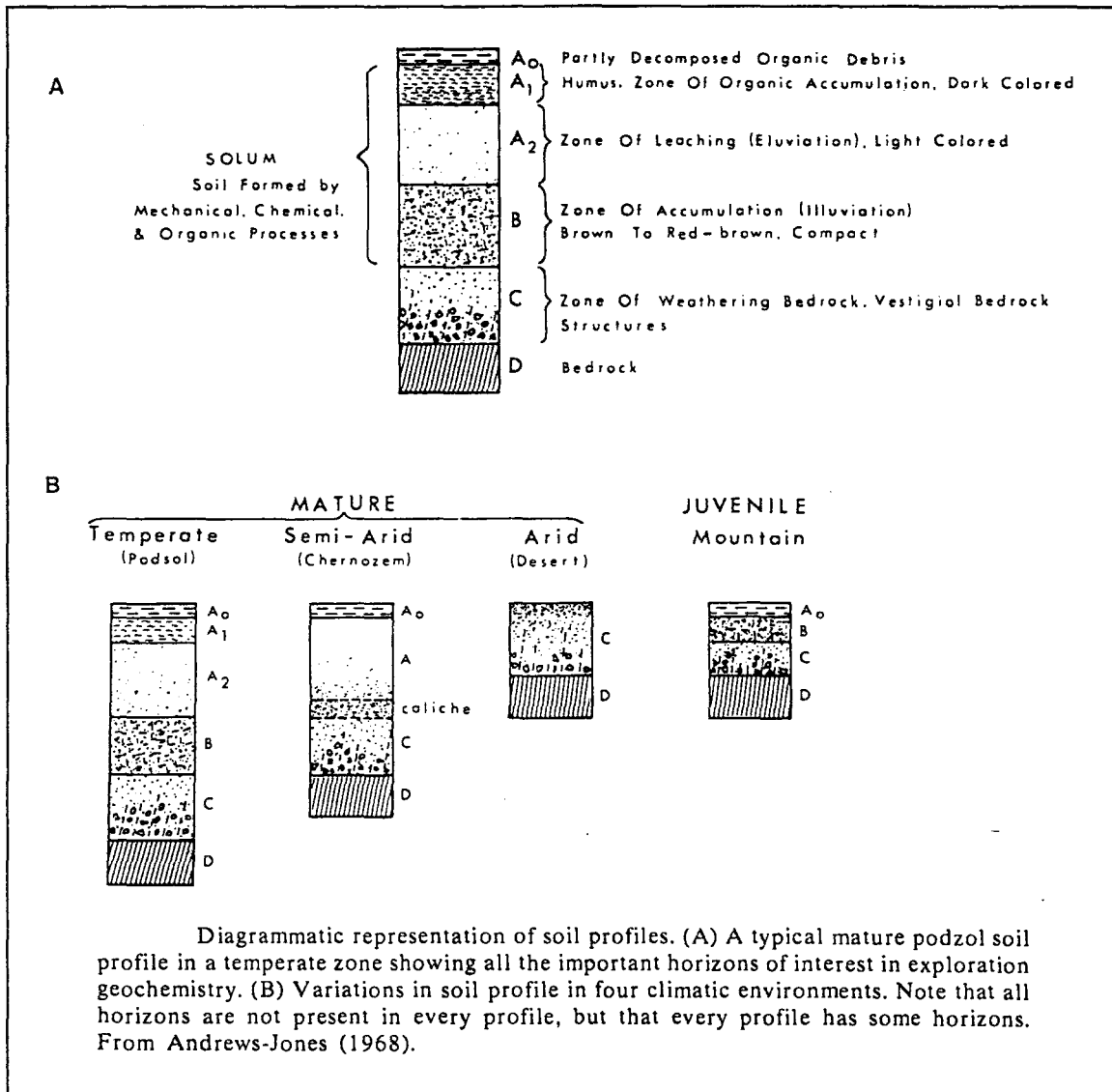


Figure 10
Soil profiles (after Levinson, 1980).

case of podsol soils. The C horizon is similar to the saprock/saprolite and the B horizon is a ferruginous zone of illuviation, equivalent to the laterite. The A horizon is divided into a lower pallid zone of eluviation and an upper zone of organic accumulation. Detailed systems of soil horizon classification are tabulated by Levinson (*op.cit.*, p.92).

Soils can be classified into three broad types based on climatic control (Levinson, *op.cit.*):

- i) the zonal type that is controlled by vegetation and

climate over a large area and includes the entire range of weathered profiles formed under different climatic conditions, (Fig. 11). With annual average rainfalls greater than 600 mm *pedalfer* soils may develop as (Krauskopf, 1979):

- a) lateritic soils in the tropics
- b) podzol soils in a temperate climate
- c) tundra soils in the polar regions.

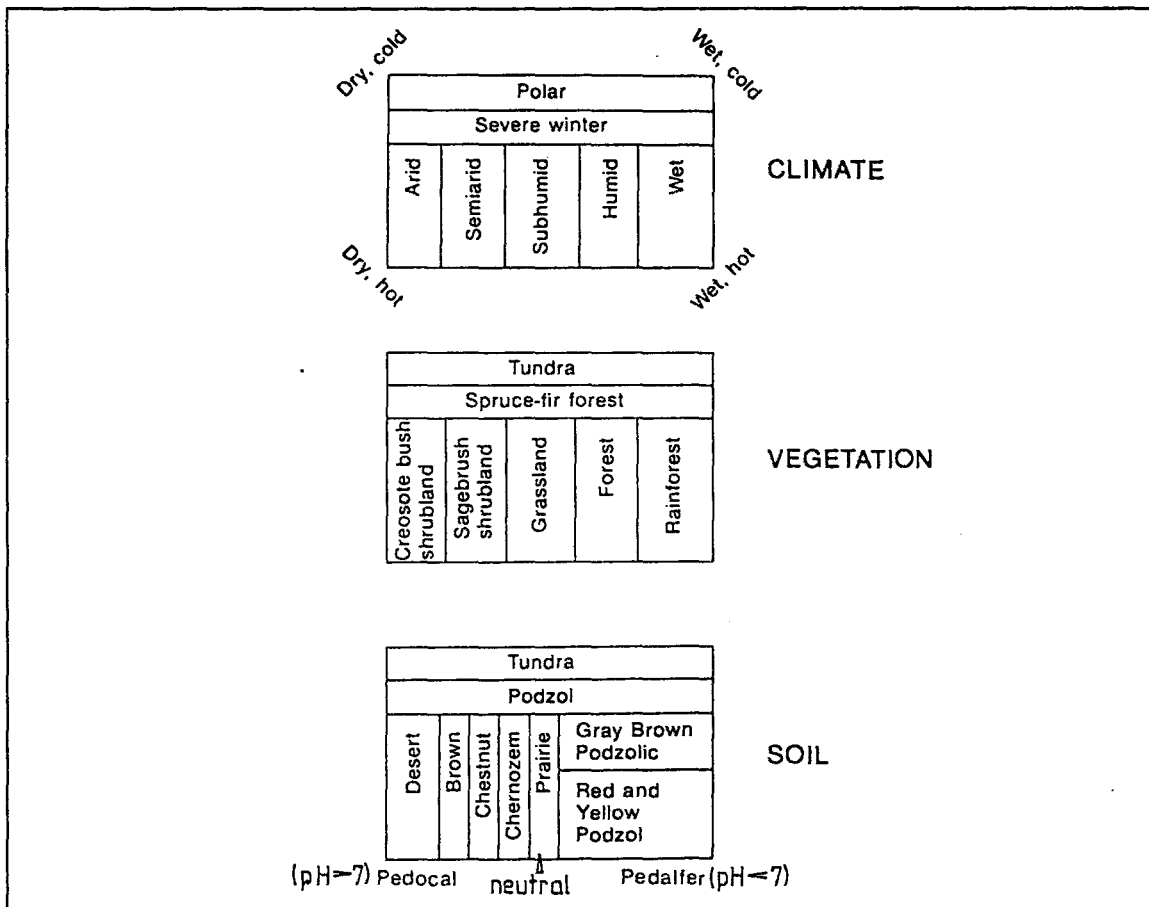


Figure 11

The relationship of climate, vegetation and soil based on the zonal classification as applied to North America (modified after Levinson, 1980)

Pedocal soils are:

- a) chernozem soils (black earths) that form under cool climates with annual precipitation between 300 and 600 mm,
- b) chestnut-brown soils that form under warm climates

- with annual precipitation between 250 and 400 mm
- c) desert soils that develop under hot conditions with annual precipitation less than 250 mm.

Pedalfers are formed under acidic conditions in an open system while pedocals are influenced by alkaline solutions in a closed system. Gley (Fe^{2+} dominated, organic matter- and clay-rich) soils are formed in an environment that falls under the influence of both an open, humid and closed, poorly drained bog system.

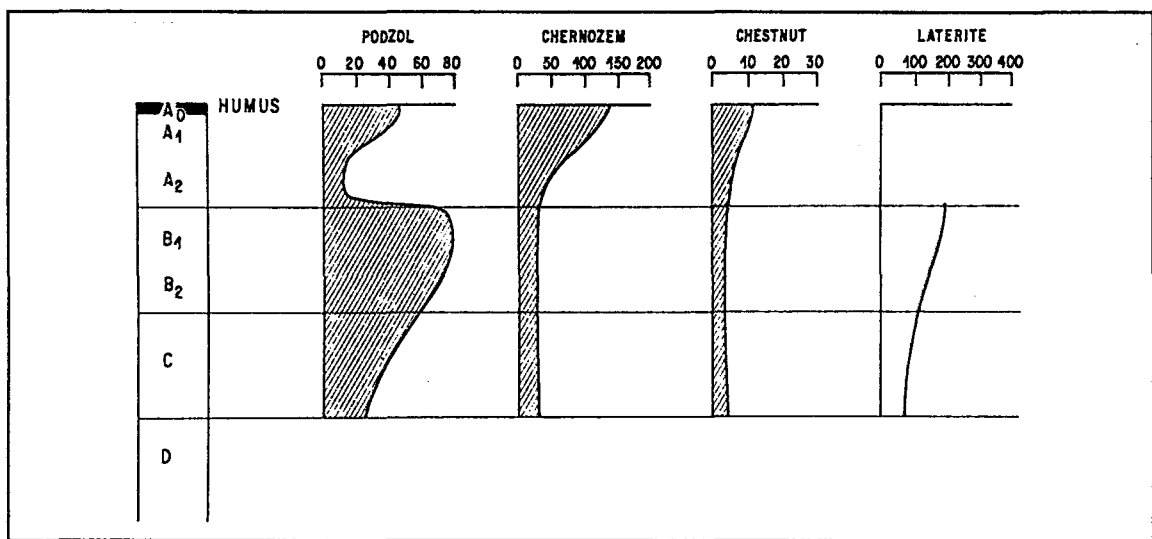


Figure 12

Generalised representation of the distribution of copper in four different types of soils. Based on data from the CIS. All values in ppm (after Levinson, 1980).

- ii) the intrazonal type is influenced by a local control such as relief, parent material and/or age that is superimposed upon the normal effects of climate and vegetation. Intrazonal soils are characterised by:
- poor drainage conditions in wetland environments (*hydromorphic* soils)
 - poor drainage in arid regions (*halomorphic* soils) that produce salt concentrations in the upper horizons to give solonchaks and solonetz
 - high lime content (*calcimorphic* soils).

iii) the azonal type that has a profile either poorly developed or absent and is determined primarily by the nature of parent material, eg.:

- a) regosols, eg., aeolian dunes and loess
- b) alluvial
- c) lithosols developed on steep slopes.

The general pattern of distribution of trace elements within various soil and laterite profiles are illustrated by copper in Fig. 12. The distribution of ferrometals in a Zambian latosol, i.e., V, Cr, Mn and Fe, mimic this trend (Rose *et al.*, 1979, p.153)

B. Secondary gold distribution

1. Introduction

The gold ionic species and their standard electrode potentials at 25°C and 1 atm in acid solution are (Krauskopf, 1979):

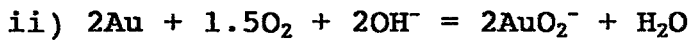
- i) $\text{Au} = \text{Au}^+ + e^-$ (approx. + 1.68 volts)
- ii) $\text{Au} = \text{Au}^{3+} + 3e^-$ (+ 1.50 volts)

The above ions have relatively high oxidation potentials and do not exist in appreciable amounts in natural solutions (0.03 - 0.4 ppb Au range (Wedepohl, 1978, p.79-I-5 and Boyle, 1979, p.57)). For primary gold to be taken into solution, the element requires oxidation. Experimentally, pyrolusite behaves as a strong oxidant and allows an order of magnitude more gold (approximately 20 ppm in 10 days) to enter an acidic and chloride solution (1N in H_2SO_4 and 0.1M in NaCl) than goethite does (Cloke and Kelly, 1964). Krauskopf (1951) suggests that the cupric ion, Cu^{2+} , may behave as an adequate oxidising agent in an acidic and chloride solution. An oxidising agent weaker than the cupric ion ought not effect the solubility of gold at ordinary temperatures. Krauskopf (*op.cit.*) also suggests that oxygen in atmospheric air ought

be a sufficient oxidant for gold both in an acid, chloride and an alkaline solution. The above is disputed by Cloke and Kelly (1964) and by the Eh/pH diagram of Levinson (1980) (Fig. 13). Boyle (1979) includes As^{5+} and Sb^{5+} as strong oxidising agents. The auric ion is taken experimentally and theoretically into solution, in preference to the aurous ion (Krauskopf, 1951):



(under acidic conditions)



(under alkaline conditions)

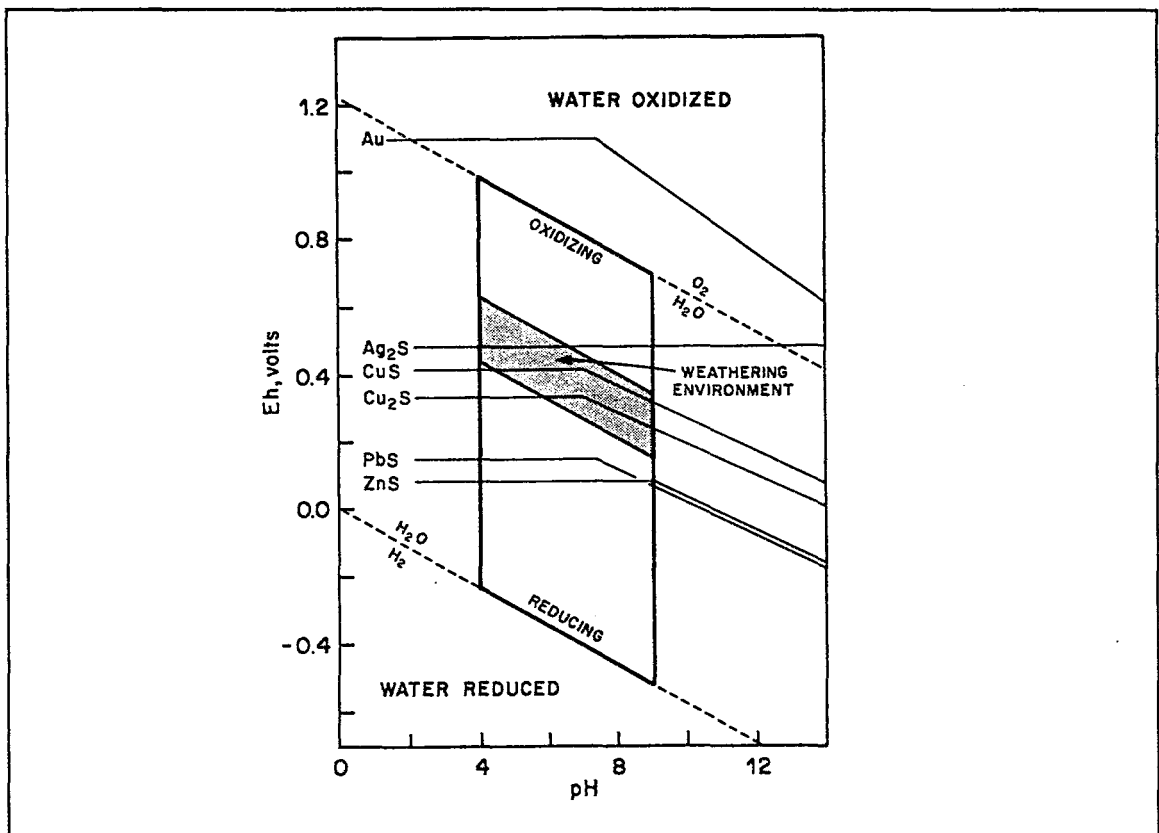
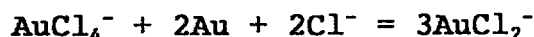


Figure 13

Oxidation-reduction potentials for some simple sulphides and gold. ($T = 25^\circ\text{C}$, $p = 1 \text{ atm}$, metal ion activity = 10^{-6}M) (after Levinson, 1980).

Experimentally, soluble gold in the trivalent oxidation state is adsorbed rapidly on to clays in natural waters. This is followed by the release of the gold within approximately 24

hours of the mixing time and appears to be the point at which there is a equilibrium shift from auric to aurous gold (Wood, 1977 in Boyle, 1979, p.61):



The calculated solubilities for gold in river water at 25°C and in contact with air are greater for the $[\text{AuCl}_2]^-$ complex than the $[\text{AuCl}_4]^-$ species (Ong and Swanson, 1969).

2. Gold complexing species

The most important complexes responsible for the dissolution and transport of gold in the regolith are summarised in Table I.

TABLE I
(after Lawrance, 1990 and 1988).

Summary of chemical environments suitable for gold remobilization via ligands commonly found in the weathering profile. a = CN, amino acid, humic acid, and other potential biological ligands; b = note that AuCl_4^- has been produced experimentally but AuCl_2^- is thermodynamically favoured in the geological environment.			
Ligand	Chemical environment for dissolution	Dissolution reactions	References
Organic complexes	oxidizing neutral-acid biological activity	$\text{Au (electrum)} + \text{Organic Acid}^a + \text{O}_2 + \text{H}^+ \Rightarrow \text{Au(Organic)}^{n+} + \text{H}_2\text{O}$	Lakin <i>et al.</i> (1974), Baker (1978)
Thiosulphate complexes	oxidizing mildly acid to mildly alkaline low-moderate carbonate	$\text{Au (electrum)} + 2\text{S}_2\text{O}_3^{2-} \Rightarrow \text{Au(S}_2\text{O}_3)_2^{3-}$	Stoffregan (1986), Webster (1986)
Chloride complexes	oxidizing acid high Cl^- concentration	$4\text{Au (electrum)} + 8\text{Cl}^- + \text{O}_2 + 4\text{H}^+ \Rightarrow 4\text{AuCl}_2^- + 2\text{H}_2\text{O}$	Cloke & Kelly (1964), Krauskopf (1951), A.W. Mann (1984a, 1984b), Webster & A.W. Mann (1984)

Plants have the capacity to contain substantial amounts of gold which appears to be a function of their ability to produce the organic compounds required for the fixing of colloidal gold derived from solutions absorbed by the plant (Table II). Organic complexes are produced from ligands derived from plant matter both living and decaying. They are

in the form of cyanide, thiocyanate, amino acids, fulvic acids, humic acids and probably other biological species not yet identified (Lawrance, 1990 and Butt, 1988). Humic acid appears to be the most important organic compound that provides ligands responsible for the complexation and transport of gold in natural systems under oxidising, weakly acidic conditions (Baker, 1973, 1978, Lakin *et al.*, 1974 and Butt, 1988). Eighty to 90% of the organic matter extracted from the podzolic soils investigated by Baker (1973), consisted of humic acid.

TABLE II
Gold content of plants (after Boyle, 1979).

Type of plant	Au in ash (range) (ppm)
<i>Nonvascular</i>	
Bacteria	no data
Algae (marine)	0.00015-1.7
Algae (terrestrial)	no data
Fungi (terrestrial)	trace-11.6
Lichens	1-1.3
Mosses	0-19.2
<i>Vascular</i>	
Herbs	
Grasses and sedges	0-8.6
Forbs	0-610
Shrubs	0-600
Trees	
Coniferous	0-6
Deciduous	0-10
<i>Miscellaneous</i>	
Honey	not detected
Wine (U.S.S.R.)	0.030-0.758 μg/L (ppb)

Humic acid is an ill-defined group of high molecular weight compounds derived from the digestion of wood by strong alkaline and subsequent neutralising, acid solutions (Krauskopf, 1979). The humic acids appear as gelatinous precipitate which, if washed carefully, shows practically no acid properties. Associated acidity is probably ascribed to the presence of carbonic acid and simple organic acids, like acetic acid. Experimental data indicate that gold is mobilised in the presence of humic acid with as much as 330 ppb Au being taken into a 500 ppm solution of humic acid over

a period of 50 days (Baker, 1978). According to Baker (*op.cit.*), gold is taken into solution as the $[\text{AuCl}_4]^-$ complex prior to being absorbed by plants. In this case, the chlorine is apparently derived from the plant material itself. Upon defoliation or death of the plant, the $[\text{AuCl}_4]^-$ complex is reduced to colloidal gold in the presence of humic acid within the humic soil layer. The weaker the complex, the greater the affinity for reduction by the humic acid (Fedoseyeva *et al.*, 1986). Fungi have the capacity to extract gold from solution and deposit colloidal gold on its membranes (Boyle, 1979, p.80). With sufficient residence time in the humus layer, the colloidal gold is oxidised and this time, complexed with ligands derived from humic acid. This complex migrates readily in the hydrosphere (Baker, 1978 and Curtin *et al.*, 1970). The experimental work of Kolotov *et al.* (1980) suggests that gold is not transported in colloidal form ($> 1 \mu\text{m}$) in "natural waters" sampled from the regolith of a certain gold deposit. The gold concentrations in these waters are approximately an order of magnitude greater than the concentrations of natural solutions quoted by Wedepohl (1978) and Boyle (1979) above.

Ong and Swanson (1969) conclude that the negatively charged colloidal gold is not oxidised and complexed but rather, is protected from growth, coagulation and precipitation by coatings of colloidal organic (humic and fulvic) acids. In an acidic environment, gold complexed with chloride, is reduced by organic acids to colloidal gold and intimately associated with and fixed by organic matter. In slightly acidic to alkaline waters, gold is transported as stable organic-protected colloids upon solubilisation of the organic acids. The fine size of the colloidal gold ($< 10 \mu\text{m}$) allows for easier physical transport of the metal. Ong *et al.* (1970) demonstrated that the colloidal transport of Cu, Pb, Zn, Fe and Al cations increases generally, with an increase in both the concentration of organic acids and pH (in the range 5 to 9). Organic acids are considered as negatively

charged hydrophilic colloids that "complex", transport and deposit metals as humates (Fig. 14).

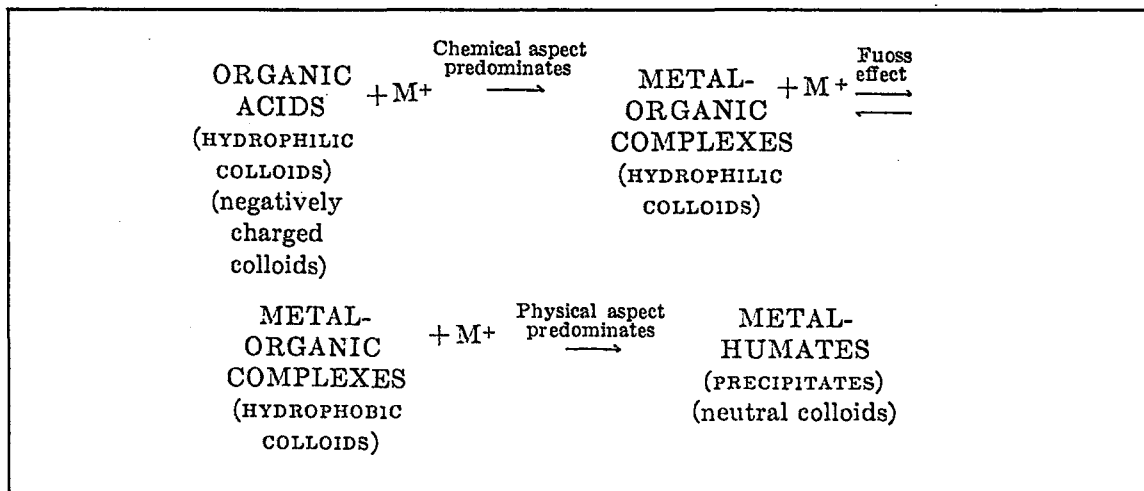


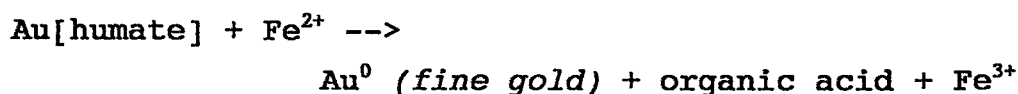
Figure 14

The mechanisms of the metal-organic "complex" association theorised by Ong et al. (1970). [M⁺ = metal ion].

The CN⁻, and CNS⁻ ligands also have been considered for the dissolution and transport of gold (Lakin et al., 1974, Levinson, 1987, p.184 and Curtin et al. 1970). The formation of the very stable [Au(CN)₂]⁻ complex by the reaction of cyanoglycosides could explain the gold uptake by plants but the [Au(CN)₂]⁻ species may experience difficulty in forming due to the rapid hydrolysis and enzymatic destruction of the CN⁻ in nature (Baker, 1978).

Iron-oxidising bacteria such as *Ferrobacillus ferrooxidans* and *Thiobacillus ferrooxidans* may have a considerable impact on the mobilisation of gold as chloride and/or organic complexes in the oxidised zones of gold deposits containing abundant iron minerals (Boyle, 1979).

Gold humate is precipitated by ferrololysis (Butt, 1987 and 1988):



According to Ong and Swanson (1969), organic-protected gold colloids are precipitated on encountering sea or brackish water by reaction with ions and/or clay colloids. Reduction may occur upon pregnant solutions encountering a very acidic environment, i.e., with a pH of less than 3. Fedoseyeva *et al.* (1986) came to similar conclusions concerning the behaviour of gold in the presence of organic acid solutions as a function of pH but ascribed this behaviour rather to the stability of organic complexes.

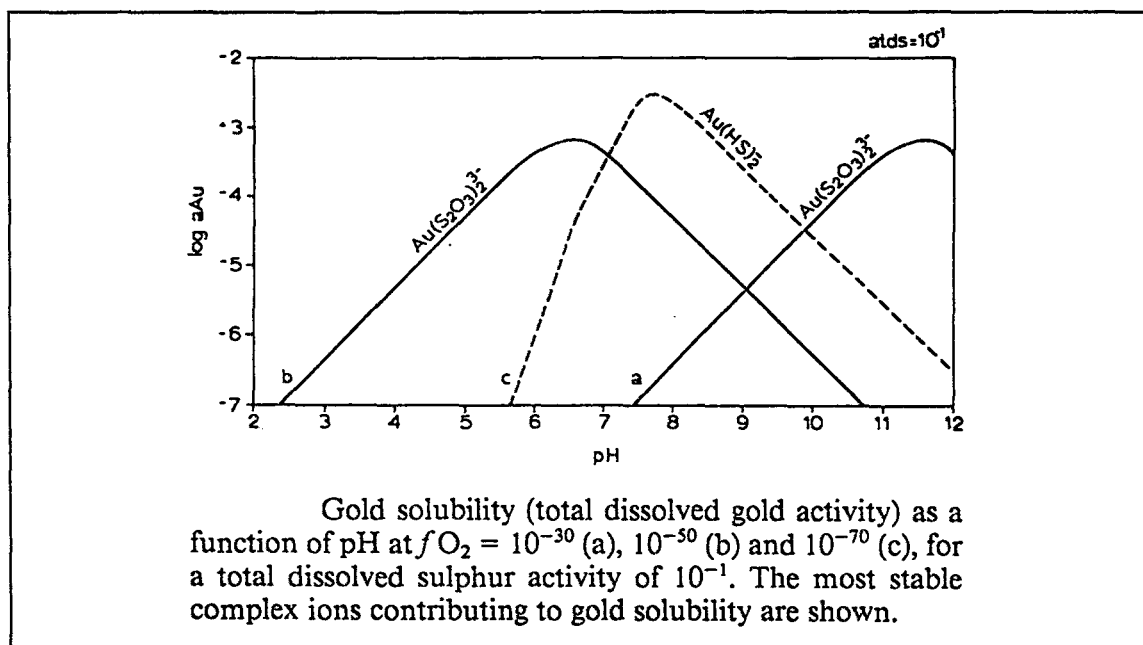
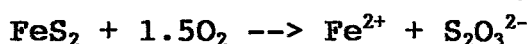


Figure 15
Total dissolved gold activity in the system Au-S-O₂-H₂O (after Webster, 1986).

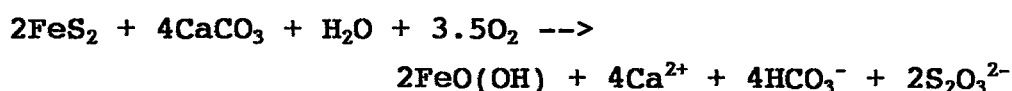
The most important ligand for thio complexation of gold in the secondary environment is the thiosulphate ion ($S_2O_3^{2-}$) (Webster and Mann, 1984, Webster, 1985 and Webster, 1986). Other potential complex ligands include HS^- and SO_3^{2-} . The sulphite anion is rarely stable in the natural environment. The HS^- anion may be generated perhaps in a humus layer by bacterial decay but its existence within downward, migrating fluids is limited by the oxidising environment of the vadose zone. Experimental studies of pyrite oxidation within the pH range from 6 to 9 and at 30°C, indicate that four metastable

sulphur oxyanions are generated as a function of pH (Goldhaber, 1983). At pH > 7, the thiosulphate anion is the dominant species in solution while at pH < 7, the sulphate and tetrathionate anions are prevalent. The sulphite anion has a relatively low activity in slightly alkaline solution. The most stable gold complexes are $[\text{Au}(\text{S}_2\text{O}_3)_2]^{3-}$ and $[\text{Au}(\text{HS})_2]^-$ in mildly reducing to oxidising, neutral to alkaline and reducing, alkaline conditions, respectively (Fig. 15). The total dissolved gold activity in the Au-S-O₂-H₂O system, $a_{\text{Au}} = a_{\text{AuS}_2\text{O}_3^-} + a_{\text{Au}(\text{S}_2\text{O}_3)_2^{3-}} + a_{\text{AuHS}^0} + a_{\text{Au}(\text{HS})_2^-} + a_{\text{AuS}^-} + a_{\text{Au}_2(\text{HS})_2\text{S}^{2-}}$ (Webster, 1986).

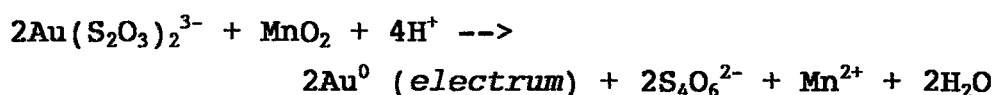
The thiosulphate anion is produced by the oxidation of pyrite in a mildly acid to mildly alkaline solution having a low to moderate carbonate activity (Granger and Warren, 1969, Stoffregan, 1986 and Butt, 1987):



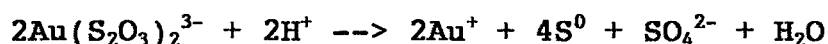
The oxidation of pyrite in gold lodes containing abundant gangue carbonate and under alkaline, mildly oxidising conditions in order to produce the thiosulphate ligand is given by (Webster and Mann, 1984 and Butt, 1987):

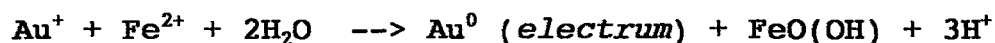


Both gold and silver-thiosulphate complexes become unstable with reduction, acidification or dilution of the solvent (Webster, 1986). Gold precipitation by oxidation and acidification is given by the equation (Webster and Mann, 1984):



Gold precipitation under reducing conditions and acidification is achieved through a two step reaction (Butt, 1987):

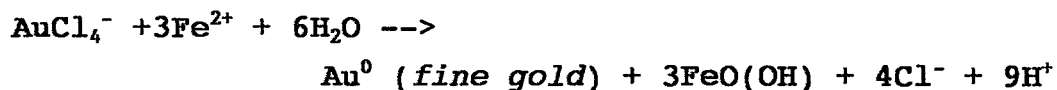




The chloride complex is important for the transport of gold required for the absorption by plants and for the redistribution of gold in the aridified, lateritic profiles of Western Australia (Baker, 1978, Mann, 1984, Butt, 1989 and Mann and Webster, 1990). The source of chlorine appears to be derived from plants and from rainfall, in the Western Australian environment. Bromide and iodide form stronger complexes with gold than chloride but are rarely in sufficient natural concentrations to be of importance as a supergene mobiliser of the metal (Lakin et al., 1974). The formation of the auric chloride complex requires acid, oxidising and high Cl^- activity conditions (Krauskopf, 1951 and Mann, 1984):



The chloride complex provides for the chemical refinement of electrum that takes place in the secondary environment (Fig. 16). The solubility of silver and the stability of the silver chloride complex is considerably greater than that of gold. On mobilisation of the electrum by complexation with chlorine, gold is readily precipitated while silver is lost from the system by incorporation into the groundwater as the AgCl^0 and AgCl_2^- complexes. The Au-Ag alloy dissolves more readily than pure gold with reprecipitation of almost pure gold from solution (Mann, *op.cit.* Webster and Mann, 1984 and Butt, 1987). Gold precipitation may be a function of reducing conditions, an increase in pH and/or dilution of the saturated solution:



Colin and Vieillard (1991) have constructed a solubility diagram that illustrates the competition between chloride and fulvic acid as complexing agents in lateritic equatorial forest conditions. The chloride species has a relatively

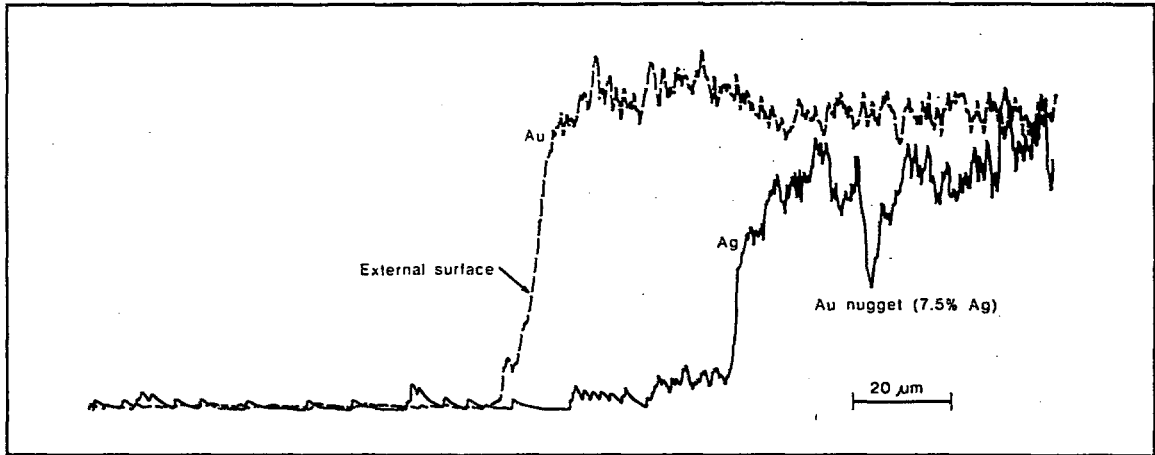


Figure 16
Electron microprobe scan across the exposed outer edge of an electrum nugget in contact with iron oxide. This depletion in silver is after residual refinement (after Mann, 1984)

high solvent capacity at very low pH while the fulvic acid ligand becomes the dominant solvent in moderately acid to neutral solutions (Fig. 17).

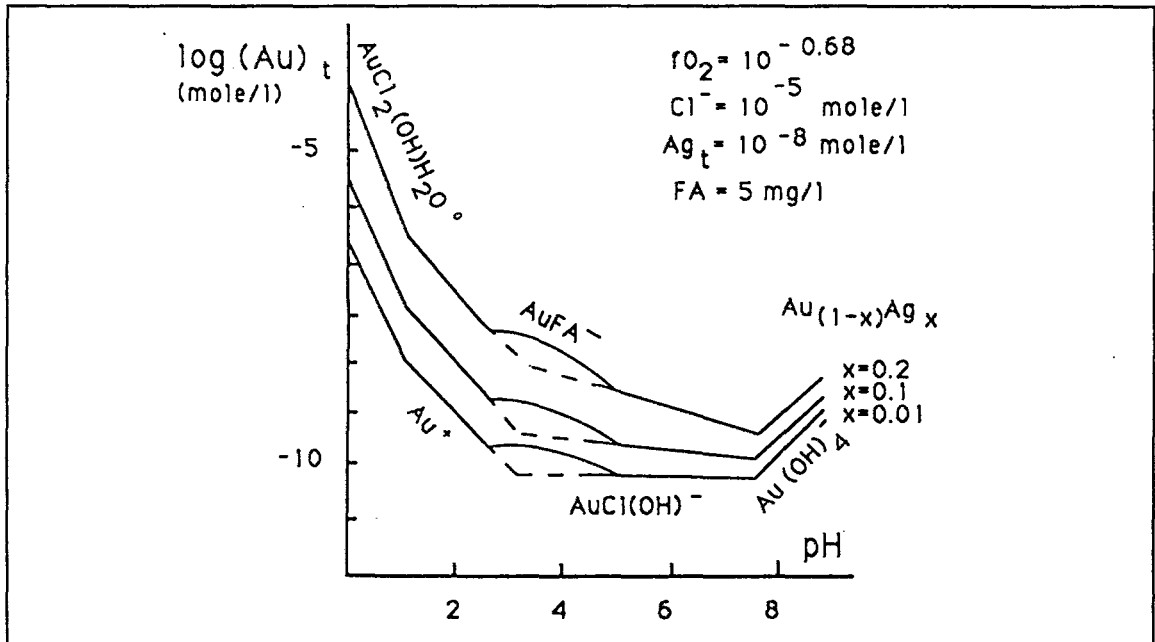


Figure 17
Log Au solubility vs pH showing stability of Au for varying electrum composition and competition between chloride vs fulvic acid (FA) (after Colin and Vieillard, 1991).

3. Gold morphology

The morphology of primary and secondary gold particles is studied in order to find clues to the dissolution and precipitation history of secondary gold grains. The etching of primary grains may give an indication of the efficiency of the supergene environment. Repeated episodes of supergene mobilisation may be evident in the shapes of precipitated secondary gold and redissolution features. The mobilisation of electrum by both the chloride complex and organic complexes contribute to the high fineness of secondary gold. Superior fineness of secondary gold may provide a qualitative measure of the extent to chemical reworking of secondary gold (Wilson, 1984 and Mann, 1984).

Supergene gold has been found in the following forms (Wilson, *op.cit.* and Freyssinet *et al.*, 1989a):

- i) octahedra up to 0.5 mm in size set on felted surfaces of Mn oxide and in puggy clays
- ii) filamentous and arborescent forms in decomposed rock
- iii) dendritic or paint gold on cracks in weathered rock, clay and laterite
- iv) gold impregnations of fossil wood and animals
- v) nuggets of mamilliary form
- vi) microglobule precipitates in etched cavities within primary grains.

In some cases the octahedra are "flattened" to produce a pseudo-trigonal shape. In laterites, secondary gold is often found to be precipitated in zoned limonitic and/or bauxitic nodules or pisoliths. An example from Golden Grove in Western Australia, displayed thin sheets of supergene gold interlayered with concretionary iron oxides (Wilson 1984). Extremely fine grained gold that perhaps reaches the size of colloids, has been used to explain "invisible" particles associated with laterite. Samples with concentrations of up to ± 60 ppm Au (and no Ag) have managed to hide their grains, even under the scrutiny of the electron microscope. The gold in such occurrences is probably absorbed on to the Fe/Al

oxyhydroxides (Wilson, *op.cit.*). Gold nuggets are best developed near the base of the pisolithic portion of the laterite profile, or within nodular ironstone soils that may be developed immediately below recently-stripped laterite. Some of the gold appears to have accreted within the laterite to form tiny botryoidal blebs that resemble the "grotesque" shapes of the large nuggets (Wilson, *op.cit.*).

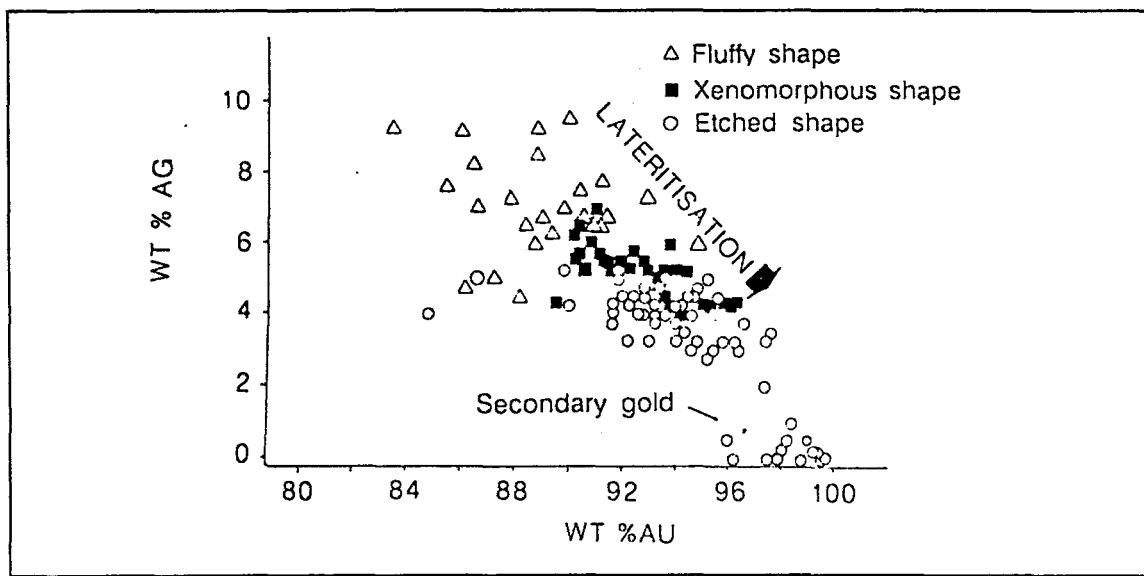


Figure 18

The changes in fineness and grain shape of residual primary gold with increased weathering, southern Mali (after, Freyssinet et al., 1989a).

From a study conducted in southern Mali, the average particle size of primary gold decreases upward through the lateritic profile from 600 μm in the saprolite, to 320 μm in the mottled zone and 240 μm in laterite (Freyssinet et al., 1989a). The primary gold grains become etched and chemically rounded, toward the top of the profile and also exhibit greater dispersion from the source quartz vein. In this case, the dispersion appears to be a function of both eluvial accumulation and secondary chemical redistribution. A "correspondence factor analysis" conducted on the grain shapes of chemically corroded primary grains indicate that the saprolite and mottled zone contain grains with fluffy to xenomorphous shapes and jagged to irregular outlines. The

grain shapes of corroded primary gold can be related to the refinement process as a function of lateritisation (Fig. 18). A decrease in gold grain size upward through the profile was also recorded at Dondo Mobi, Gabon (Colin and Vieillard, 1991).

IV. THE GOLD LODGE/DEPOSIT

A. Introduction

The reactants in the oxidising zone of a "closed", primary gold lode system are the alteration mineral assemblage, electrum of variable fineness, sulphides, gangue minerals and oxygenated, meteoric water. The sulphides as stringers and/or disseminations, are the first minerals to corrode in acidic solutions that characterise the upper portion of the weathered profile. They are replaced by goethite pseudomorphs and boxworks, with excess metals and oxidised sulphur proceeding into solution as metallic ions and a number of thiosulphate/ sulphate species, respectively. If gangue minerals include carbonate(s), they too, will dissolve readily at relatively low pH and buffer downward percolating meteoric waters to the extent that they may become slightly alkaline. The thiosulphate ligand may complex with electrum and transport the gold and silver to the position of laterite development or a lowered water table (Section III/B/2). Quartz is usually unaffected by weathering below the laterite. An open system may include solutions containing organic acids and chloride anions that will effect pH and solvent capacity of the weathering solutions. Alteration minerals ought to weather to respective clay minerals and with further leaching, contribute to the Fe/Al oxyhydroxide budget of the laterite.

B. Archean gold deposits

Archean shear zone controlled gold lodes can be both

epithermal and mesothermal related. The lodes generally consist of quartz veins with a relatively minor component of albite, carbonate (usually ferroan dolomite) tourmaline, sericite and chlorite. Opaque minerals rarely constitute more than 5% of a vein. Pyrite is the most abundant sulphide, with pyrrhotite and arsenopyrite common. The altered greenschist wall rock is characterised by an inner mineral assemblage of carbonate, sericite, pyrite and quartz. This progresses outward into a chlorite-calcite paragenesis. In some cases, quartz veining may be a minor component of the ore bodies that are largely made up of stringers of sulphide and associated silicification. Iron formations may be replaced locally by disseminated sulphides (Roberts, 1988). The Archean greenstone package consists of metamorphosed ultramafic to mafic lavas, metapsammites, metapelites, iron formations, felsic volcanic rocks and volumetrically minor but economically significant, felsic porphyries. There are a number of postulated sources to the mineralising fluids that include; metamorphic dewatering of the greenstone package, juvenile waters derived from granulitisation at the base of the crust, degassing of the upper mantle, magmatic hydrothermal fluids and recirculated seawater (Roberts, *op.cit.*).

C. Palaeoplacers

The quartzitic nature of these deposits, as in the case of the Witwatersrand situation, may not lend itself to lateritic weathering. However, should potential placers occur as relatively thin interbeds within rocks containing aluminosilicate and ferromagnesian minerals, they may well be covered by a lateritic mantle. The palaeoplacers of the Pongola Sequence, the Witwatersrand Sequence, the Jacobina/Moeda environment in Brazil and the Tarkwaian in Ghana are late Archean to mid-Proterozoic in age. They are products of a braided stream environment developed on alluvial fans within an intracratonic rift system (Minter,

1991).

D. Turbidite-hosted gold deposits

Turbidite-hosted gold deposits are recognised as being most prolific in the Phanerozoic (Nesbitt, 1991) although they have been identified throughout the geological record (Leeming, 1985 and Boyle, 1986). Metagreywackes associated with the Archean metasedimentary packages have been interpreted as turbidites. The style of mineralisation and alteration within greywacke sequences of the Proterozoic and Palaeozoic are similar to that of Archean gold lodes, suggesting genetic similarities (Nesbitt, 1991). Host rock lithology is the apparent control on variations in alteration style of these mesothermal deposits. Hydrothermal alteration of arenaceous wackes is generally minimal, with minor disseminated sulphides, sericite and carbonate. A pervasive but cryptic silicification is present, in some cases. In feldspathic to pelitic units, alteration may be more pronounced with extensive albitisation occurring in certain instances. In intermediate to mafic and ultramafic rocks, alteration is much more intense and pervasive with the dominant style of alteration being carbonatisation. Chlorite, pyrite, sericite, graphite and talc are common alteration minerals. Fuchsite is common in altered ultramafic units (Nesbitt, *op.cit.*) Leeming (1985) envisages that these turbiditic sequences are developed in a back-arc basin environment marginal to a magmatic arc generated by subduction. Sediments being shed from the magmatic arc may have provided the source of a protore that was mobilised by metamorphogenic fluids, channelled and focused by orogenesis/accretion and penetrative shears/faults, respectively. Some of the middle to late Proterozoic sediment-hosted deposits like Telfer in Western Australia, appear to be related to either the relatively passive margins of or rifting within intracratonic basins. The volcanic rocks in the stratigraphic footwall to the Fortnum gold

deposit, Western Australia, appear to be products of rifting (Hill and Cranney, 1990 and Hynes and Gee, 1986).

E. Epithermal gold deposits

The alteration associated with felsic volcanic related epithermal deposits allows a two-fold classification into a acid-sulphate and adularia-sericite type. The mineralogy of the above types and the similar silicic volcanics associated, suggest that their mineralising fluids are similar in composition. The styles of alteration indicate that the evolutionary paths of the mineralising fluids are different, consequently producing epithermal solutions of differing pH, respectively. These deposits tend to be spatially associated with calderas that are developed at convergent plate boundaries, above subduction zones. The acid-sulphate type and the adularia-sericite type are related to shallow and deep hydrothermal systems, respectively (Heald *et al.*, 1987). The copper association of the acid-sulphate type, suggests a genetic relationship with their porphyritic rhyodacite host rocks. The source of the mineralising fluids to the adularia-sericite type appears to be related to deep seated granitoid intrusion(s). The characteristic mineralogy of the different types is given in Table III.

Carlin-type deposits are associated with carbonaceous silty dolomites and limestones, calcareous siltstones and claystones. Gold mineralisation is disseminated in the host rock as micron size grains. Alteration includes silicification (jasperoid), decalcification, argillisation and carbonisation. The location of major deposits of this kind are in the western U.S.A. In general, the deposits are associated with accreted terrains and occur within allochthonous thrust sheets, mid-Palaeozoic in age, that overlie the Precambrian basement (Bagby and Berger, 1985). The age of mineralisation ranges from early Cretaceous to mid-Tertiary that pre-dates marginally, the advent of

TABLE III
Mineralogical characteristics of the Acid-sulphate- and Adularia-sericite-type deposits (after Heald *et al.*, 1987).

Acid-sulfate type	Adularia-sericite type
<i>Enargite + pyrite ± covellite</i>	No enargite
<i>Extensive hypogene alunite</i>	Sericitic alteration dominant
<i>Major hypogene kaolinite</i>	Sometimes kaolinite ¹
No adularia	Adularia
No selenides	Often selenides
Mn minerals rare	Mn gangue present
Chlorite rare	Often chlorite
Sometimes bismuthinite	No bismuthinite

Italicized words denote key distinguishing characteristics
¹ Could be supergene in some districts

plutonism and associated molybdenum/copper deposits. The regional spatial association of the Carlin-type and copper/molybdenum porphyry deposits (Bagby and Berger, *op.cit.*, p.178 and Westra and Keith, 1981, p. 857) suggests that the hydrothermal gold-bearing fluids were driven by genetically similar plutonism (Veselinovic, 1992). The thrust faults, related structures and allochthonous permeable/chemically reactive sediment packages have channelled and focused hydrothermal fluids, respectively.

F. Intrusion-related gold deposits

These deposits are associated with the deeper-seated intrusive equivalents of the volcanic-hosted epithermal deposits described above. They are subdivided into (Sillitoe, 1991):

- i) intrusion-hosted stockwork/disseminated deposits of both porphyry and non-porphyry types. The porphyry types have all the geological attributes of Cu/Mo deposits
- ii) skarn and non-skarn replacement deposits in carbonate rocks
- iii) stockwork, disseminated and replacement deposits in non-carbonate rocks

- iv) wallrock-hosted breccia pipes
- v) veins in both intrusions and wallrocks (Fig. 19).

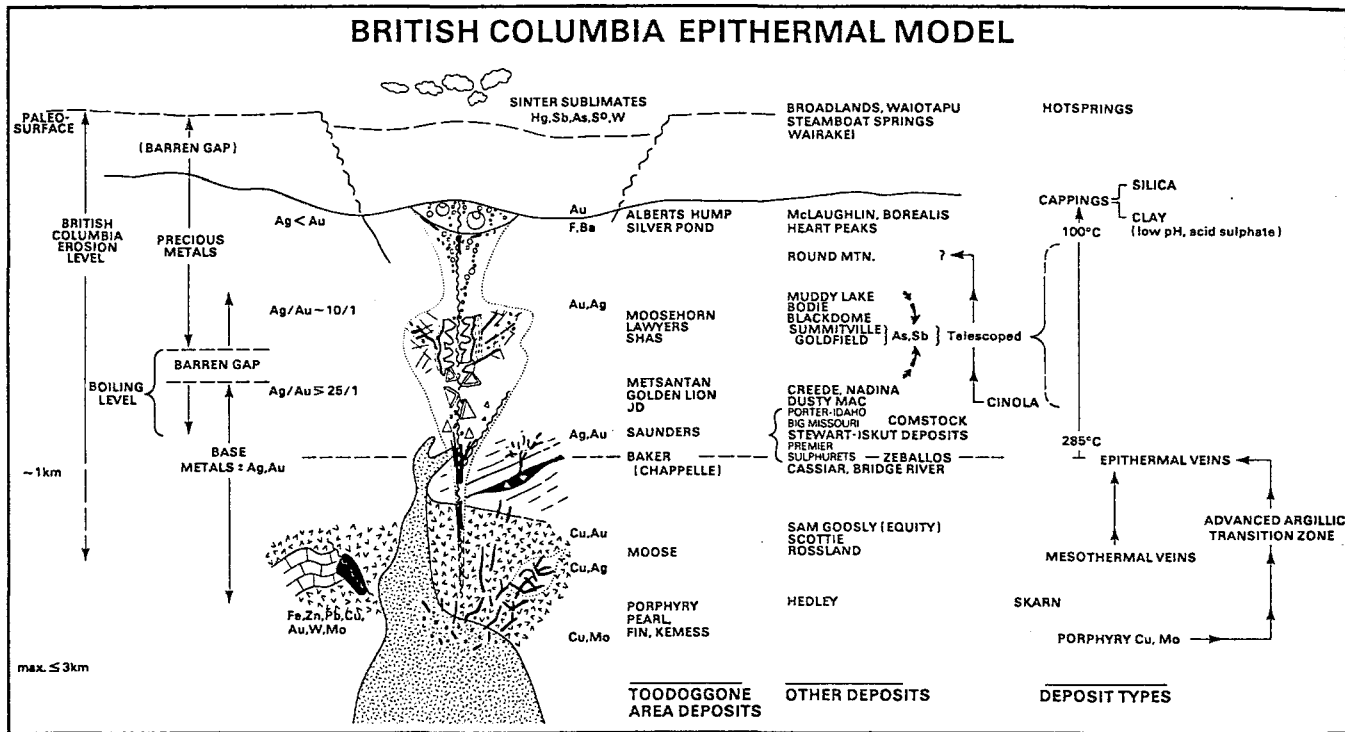


Figure 19
The British Columbia epithermal and associated porphyry Cu/Mo intrusion model (after Panteleyev, 1988).

At least 85% of the intrusion-related deposits reviewed by Sillitoe (*op.cit.*) are generated at Phanerozoic convergent plate margins above zones of active subduction.

V. CASE STUDIES

A. Introduction

1. Climate and geomorphology

The geomorphology of the landscape is influenced as the regolith is developed in response to the chemical system established by the prevailing climatic regime. The climate controls the extent of interaction between the regolith, hydrosphere, atmosphere and the biosphere. The variation in climate produces changes in the relationship between the daylight surface and the water table, producing four different elementary landscape types (Fortescue, 1975 and Polynov, 1937) (Fig. 20).

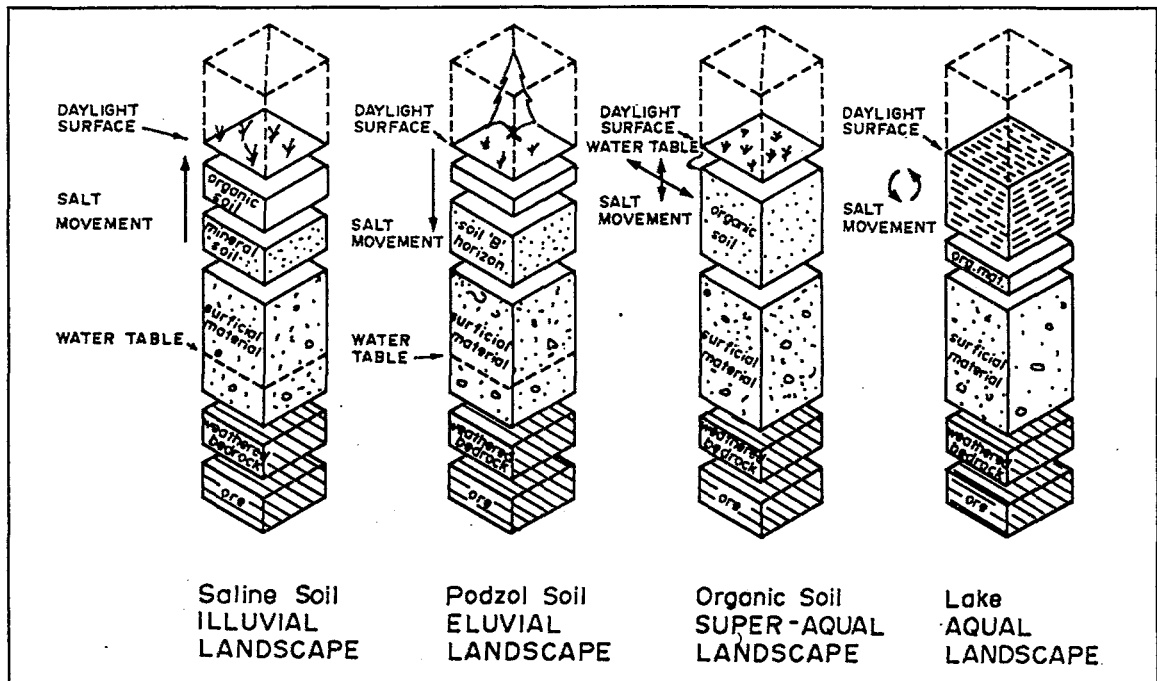


Figure 20

Diagrammatic prisms representing four elementary landscape types (after Fortescue, 1975).

In equatorial areas, denudation processes are restricted to the upper most layer of the soil cover on gentle slopes. In mountainous terrane, erosion processes remain inhibited and

are in the form of subsurface earth flows and slips (Büdel, 1973). In temperate regions, there is a clear difference between oceanic and continental climates. The former are more humid and the latter, drier with greater temperature variations that allow mechanical decomposition to become relatively, as important as chemical decomposition in the weathering process (De Martonne, 1973). For palaeo-landform analysis, a distinction between "weak" and "strong" climatic processes is required in order to assess the duration these processes take to modify the landscape (Büdel, 1973).

Table IV
Effects on the lateritic regolith with tectonic and climatic changes (after Butt and Zeegers, 1989).

A. *Tectonic activity*

Uplift:

- lowering of the water-table;
- irreversible dehydration and hardening of ferruginous and siliceous horizons;
- increased leaching of upper horizons under more oxidizing conditions;
- increased erosion.

Downwarping:

- waterlogging of lower parts of the landscape and imposition of reducing conditions;
- decrease in erosion, increased sedimentation in valleys.

B. *Climatic change*

To a more humid climate:

- increased leaching and deeper soil development;
- decreased erosion (due to thicker vegetation);

To a less humid climate:

- decreased leaching;
- increased erosion;

To a semi-arid or arid climate:

- decreased leaching;
 - retention and precipitation of silica, alkaline earths and alkalis in silcretes, clays, calcretes, salts;
 - increased erosion
-

Changes in climate and the base level will modify the regolith either by chemical leaching/ accumulation or by truncation/burial, respectively (Table IV). In order to build geochemical exploration models in an attempt to understand geochemical dispersion characteristics, the following factors require consideration (Butt and Zeegers,

1989):

- i) preservation of the pre-existing profile
- ii) intermediate and present climates and related chemical changes to the original profile
- iii) presence and nature of the overburden.

Table V
Classification of lateritic profile models in weathered, tropical terranes (after Butt and Zeegers, 1989).

Present climate: Savannah (seasonally humid) Warm arid Rainforest (humid)			
Modifications to pre-existing profile within each climatic zone:			
Pre-existing profile	Recent leaching	Recent accumulation or neoformation	Overburden
A: mostly preserved	0: none 1: low	0: none Al: Al-silicates or oxides	0: none 1: in situ
B: partly truncated	2: moderate 3: strong	Ca: calcrete Fe: iron oxide Si: silica Sm: smectite	2: transported
C: fully truncated			

Examples: A 0 0 (0): outcropping lateritic cuirasse.
B 0 Ca (2): truncated profile with pedogenic calcrete and transported overburden.

The above criteria are expressed in Table V and illustrated in Fig. 21 as partly eroded, tropical, weathered profiles. The model may help accommodate and avoid confusion associated with apparent contradictions. In the Western Australian case, for example, the onset on aridity accommodated the induration of the laterite which became resistant to degradation. On the other hand, degradation of the ferruginous cuirasse may be hastened by the displacive growth

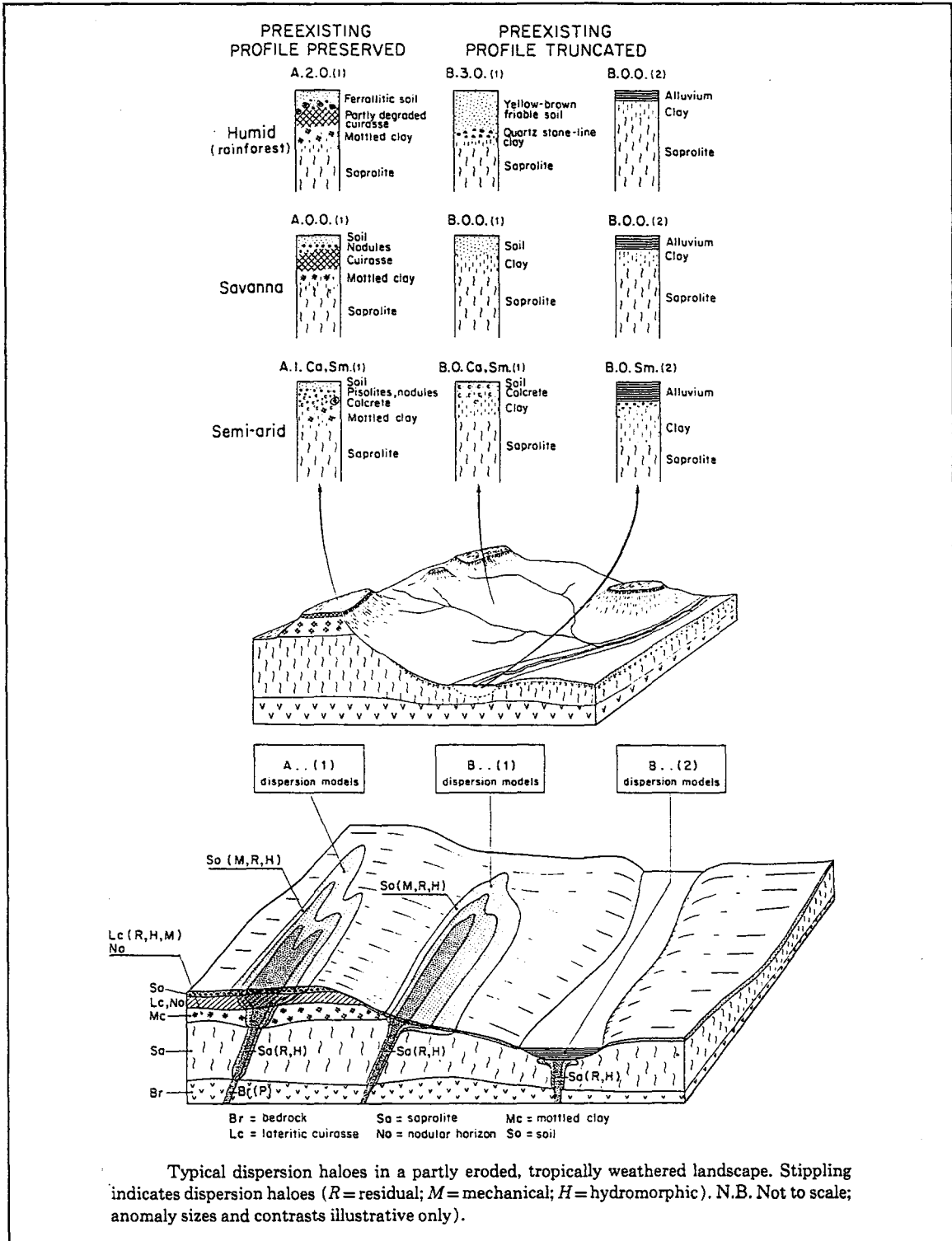


Figure 21
Diagrams illustrating the effects of truncation and climate on the lateritic profile (after Butt and Zeegers, 1989).

of calcite during calcrete formation under arid conditions (Butt and Zeegers, *op.cit.*). In rainforests, chemical

reworking of the cuirasse results in the formation of ferrallitic soils and, in highly leached environments, lateritic stone lines (Lecomte, 1988).

Climates are classified by Horrocks (1981) into:

- i) hot climates with mean annual temperatures of greater than 21°C
- ii) warm temperate climates
- iii) cool temperate climates
- iv) cold climates

Hot climates extend their influence from approximately 30°N to 30°S and are subdivided into three major types:

- i) Equatorial with rain all the year round and sometimes exhibiting a double maximum of rainfall
- ii) Tropical:
 - a) continental, with rain in the hot season only
 - b) marine, with rain in all seasons but with a distinct maximum of rainfall at one period of the year
 - c) monsoonal with rain mainly in the hot season.
- iii) Hot desert.

The world distribution of gold deposits of the Precambrian, Palaeozoic, Mesozoic and Cenozoic are given by Boyle (1979) in Appendix I. Present day equatorial and tropical climates influence (Fig. 22):

- i) Precambrian deposits in West and Central Africa, Madagascar, India, South-east Asia, northern Australia and northern South American countries
- ii) Palaeozoic deposits in South-east Asia and Queensland, Australia
- iii) Mesozoic deposits in South-east Asia
- iv) Cenozoic deposits in South-east Asia, Polynesia, Oceania, northern South America, Central America and the Caribbean.

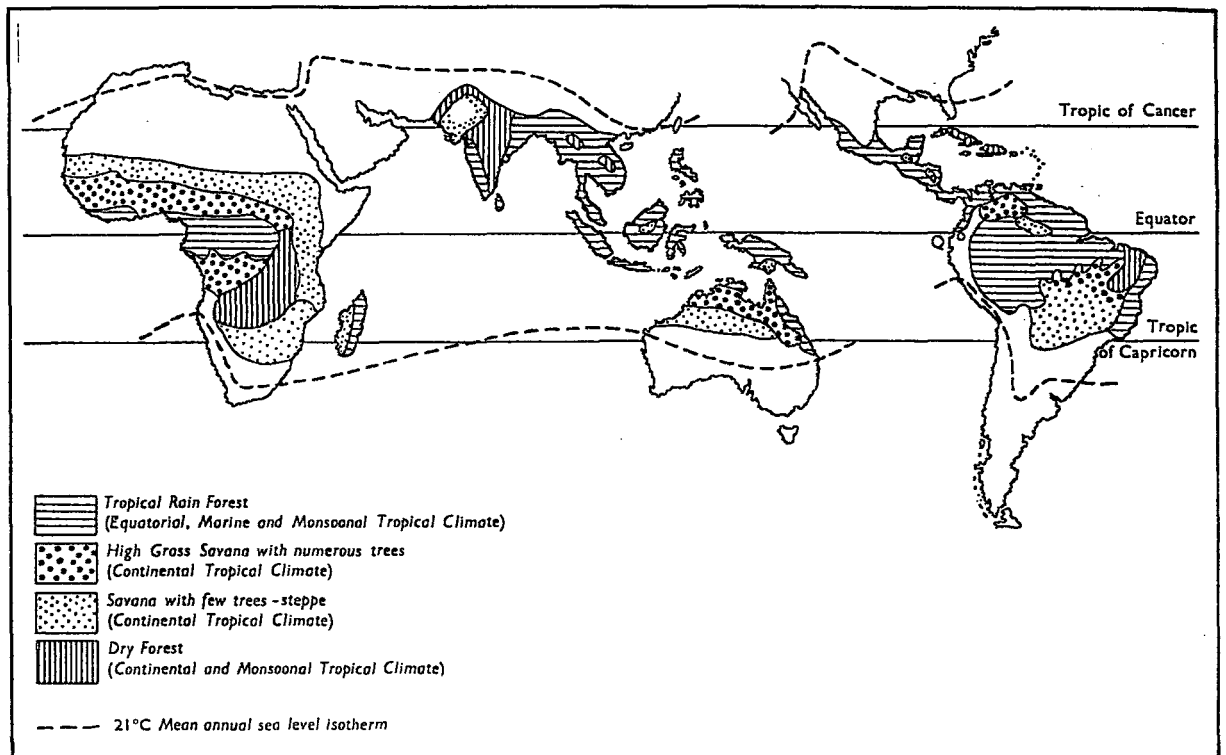


Figure 22
Present equatorial and tropical regions (after Horrocks, 1981).

2. Weathering dispersion mechanisms

The tropical environment, dominated by chemical weathering, redistributes elements by hydromorphic and physical processes through lateral dispersion from the primary source and by vertical degradation (Fig. 23). Hydromorphic dispersion appears to be minimal below the water table with physical and chemical dispersion above and at the water table, respectively, producing a "mushroom-shaped" pattern in section. With the lowering of the water table, appreciable lateral chemical dispersion may occur at the newly established redox front.

The geochemical signature of the mineralised bedrock is qualitatively and quantitatively altered in the different horizons of the lateritic profile. Some ore elements are leached, some remain immobile and in certain instances, may be enriched. Most of the pathfinder elements for gold are

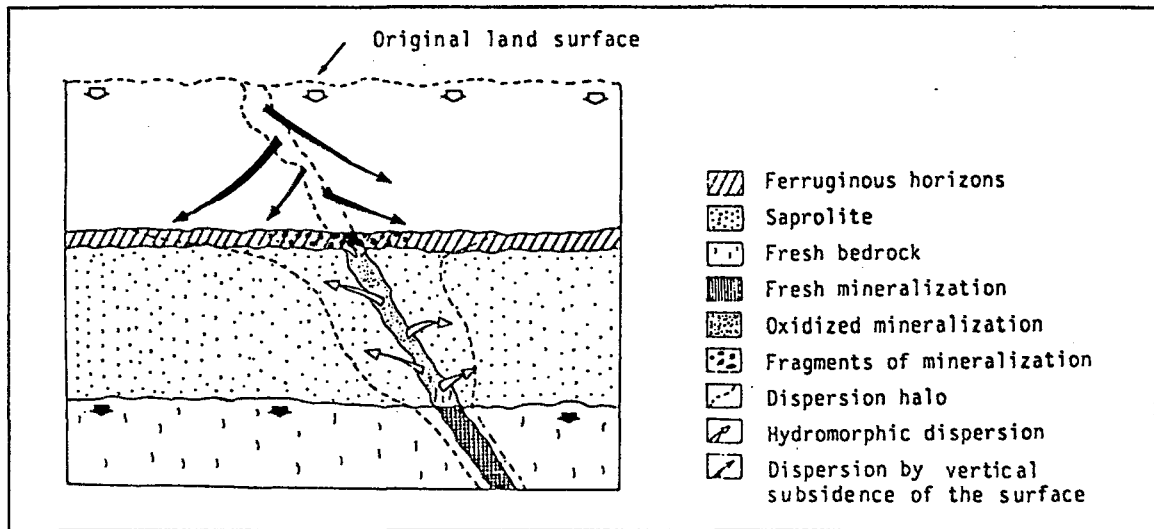


Figure 23

A dispersion model for gold and associated pathfinder elements (after Freyssinet et al., 1989b).

relatively immobile or only partially mobilised during intense weathering (Zeegers and Leduc, 1991) (Fig. 24).

The symmetry of the dispersion "halo" around the weathered ore body is a function of the respective mobilities of the associated pathfinders, geomorphology and degradation rates. The greater the topographical slope, the greater the asymmetry of dispersion. Extreme dispersion, with the help of complexing ligands may produce a transported anomaly at a break in slope. In the case of transported overburden, hydromorphic and biological activity may give rise to anomalies in the transported cover should this activity not be overwhelmed by aggradation (Levinson, 1980 and Butt and Zeegers, 1989).

3. Potential pathfinder elements

With the exception of the palaeoplacers, gold deposits, in general, are associated genetically with compressional regimes. Phanerozoic deposits are associated largely with the overriding plate above a subduction zone, either as a facies of a magmatic arc or as a metamorphogenic, turbiditic facies developed in a back-arc environment. They also

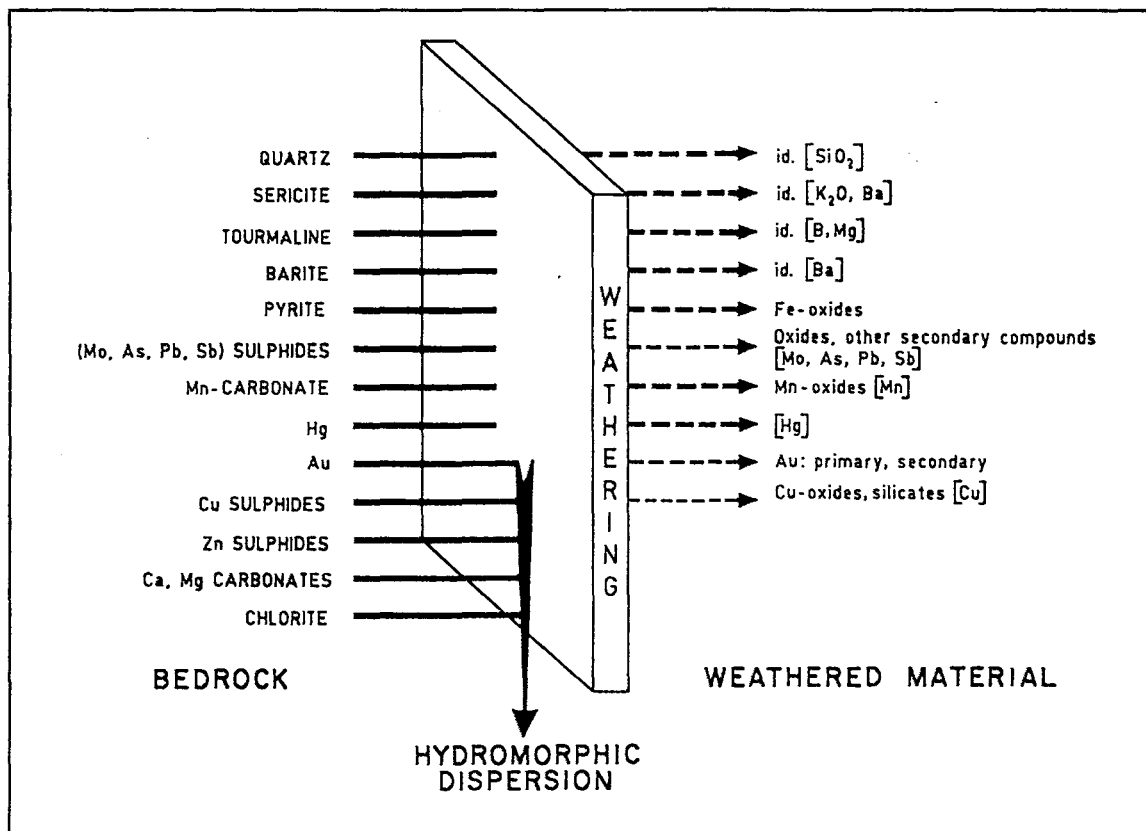


Figure 24

Diagram illustrating the geochemical behaviour of pathfinder minerals and elements during weathering (after Zeegers and Leduc, 1991).

exhibit similarities in styles of alteration and metal geochemistry. The absence of barite and tourmaline appears to separate the various deposits into two groups, respectively:

- i) barite is absent from Archean, Proterozoic, Phanerozoic, intrusion-related, banded iron formation and stratabound epigenetic deposits
- ii) tourmaline is absent from or occurs only in small quantities within epithermal acid-sulphate-type, sericite-adularia-type, Carlin-type and volcanogenic massive sulphide deposits (Table VI).

For the Archean, Rb and Na may be useful pathfinders after alteration of associated felsic intrusions (Roberts, 1988). Mafic rocks with high Fe/(Fe+Mg) ratios appear to be

Table VI

Mean relative abundance of some specific minerals and elements for different types of gold deposits (modified after Zeegers and Leduc, 1991).

	(1)*	(2)	(6)	(7)	(9)	(3)	(4)	(5)	(8)
Silica	+++	++++	+++	++++	+++	+++	+++	+++	0++
Carbonates	++++	0++	0	++++	++++	0	0+	0	0+
Sericite	++++	0++	++++	0+	0++	0+	++++	0+	++++
K-Feldspar	0++	0+	++++	0	0+	0+	++++	0	0+
Chlorite	0++	+++	+	0++	+++	0	+++	0	++++
Tourmaline	0++	0+	0+	0++	0+++	0	0+	0	0+
Barite	0	0	0	0	0	0++	0++	+++	0+++
Pyrite	++++	+++	++++	++++	+	+++	+	+	++++
As	0+++	++++	0+	++++	+	+	+++	+	+++
Pb	0++	0+++	0++	0+	+	+++	++++	+	+++
Zn	0+	0+	0+++	0+	0+	0++	++++	0+	0+++
Cu	0+++	0+	++++	0+	0+	0+++	+	0+	++++
Sb	0+	0+++	0	0+	+++	+++	++++	0++	+
Hg	0+	0+++	0+	0	+++	++++	0+++	++++	0+++
W	0+	0+++	0++	0	+++	0+	0++	0+	0
Mn	0	0	0+	0+	+++	+++	++++	0++	0
Mo	0++	0+	0+++	0+	0++	0	0	0+	+

*Column heading: (1) Archaean and Proterozoic lodes; (2) Phanerozoic lodes; (3) epithermal, acid sulphate; (4) epithermal, sericite-adularia; (5) Carlin, sediment-hosted; (6) intrusion related; (7) BIF; (8) volcanogenic massive sulphides; (9) stratabound epigenetic.

0, none; +, small; ++, medium; +++, high.

particularly prospective (Groves and Foster, 1991) and may ultimately contribute to thicker development of laterite within the regolith. Gold mineralisation is associated with laterally zoned, wallrock alteration haloes related to metasomatic addition of SiO₂, K₂O, CO₂, H₂O and Au. The deposits are characteristically "gold only" with associated As, Ag, W, Sb, Te, B and attendant, variable but commonly low, Cu, Pb, Zn and Mo (Groves and Foster, *op.cit.*).

Uranium associated with the palaeoplacers of the Witwatersrand and some gold deposits of the early Proterozoic, orogenic, Pine Creek Inlier, Northern Territory, Australia, may be a useful pathfinder (Minter, 1991 and Needham and De Ross, 1990). Anomalous values for Sc, La, Y and Ce were recorded at the Fortnum deposit, Western Australia (Hill and Cranney, 1990). Phanerozoic, mesothermal gold lode deposits have a relatively high Au/Ag ratio and as

in the case of the Archean, are "gold-only" deposits. A typical suite of associated elements in anomalous concentrations are Ag, Sb, As, W and Hg ± Bi, Mo, Pb, Zn, Cu and Ba (Nesbitt, 1991). Boyle (1986) includes Cu, Mg, Ca, Zn, Cd, B, Si, Pb, S, Mn and Fe as elements having a high frequency of occurrence with Hg, In, Tl, Se, Te, F, Co and Ni, included as elements of low frequency. A vertical zonation from Au (hotter) to Sb ± W to Hg (cooler hydrothermal environment) is evident. The significant difference between Archean and Phanerozoic deposits is the overall larger accumulation of gold in Archean mesothermal deposits (Boyle, 1979 and Nesbitt, 1991).

For epithermal gold deposits in volcanic terrains, As, Sb and Hg may be useful pathfinders with Pb, Zn and Cu useful for some deposit styles (Henley, 1991). From the mineralogical characteristics of acid-sulphate and adularia-sericite-type deposits listed by Heald *et al.* (1987), Cu, As, Bi and Se, Mn may prove useful pathfinders, respectively (Table III). Other elements associated with these deposits are Te, Tl and U (Silberman and Berger, 1985). A vertical zonation in the Paramount mining district, California, U.S.A. is characterised by (Silberman and Berger, *op.cit.*):

- i) Au, As and Sb at the oxide-sulphide interface
- ii) Ag, Cu, Pb, Co and Ni appears to be related to the total sulphide content
- iii) Hg, Tl, Mn, B, Sr and Ba form halos of varying degrees of definition around the gold mineralised zone.

Mineralised geothermal systems display a zonation similar to the above, with As, Sb, Hg, Au and Tl enriched near the surface and Zn, Pb, Cu, Ag, Se, Te, Bi and Co enriched mainly at depth (Rossiter, 1984).

The characteristic mineral assemblage that accompanies Carlin-type gold mineralisation is pyrite, realgar, orpiment, stibnite, cinnabar and barite. Concentrations of base metals

Table VII
Intrusion-related gold deposits; their ideal metal associations and alteration minerals/products (after Sillitoe, 1991, Tables 6.1 to 6.7, inclusive).

INTRUSION-RELATED DEPOSIT	METAL ASSOCIATION	ALTERATION MINERALS/PRODUCTS
i) porphyry gold and copper-gold	Cu-Au-Mo-W	biotite, K-feldspar, sericite, clay, actinolite, chlorite, anhydrite, magnetite, haematite, tourmaline and epidote.
ii) non-porphyry gold	Au-Ag-As-Cu-Mo-Sb-Te (Pb-Zn-Bi)	sericite, orthoclase, fluorite, kaolinite, albite, dolomite, calcite.
iii) skarn gold	Au-Ag-Cu-As-Zn-Pb (Bi-Te-W-Mo-Sn-Co-Ni)	garnet, clinopyroxene, chlorite, calcite, K-feldspar, epidote, clinozoisite, actinolite, prehnite, phlogopite, biotite, tremolite, wollastonite.
iv) carbonate-replacement gold	Au-As-Sb-Ag-Mn-Tl-Te-Cu-Zn-Pb-Sn (Bi-Hg)	jasperoid, silicification, decalcification, sericite, clays, fluorite, barite, rhodochrosite.
v) non-carbonate-replacement, stockwork and disseminated gold	Au-Ag-Cu-Zn-Pb-As-Sb-W-Te-Bi (Mo)	silicification, sericite, chlorite, alkali feldspar, carbonate, clays, tourmaline, quartz-pyrite, anhydrite, biotite, tremolite, epidote, andalusite, corundum, dumortierite.
vi) breccia-hosted gold	Au-Zn-Cu-Pb-Ag-W-Mo-Mn (As-Bi-Te)	sericite, carbonation, biotite, K-feldspar, decalcification.
vii) vein gold	Au-Cu-Pb-Zn-Ag-Bi-Hg (As-W-Sb-Te-Mo)	sericite, chlorite, carbonates, K-feldspar.

tend to be consistently low with anomalous As, Sb, Hg and W associated, in general. Fluorite is ubiquitous and the occurrence of tungsten and molybdenum deposits appears to be a good exploration guide for these gold deposits (Berger and Bagby, 1991).

Intrusion-related deposits are components of intrusion-

centred base- and precious-metal systems, many of which possess porphyry-type Cu, Mo and/or Au mineralisation as a central focus (Table VII).

The gold in most deposits is free or combined as a telluride or antimonide. In some deposits the gold is intimately associated with arsenopyrite, pyrite or sulphosalts as a lattice or submicroscopic constituent. These ores frequently have to be roasted before cyanidation (Boyle, 1979). The lateritisation process liberates any gold that may be "locked up" by sulphides in the primary environment.

B. Western Australia

1. *Palaeoclimate*

The proximity to the equator is the most important factor that influences climate. With continental drift, the various continents have been exposed to changing climatic elements as they have wandered across the latitudes. From palaeomagnetic data, Smith *et al.* (1973 in Lamb, 1977) have plotted the positions of the continents as they were in the late Cambrian, Carboniferous, Permian and the early Tertiary, respectively (Fig. 25). These data suggest that after the Carboniferous, the Australian continent drifted into a position south of the 30°S line of latitude and out of the potential zone of lateritisation. On the contrary, King (1962, p.576) suggests that the Australian continent began its migration northward after the Permian and by Mesozoic times, the Western Australian subcontinent had moved well within the tropics.

Humid, warm periods from the Cretaceous to the mid-Miocene were responsible for the economically important lateritisation in Western Australia (Butt, 1989). The deep nature of weathering appears to be a function of geomorphological stabilisation, with maintenance of a

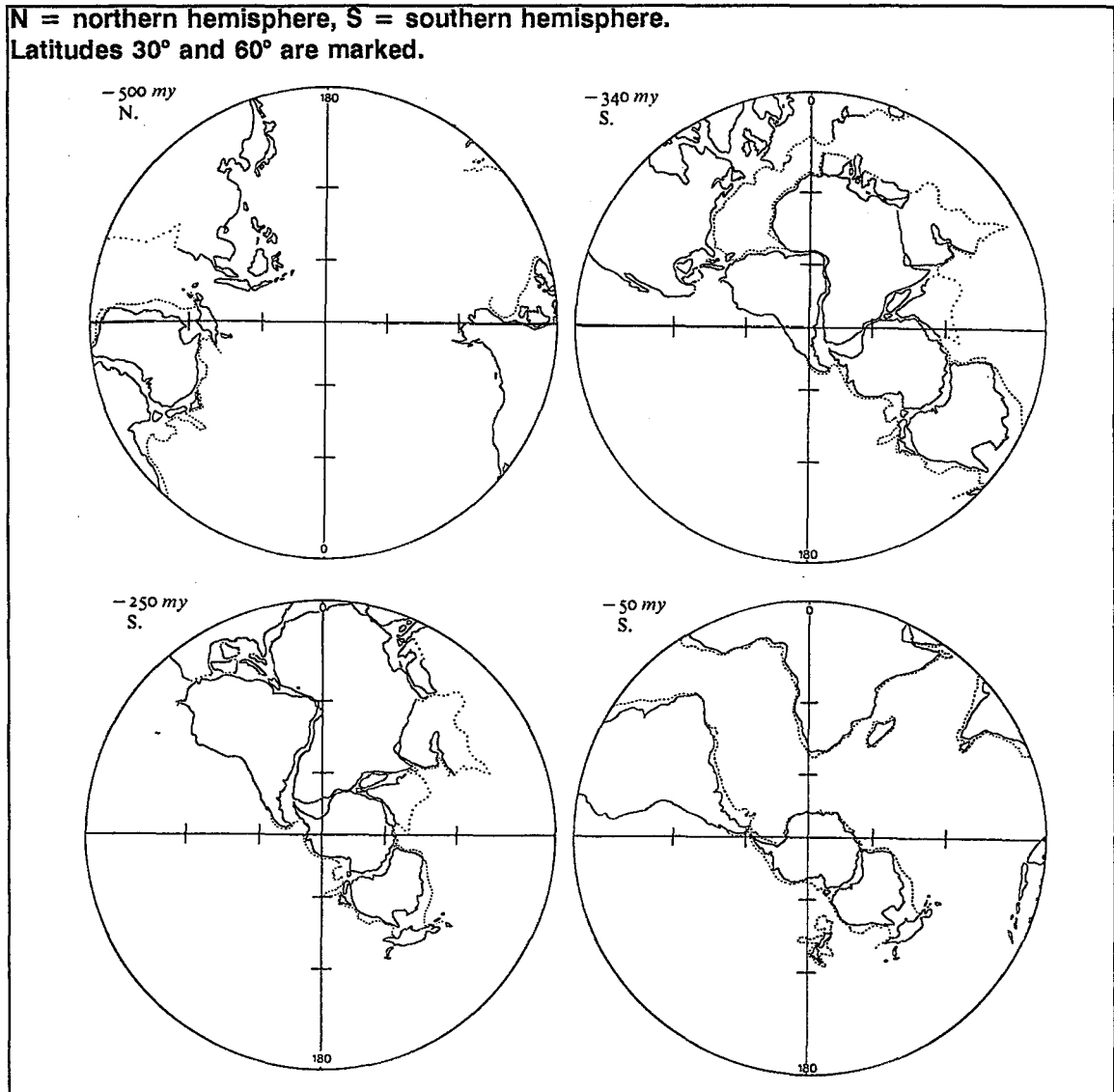


Figure 25

Polar stereographic projections of the drifting continents. The circumference of each map is the equator (after Smith et al., 1973 in Lamb, 1977).

relatively static to slowly subsiding base level, over a long period. Large portions of the Yilgarn Block have been exposed to subaerial weathering since the mid-Proterozoic with intense Cainozoic weathering having continued into the early Pleistocene on some parts of the continent (Fig. 26) (Mabutt, 1980). The termination of lateritic weathering is coincident with the culmination of Pleistocene glaciation after cooling of the Earth's atmosphere was initiated during the early Tertiary (Hilton, 1985).

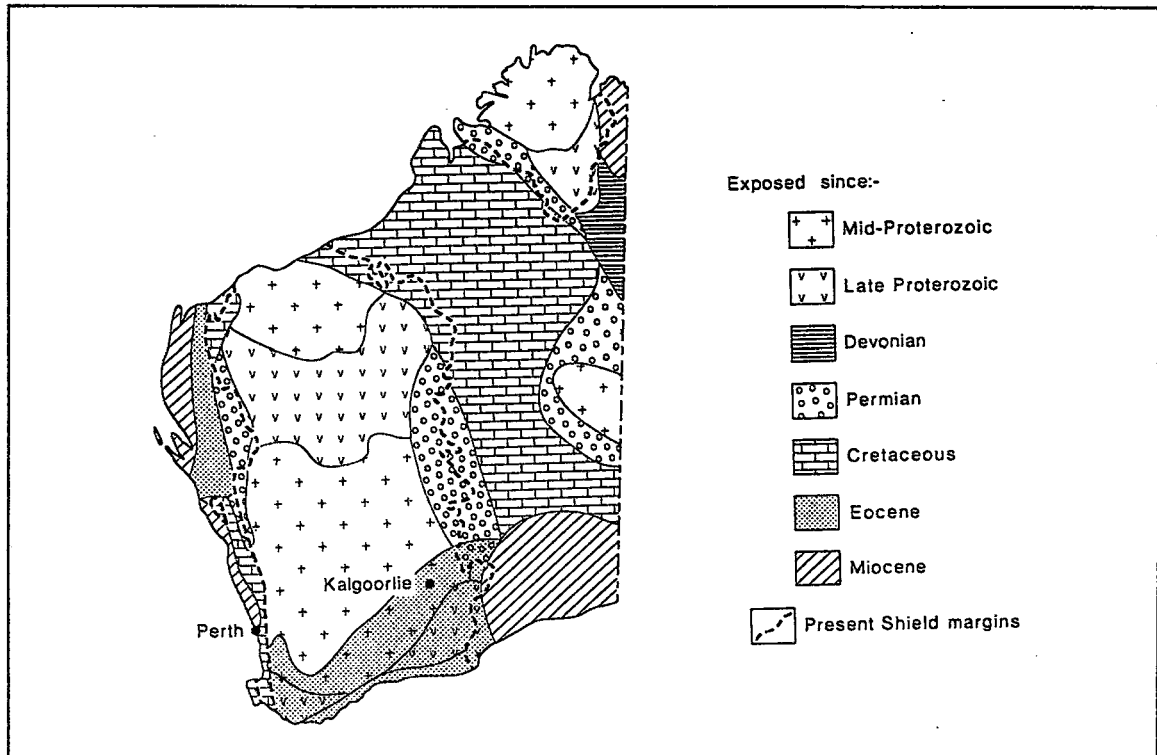


Figure 26
Periods of exposure to subaerial weathering in Western Australia (after Butt, 1989).

The onset of aridity may have been induced either by the establishment of or the Australian continent drifting into the zone of influence of a cool, west coast current. Similar cold currents dramatically effect the present climates of the coastlines of South America and Africa (Fig. 22). This aridity and the "elements" associated with it, are critical factors that have contributed to the formation of secondary ore bodies. South-westerly winds that are part of the system that drives the cool, west coast current, are largely responsible for supplying the hinterland with chloride salts (Hingston and Gailitis, 1976). The aridity allows for the concentration of chloride within the regolith, providing a potentially, unlimited reservoir of chloride for complexation and transport of gold in the supergene environment. Butt (1989) suggests that the onset of aridity was a gradual process that entailed climatic reversals to relatively more humid conditions on a cyclic basis. This may explain the

stabilisation of the receding water table required for the precipitation of supergene "saprolite" gold (Fig. 27). The alpha-numeric codes in Fig. 27 indicate initial supergene mobilisation by organic (2) complexing, followed by thiosulphate (1A/1B) and chloride (3) complexing (Butt, 1987 and 1989).

Regional variations in the palaeoclimate have effected the style of profile development. For example in the south-west of the Yilgarn Block, profiles developed upon granites in the Darling Ranges contain ferruginous bauxites. Inland toward the north-east, the weathering of similar bedrock produces a residual quartz sand horizon that subsequently becomes silcretised (Butt, 1985). Present regional variations in climate still have an influence on the nature of the regolith. The "Menzies Line", an east-west line at approximately 30°S, defines the change in influence of winter and summer rainfall from south to north, respectively (Butt *et al.*, 1977 in Butt, 1989). The respective rainfalls control the respiratory character of plant life and therefore the CO₂ input into the regolith. This directly influences the style of calcrete formation. The winter rainfall climate allows for a longer growing season and greater retention of CO₂ in the regolith for pedogenic calcrete formation. A shorter growing season, associated with the summer rainfall climate, inhibits pedogenic calcrete precipitation but introduces sufficient CO₂ into the system for groundwater calcretes to precipitate (Butt, 1989).

2. *Geomorphology*

The combined effects of arid climatic conditions and epeirogenic uplift have led to the partial stripping of the deeply weathered mantle by headward stream erosion and pedimentation (Butt, 1989). Pedimentation proceeds by scarp retreat following cavernous undercutting of the cuirasse and subsequent removal of debris across the pediment by sheetwash

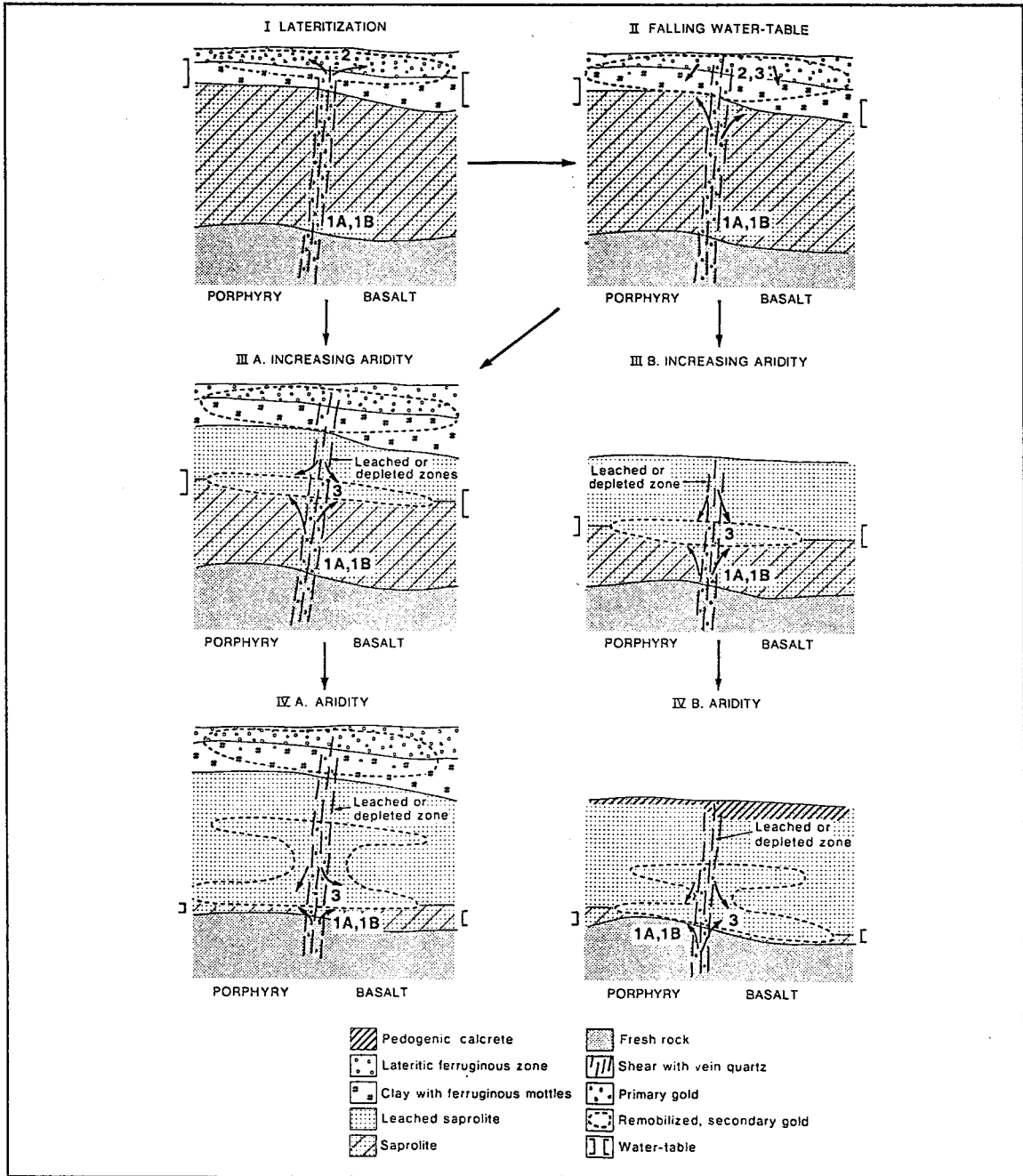


Figure 27

The effects of lateritisation, epeirogenic uplift and subsequent aridification on secondary gold distribution (after Butt, 1987). See text for explanation of alpha-numeric codes.

(Fig. 28). Playa lake evaporites may be reworked by deflation processes and recycled through the upstream environment. The erosion products are deposited commonly in lower parts of the landscape and in many cases, transported overburden overlies completely or partially truncated

profiles. The resultant landscape is complex, with erosional and depositional phases of various ages set in an environment of already ancient weathering. Some of the sediments may be quite old and have been deposited before or during the period of lateritisation (Butt, *op.cit.* and 1987) as in the case of the mineralised "Wash Zone" at the Westonia Mine (Drummond and Beilby, 1990). The overall effect of chemical and physical weathering has been to reduce the relief and to achieve the considerable planation that is evident in the interior of the Yilgarn Block. Extensive colluvial and alluvial plains conceal a marked subsurface topography that need not necessarily be reflected in the pattern of present surface drainage lines (Butt, 1989).

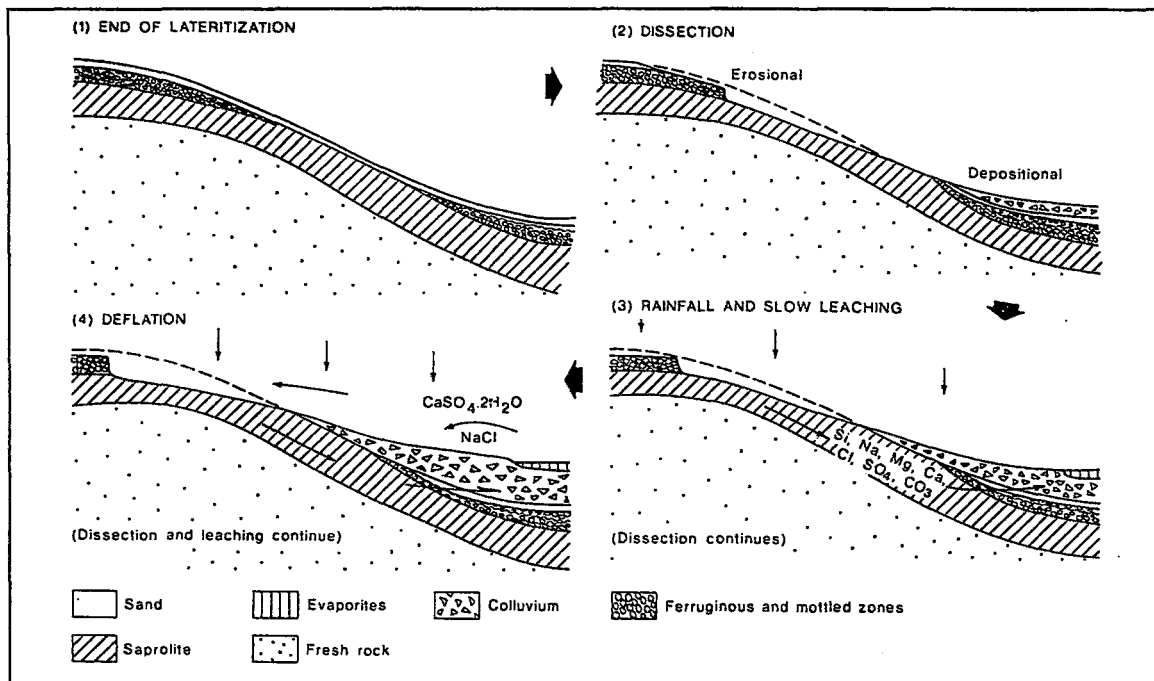


Figure 28

Landscape modifications with the onset of aridity and epeirogenic uplift (Butt, 1981 in Butt, 1987).

3. Case study modelling

The primary gold lodes most effected by economic, lateritic weathering are situated within the Yilgarn Block. The Boddington, Westonia and Gibson Mines are operations that

contain substantial mineable reserves within the regolith. Their location is in the south-western quadrant of the Archean shield and are associated with chloride "precipitation" rates of greater than $10 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{a}^{-1}$ as measured in 1973 (Hingston and Gailitis, 1976) (Fig. 29).

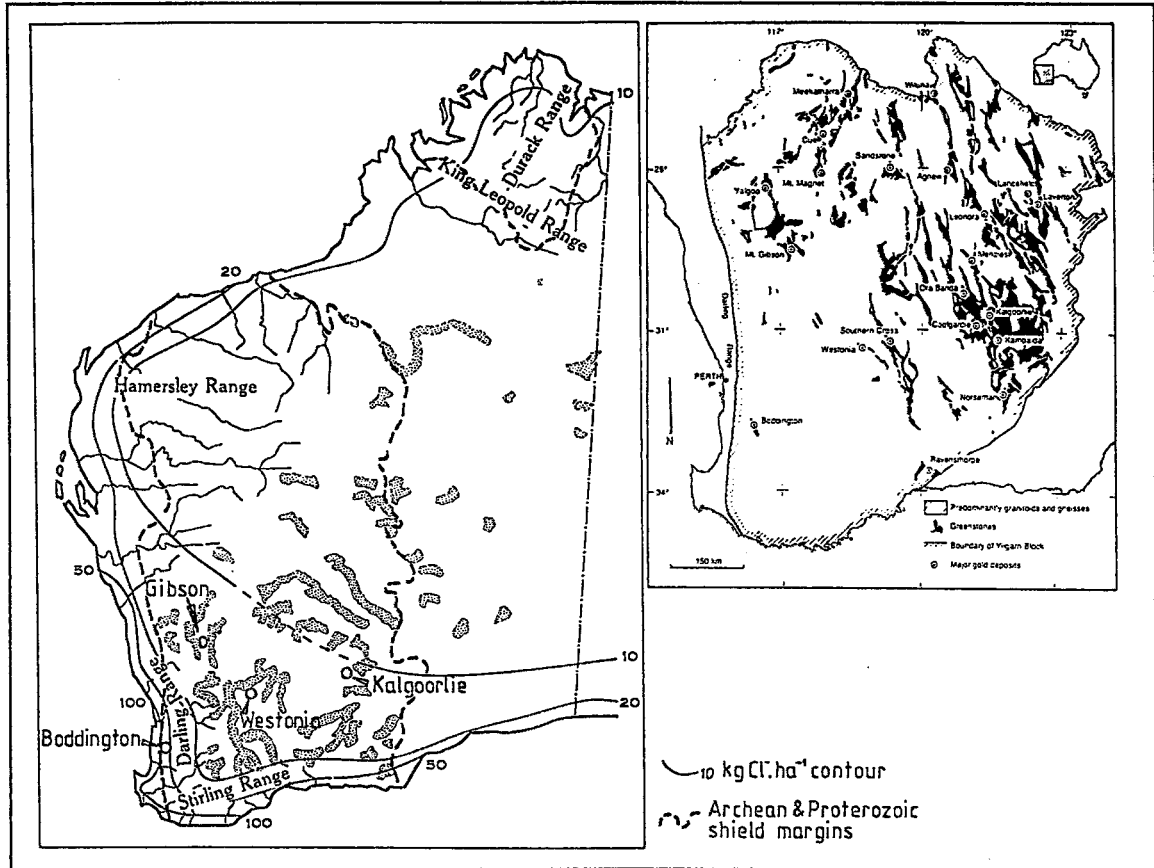


Figure 29

The localities of Boddington, Westonia and Gibson (after Hingston and Gailitis, 1976 and Lawrance, 1988 with adaptations from Butt, 1989).

The Boddington deposit contained reserves and indicated resources of 93,5 t of gold in lateritic ore at June 1987, ranking it the third biggest gold occurrence in Australia (Woodall, 1990, p.64). The supergene ore bodies of Westonia and Gibson are relatively small and in the case of the Gibson lateritic deposit, ± 8,5 t of gold were delineated as mineable reserve (Gee, 1990). From crude calculations using estimates of thicknesses, S.G. and the maps of the lateritic ore bodies in Drummond and Beilby (1990, p.294 and p.295),

supergene ores at Westonia contained a minimum of 2 t of mineable gold.

The Boddington deposit is associated with the Saddleback Greenstone belt within the Western Gneiss Terrain (Groves and Ho, 1990, p.540). This secondary ore body occurs within a bauxitic laterite that overlies the contact between calc-alkalic and mafic volcanics at the edge of an interfluvium (Fig. 30). Mineralisation as pyritic casts in felsic metavolcanic rocks was recognised in the area by members of the Geological Survey in 1977. Anomalous Cu values (0,17%) in these rocks prompted follow-up geochemical sampling which defined an anomalous zone of As, Cu, Pb, Mo, Zn and Au (up to 1,6 ppm). Reynolds Australia Mines Pty. Ltd. discovered the mineralised laterite 500 m east of the anomalies defined by the Geological Survey (Davy and El-Ansary, 1986). Symons *et al.* (1990) estimated a mineable reserve of 60 Mt grading at 1,6 g/t gold within the laterite.

Boddington occurs on the eastern margin of the Darling Ranges on a dissected plateau with gentle to moderate undulating relief and broad swampy drainage-ways and basins (Baker, 1975). Hills at the either end of the greenstone belt stand out as prominent monadknocks (Mt. Wells, 547 m and Mt. Saddleback, 575 m, Fig. 30). The elevation of the plateau is in the range of 300 to 350 m.a.m.s.l. with valleys up to 100 m deep. Bedrock is exposed on the flanks of the ridges, on the upper slopes of river valleys and on tors which penetrate the overlying lateritic cover (Davy and El-Ansary, 1986). The annual rainfall of approximately 800 mm precipitates during the winter months. Lateritisation is of uncertain age and perhaps has a multi-cyclic origin that spanned the Tertiary period. The Mount Saddleback commercial bauxite deposits are located south of the Hotham River (Fig. 30) and overlying greenstone bedrock (Owen and Hargreaves, 1975, p.988). The laterite is draped on hilly topography with the thickest development of ore on the slopes. The regolith is

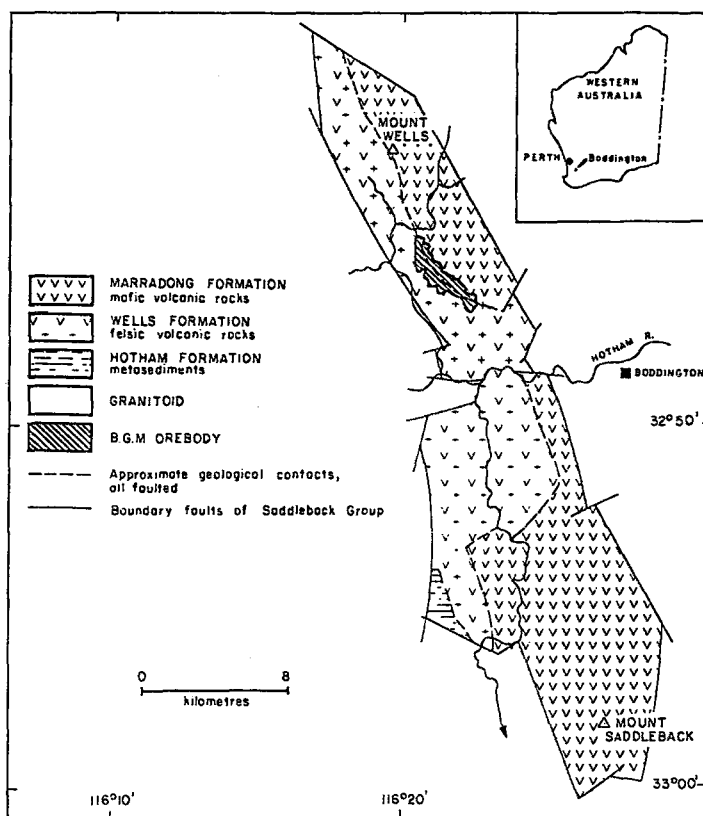


Figure 30

The regional geology of the Saddleback greenstone belt and geomorphological situation of the Boddington Gold Mine (BGM) (after Symons et al., 1990).

zoned with a base of saprolite and clay overlain by bauxite or the "B zone" (Davy and El-Ansary, 1986) with an average thickness of ± 6 m. The profile is capped by a ± 2 m thick iron-rich cuirasse containing approximately 50% Fe_2O_3 . The contacts between these zones are transitional. These lateritic bauxites can vary greatly in chemical and mineralogical properties, partly as a function of bedrock composition. In general, granitic and doleritic bauxite ores are iron oxyhydroxide poor and rich, respectively (Anand et al., 1991, p.237). The mineralogy of the bauxitic laterite profile at Boddington is similar to that of the ores described by Anand et al. (*op.cit.*) (Fig. 31).

Bedrock and surface samples taken along two traverses were analysed for Ag, As, Au, Co, Cu, Mo, Ni, Pb, Sn, W and Zn.

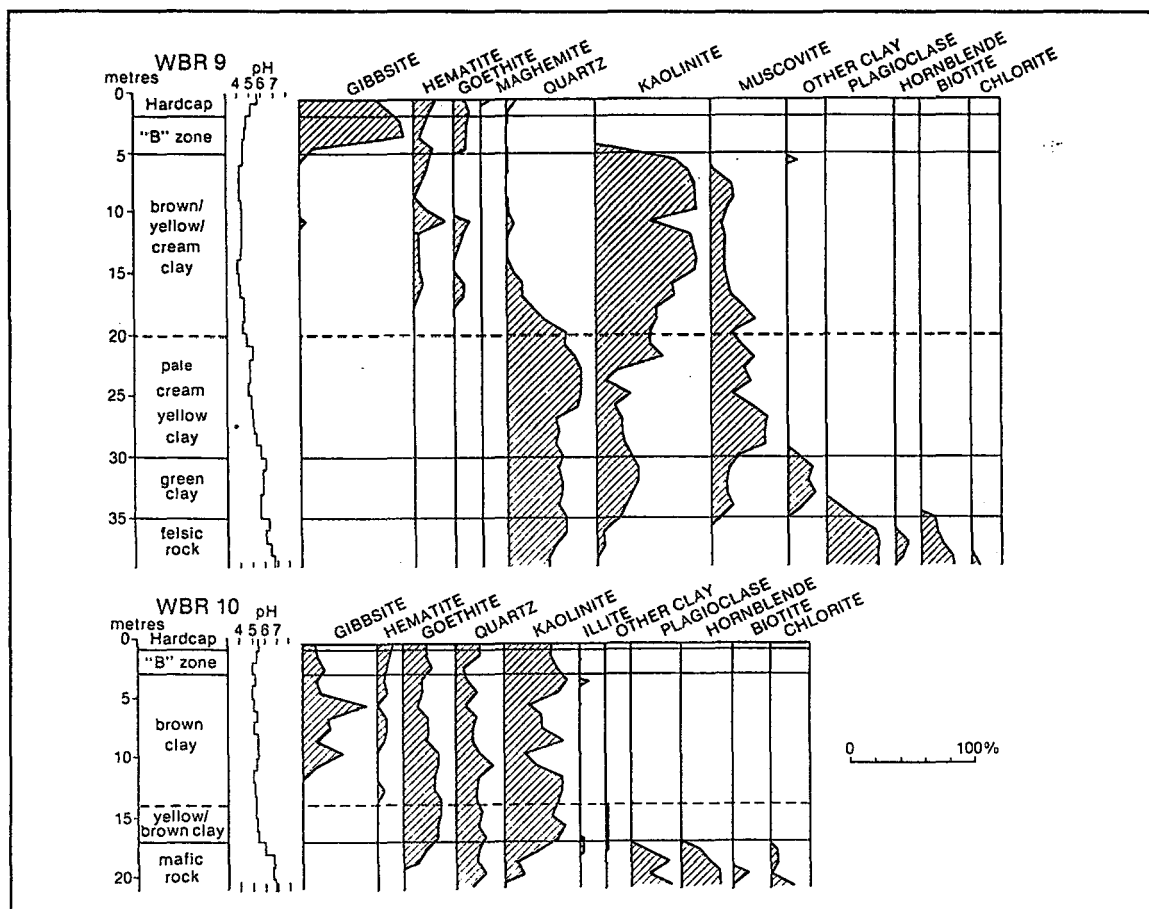


Figure 31

The distribution of dominant minerals through the lateritic profile overlying felsic and mafic rocks at Boddington, respectively (after Davy and El-Ansary, 1986).

Surface samples were taken from laterite fragments, pisolites or hardcap except where the soil exceeded a thickness of 0,7 m. In that case, the soil was sampled (Davy and El-Ansary, 1986). The felsic and intermediate volcanics contain the highest values of Cu, Au, Mo and W. Gold and W are patchily developed while there is little distinction between the various lithologies for Pb, Ni or Zn. Gold shows inconsistent surface enrichment, sometimes enriched two-fold and in other cases, it is not reflected in the regolith at all. Copper is displaced from the source bedrock by no more than 50 m and appears to be associated with Au. Molybdenum values differ little between hardcap and bedrock but there is a suggestion of lateral, downhill migration. Cobalt, As, Ag and Sn do not appear to be correlatable with bedrock.

Cuttings from four drill holes drilled through the profile and into bedrock were submitted for AA analyses of Ag, Co, Cu, Li, Mn, Pb, Zn, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, K₂O. Arsenic, Bi, Ce, La, Mo, Nb, Rb, Sb, Sn, Sr, Ta, Te, Th, TiO₂, V, W, Y and Zr were analysed by the XRF method. The data were interpreted and various behavioural patterns from total leaching to residual accumulation were discerned for the various elements (Davy and El-Ansary, 1986) (Table VIII). Components with the most consistent behaviour are:

- i) Sr, CaO and Na₂O, leached at the bedrock/saprolite interface
- ii) Ba, Rb, K₂O and MgO, leached close to the interface of the clay zone with overlying laterite
- iii) Th and Al₂O₃, concentrated upwards
- iv) Mn and Co, enriched at the base of the clay zone.

Using an enrichment factor (E):

$$= [\text{conc}(w)/\text{conc}(\text{rock})] * [\text{S.G.}(w)/\text{S.G.}(\text{rock})]$$

{conc(w) ≡ mean concentration of an element within one of the weathered zones}

Monti (1987, p.360) demonstrated that the following elements have E greater than 1 within the ferruginous zone:

- i) Mo, Sb, W, Hg, Bi, Br, Au and Sc as mobile constituents
- ii) Zr, Ti, Th, V, Nb, Cr, Al, Ga, As, Sn and Pb as immobile constituents.

The highest and most continuous gold values in the laterite profile occur over mineralised bedrock. The primary mineralisation is Au-Cu-Mo-W within silica-rich veins and stockworks that transect intermediate to felsic lavas and intrusive host rocks (Monti, 1987 and Symons *et al.*, 1990). This primary environment is considered to be equivalent to a gold-rich porphyry system by Symons *et al.* (*op.cit.*) and Roth *et al.* (1991). Gold is found in the laterite profile at considerable distances (up to 500 m) away from mineralised

Table VIII

Summary of the behaviour of the chemical components within the drill hole profiles at Boddington (after Davy and El-Ansary, 1986).

Profile	WBR 9	WBR 10	WBR 12	WBR 14
Group A: Generally leached				
i) Components leached at or near bedrock-saprolite boundary	Sr, Ta, Zn CaO, Na ₂ O	Co, La, Mn, Rb Sr, W, Y, Zn, CaO, K ₂ O, MgO, Na ₂ O		Sr, CaO Na ₂ O
ii) Components leached within clay zone, no surface enrichment	Ba, (Cu), Li, (Ni), Rb, (Ta), K ₂ O, MgO	Ba	Ce, Cu, La, Li, Ni, Rb, Sr, Ta, Y, Zn, CaO, K ₂ O, MgO, Na ₂ O	Ba, Cu, La, Ni, Rb, Zn, K ₂ O, MgO
iii) Components leached at top of profile; concentrated near bedrock-saprolite boundary	Ce, Co, La, Mn, Y	Cu	Co, Mn	Co, Mn
Group B: Mobilised and reprecipitated				
i) Components reduced in, or absent from, central clay zone, but with values in hardcap or upper clay zone similar to those in bedrock	Cu*, Ni*	Ba*, Ce, Cr*, Li, Ni, TiO ₂ , (Y), (Fe ₂ O ₃)	Cr, Mo	Au, Ca, (Cu), Li, Sn, Y
ii) As B(i), but enriched in hardcap - 'B' zone relative to bedrock	Au, Cr, Mo, Fe ₂ O ₃	(Mo)	Au, Sn, V, Fe ₂ O ₃	Mo, (TiO ₂), (V), W, Fe ₂ O ₃
Group C: Components generally residually concentrated	Nb, Sn, Th, V, Zr, Al ₂ O ₃ , TiO ₂	(Au), (Cr), (Sn), (Th), Zr	Th, Zr, Al ₂ O ₃ , TiO ₂	(As), Cr, Mo, (Sb), Th, V, Zr, Al ₂ O ₃ , TiO ₂
Group D: Components enriched in clay		V	Ba, (Pb)	
Group E: Components with no consistent behaviour	(Au), W	(TiO ₂)	Nb, (Sn), W	(Pb)

*Upper clay zone only. Parentheses indicate either low levels of component or a secondary, less certain behaviour pattern.

bedrock. The gold is concentrated at three levels within the laterite (Fig. 32):

- i) Level 1 - the lower part of the bauxitic laterite
- ii) Level 2 - the middle of the oxidised kaolinitic clay
- iii) Level 3 - the bottom of the saprolite

The model for formation of the supergene ore horizons is as described by Butt (1987 and 1989) and Lawrance (1988 and 1990) (Fig. 27). Level 1 is largely a product of initial lateritisation during Oligocene to Miocene times, Level 2 and

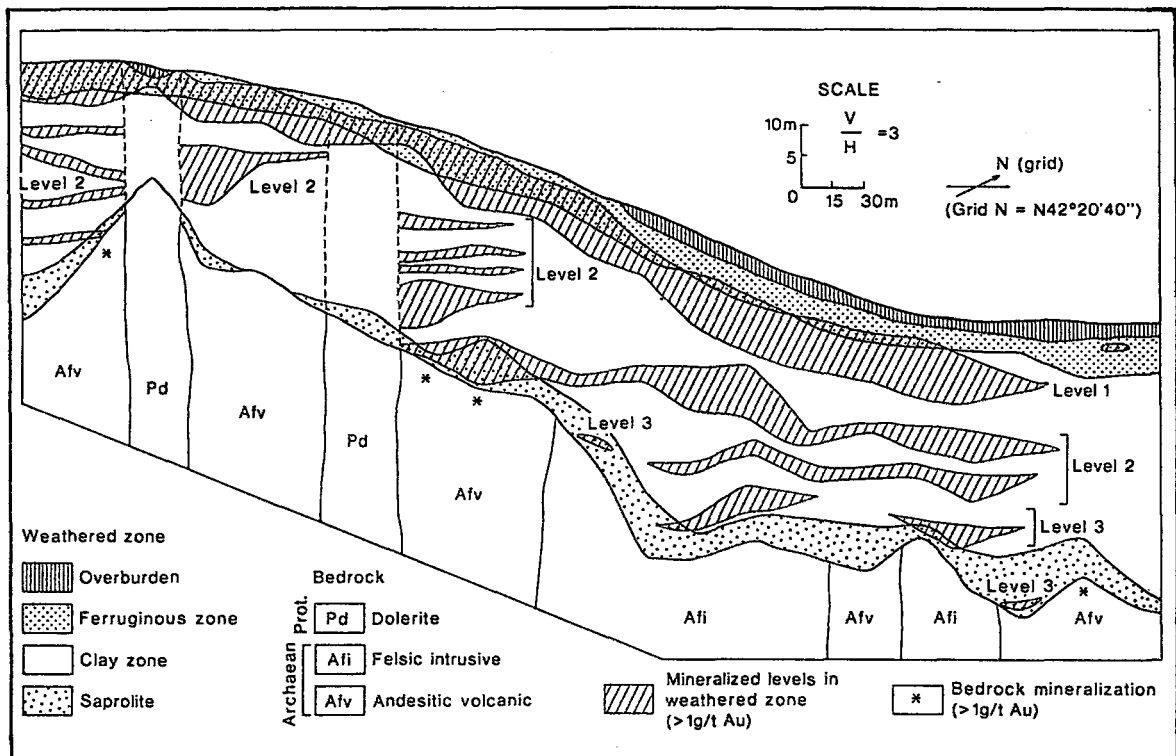


Figure 32
Cross-section of the lateritic profile at Boddington, derived from drill data. Note the various levels of ore horizon development (after Monti, 1987).

Level 3 are products of cyclic lowering and stabilisation of the water table with increasing aridity (Davy and El-Ansary, 1986 and Monti, 1987). Visible gold that has been isolated, is fine grained ($< 2\mu\text{m}$), of high fineness and associated with haematite-goethite-rich hardcap material (Monti, *op.cit.*).

The Westonia gold deposits are located within the Southern Cross Province of the Yilgarn Block (Fig. 29) (Groves and Ho, 1990, p.540). The Westonia/Edna May Mine has primary gold mineralisation associated with quartz veins developed in an intrusive tonalitic gneiss that is in sheared contact with amphibolites and meta-ultramafic rocks. Heavy minerals associated with the quartz veins are pyrrhotite, pyrite, marcasite, chalcopyrite, ilmenite, wolframite, galena, molybdenite, sphalerite, rutile, digenite, gold, uraninite, hessite (Ag_2Te), bismuth and scheelite. Wall rock alteration includes carbonatisation, sulphidisation and Na-K

metasomatism (Webster and Mann, 1984 and Drummond and Beilby, 1990).

Overlying mineralised bedrock is a complex regolith that consists of a basal Tertiary or Mesozoic grit to boulder bed channel named the "Wash Zone" (WZ) and an upper "Pisolite Zone" (PZ) (Fig. 33). Within the WZ, gold occurs in the clasts and not between them. This palaeovalley/channel fill is lateritised with secondary gold associated with ferruginous mottles and pisoliths developed in the clasts and matrix. Gold grades are generally proportional to the quartz clast content of the rudaceous sediment. The uppermost zone of 1 to 3 m is moderately pisolithic and overlies ferruginous mottling that is developed irregularly. The basal portions of the "wash" are heavily mottled in close proximity to the foot- and hangingwall contacts of the gneiss. Gold in the WZ has been significantly mobilised during weathering (Drummond and Beilby, *op.cit.*).

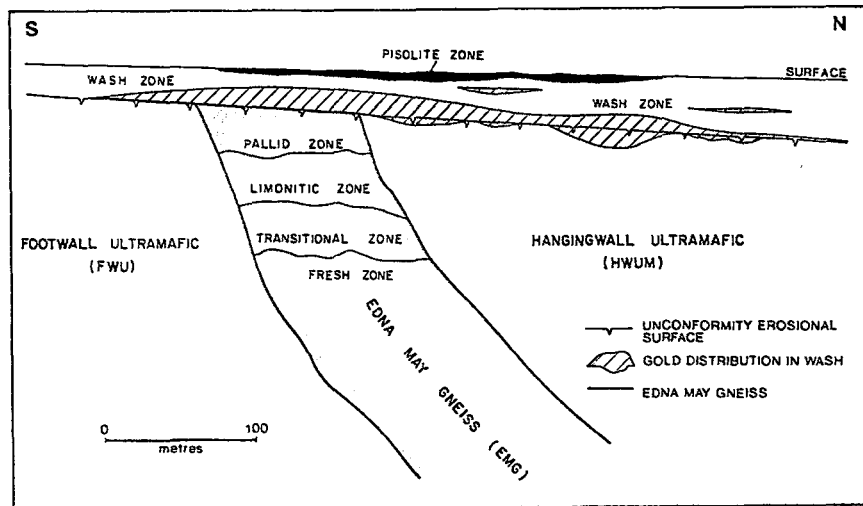


Figure 33

Schematic geological section of the Westonia Mine area, viewed west (after Drummond and Beilby, 1990).

The PZ mineralisation is hosted by the uppermost 1 to 5 m of the lateritic profile and can be divided into three ore types:

- i) footwall ultramafic type containing high Al/low Fe.

Gold content is in the 0,1 to 0,5 g/t range. High values are confined to close proximity with the gneiss contact.

- ii) *wash-gneiss type* containing high silica/low Fe. Gold content is in the 0,5 to 1,2 g/t range.
- iii) *hangingwall ultramafic type* with high Fe content and gold values in the range 1,5 to 6,0 g/t.

Most of the PZ has formed *in situ* with minor evidence of transported material at the top of the zone. The highest grades tend to be associated with the thickest mineralised intervals (Drummond and Beilby, *op.cit.*).

The north trending palaeoslope of the WZ appears to control the distribution of the PZ and is mimicked apparently by the subhorizontal slope of the present day surface (Fig. 33). The lateritic profile comprises 60 m of partially weathered rock overlain by 40 m of alumina-rich clays, quartz and iron oxide in a distinctively zoned sequence. Secondary gold of high fineness occurs as microscopic octahedra and aggregate growths along fractures and in cavities within cemented iron nodules in the vicinity of disrupted quartz veins. Three "levels" of secondary gold precipitation/enrichment occur (Webster and Mann, 1984):

- i) at the water table in ultramafic laterite profiles
- ii) in the "mottled" zone associated with iron nodules
- iii) at the surface by residual enrichment in pisolites.

Manganese amorphous dioxide and high concentrations of Co and Ni are associated with the water table. Copper is concentrated below the present water table. Lead and Mo are fixed below the acidic, near-surface environment as anglesite and cerussite, in the case of lead. Arsenic and chromite are residually enriched in the upper laterite, probably as scorodite ($\text{FeAsO}_4 \cdot 2\text{H}_2\text{O}$) and primary chromite, respectively. Tungsten shows no evidence of secondary remobilisation. Silver is readily removed from the oxidised zone as soluble

chloride complexes (Webster and Mann, *op.cit.* and Webster, 1985). The observations of Webster and Mann (1984) appear to have been made prior to the recognition and delineation of the WZ and PZ described by Drummond and Beilby (1990).

The supergene gold from the Boddington and Edna May laterites have different physical and chemical characteristics (Monti, 1987) possibly as a function of different genetic processes (Table IX). The nuggets found at Edna May are probably related to primary vein quartz gold as products of residual dissolution and reprecipitation. Similarly, high fineness gold found in a development area at the Edna May Mine, occurs adjacent to a brecciated discordant quartz vein (Webster and Mann, 1984). The sampling of Monti (1987) was reliant on pre-production drilling and two costeans that may have been located at positions relatively distant to weathered primary lodes, i.e., hydromorphous gold was sampled.

Table IX

A comparison between the characteristics of secondary gold in the Boddington and Edna May lateritic deposits (after Monti, 1987).

Feature	Boddington	Edna May
Presence of nuggets	No	Yes
Purity of Au (wt%)	99	99.9
Au enrichment in pisoliths	No	Yes
Au enrichment in lateritic zone	Yes	Yes
Au enrichment in the clay zone	Yes	No
Au enrichment at current water table	Yes	Yes
Rainfall (mm)	810	< 300
Vegetation	abundant	sparse

The Gibson lateritic gold deposit is situated within the Murchison Province of the Yilgarn Block and contained an initial mineable reserve of 5,3 Mt at 1,6 g/t Au (Fig. 29) (Groves and Ho, 1990, p.540 and Gee, 1990). The area around the Gibson deposits is almost flat with an extensive regolith

related to both the preservation and degradation of the Tertiary lateritic profile. The laterite forms an undulating blanket that reflects the Mesozoic and Tertiary palaeodrainage systems in a subdued fashion. Present day drainages largely follow these palaeodrainages. Much of the laterite blanket is either dissected or covered by the products of Quaternary erosion. Remnants of the laterite are either preserved beneath sand plains on the major interfluves or are represented by duricrusts in breakaways, small plateaus, aprons around monadnocks and lateritic slopes that pass down into old valleys (Gee, 1990). The maximum relief is about 20 m in the vicinity of mineralisation.

Laterite remnants at Gibson, 2 to 5 m thick, cover a regional drainage divide and extend down a secondary drainage depression that is a distal tributary to a palaeodrainage system in the north-east (Fig. 34). The gold-bearing laterite occurs adjacent to the contact between poorly exposed granitoids and greenstones (mafic and felsic schists) that host several old workings (Gee, 1990). The full lateritic profile is developed and can reach thicknesses of up to 100 m (Davy *et al.*, 1988). As found at Boddington and Westonia, gold enrichment of the lateritic profile occurs at three "levels", viz., within the laterite, the saprolite and at the transition from saprock to bedrock. There is a general increase in gold enrichment down the profile with oxidised bedrock containing approximately three times the amount of gold concentrated in the laterite. Zones of ferruginisation are coincident with the positions of gold enrichment (Gee, 1990 and Davy *et al.*, 1988). The trace element geochemistry of the Gibson lateritic profile after weathered bedrock is similar in behaviour to that of Boddington (Table VIII). For gold lode trace elements (Davy *et al.*, *op.cit.*):

- i) gold is usually accompanied by base metals and in some places, by Ag in the clay zones
- ii) gold occurs separately from Ag, Bi, Sb and in some

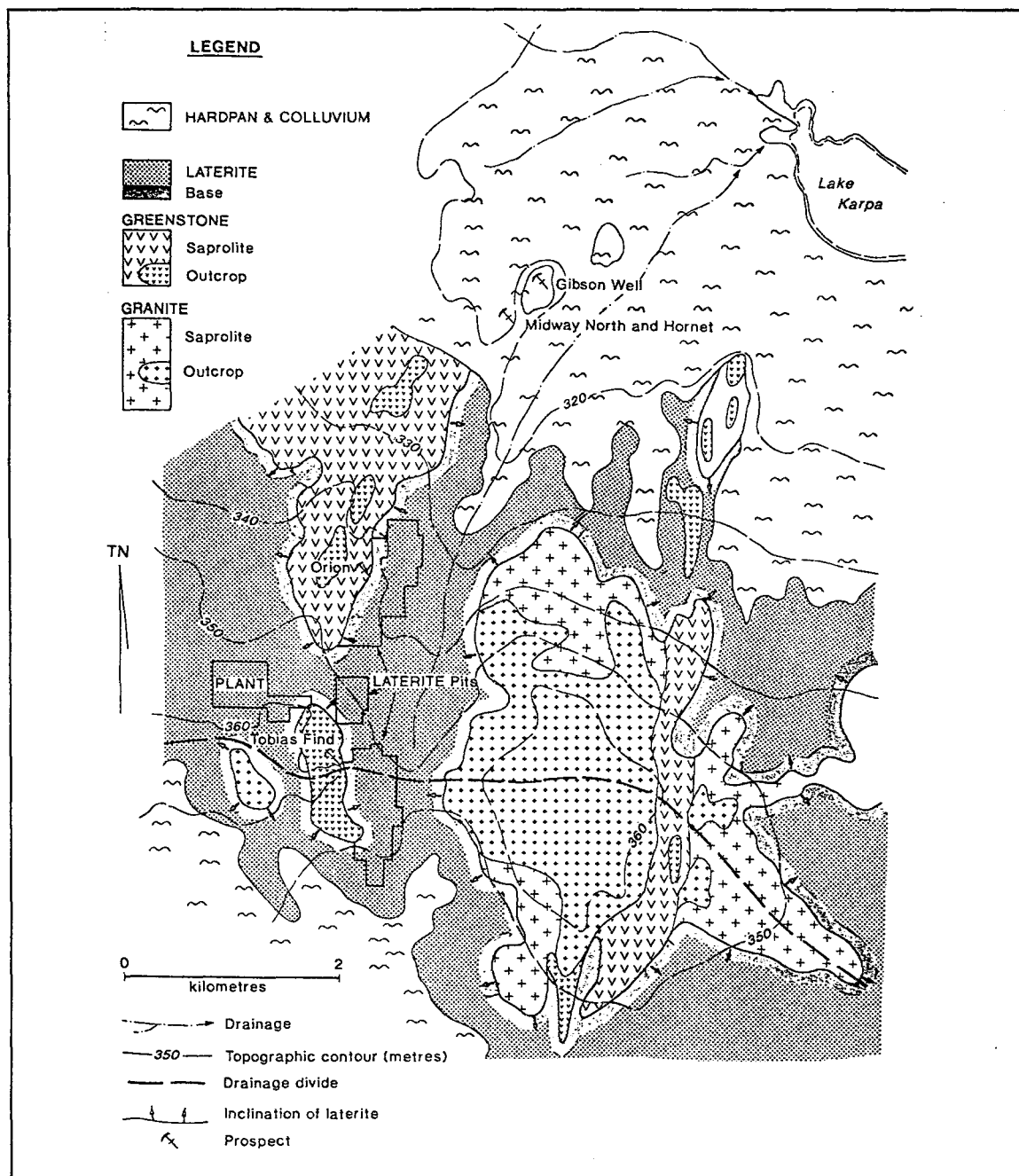


Figure 34
Geology of the area around the Gibson gold deposits. Auriferous laterite straddles the drainage divide and parallels a secondary drainage channel (after Gee, 1990).

cases, may be significantly associated with As in the laterite. Correlations with Cu, Pb and Zn are low.

Peculiarities in the geochemistry of the laterite perhaps can be explained by contamination from transported material that

has been incorporated into and chemically modified as a variable, cryptic constituent (Davy *et al.*, *op.cit.*).

C. South-western Pacific rim

1. Introduction

The Pacific rim is characterised by magmatic island arcs that are products of plate tectonic processes related to both the disintegration of Gondwanaland and present plate margin activity. In general, laterite profiles are poorly developed in this region due largely to the rugged terrane. Secondary redistribution of gold and associated metals has been described at the Upper Ridges mine and in the Vunda area in Papua New Guinea (PNG) and Fiji, respectively (Webster and Mann, 1984, Webster, 1985 and Lawrence, 1984). The deposits in PNG and Fiji are intrusion-related porphyry Au, Cu-Au and epithermal deposits. In the PNG case, volcanism has a complex history related to prolonged plate convergence at the northern margin of the Indo-Australian Plate (Rogerson and McKee, 1990). Many of the mineral deposits in the region are associated with Cainozoic arc-trench-type volcanism (Fig. 35).

2. Papua New Guinea

Lateritisation in the PNG situation is presently in an immature phase of development. Bauxites and Ni/Co/Cr laterites are either poorly developed or subeconomic (Welsh, 1990). The present climate is tropical to equatorial with rainfall reaching approximately 5000 mm.a^{-1} in the central mountain ranges. Tropical rainforest is the dominant vegetation type. The relief is rugged rising to an elevation of greater than 3500 m in the Wau region, approximately 60 km from the coast (Webster, 1985) (Fig. 36). Secondary redistribution of gold is evident at the Upper Ridges Mine in the Wau district with residual enrichment after dissolution

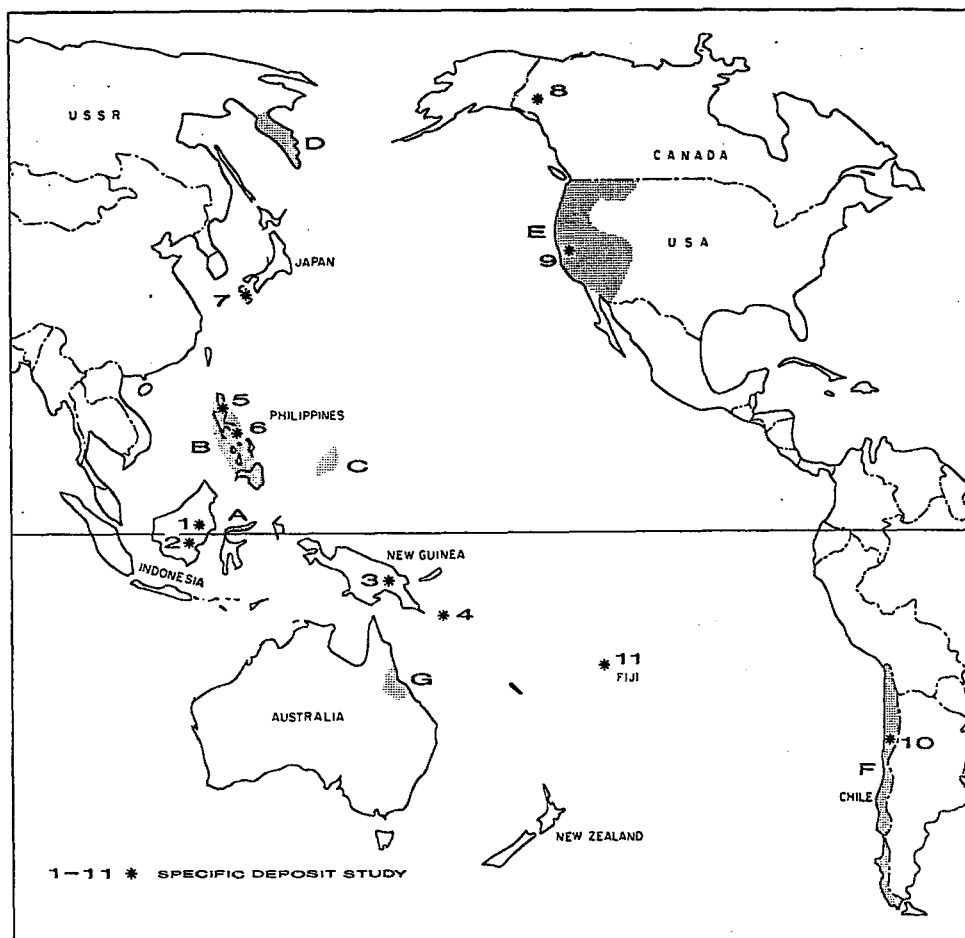


Figure 35

Major ore deposits effected by tropical climates in the south-western Pacific. (1=Kelian, 2=Mt. Muro, 3=Porgera, 4=Umuna, 5=Acupan, 6=Exciban and 11=Emperor) (after Hedenquist et al., 1990)

of lode carbonate (Webster, *op.cit.*). The mobilisation and reprecipitation of gold in the weathering environment is controlled by the permeability of the calcite, manganocalcite, quartz and sulphide lode system. Despite the high rate of physical erosion, chemical weathering often extends to considerable depth in topographic basins, on plateaus and subdued ridges. The weathered profile consists of a partially oxidised dacitic volcanic breccia, host rock overlain by fully oxidised breccia and soils. There is little evidence for lateral distribution of ore components within the profile (Webster, *op.cit.*). The dissolution of gold (electrum) appears to be controlled by thiosulphate

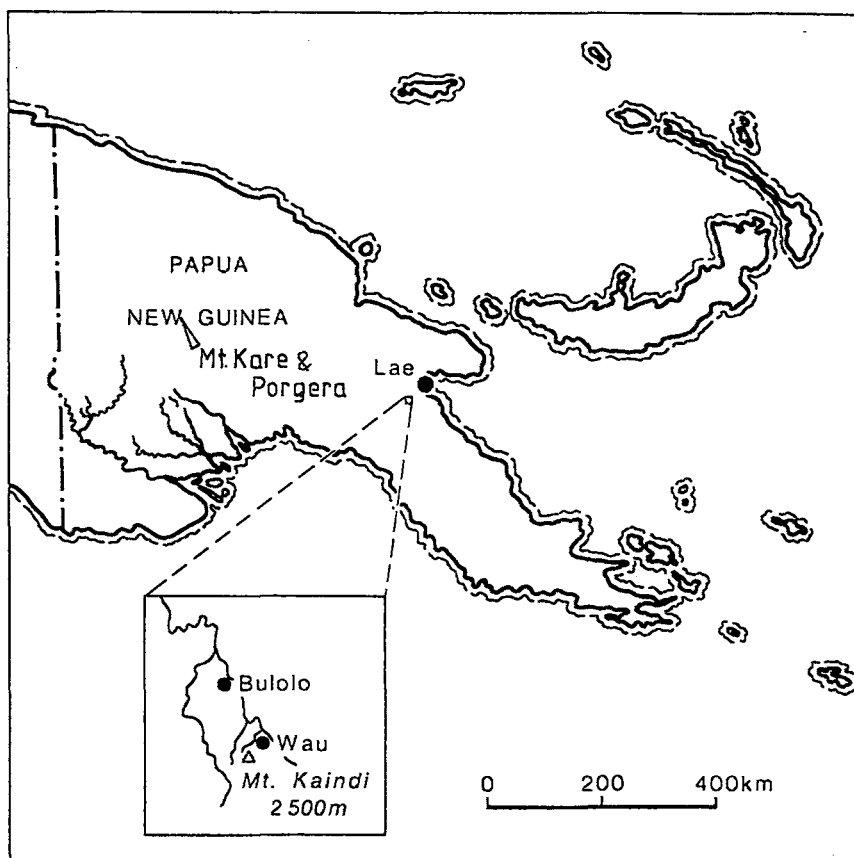


Figure 36

Locality of the Wau region, Papua New Guinea (after Webster and Mann, 1984).

complexing as suggested by the neutral to slightly alkaline pH of weathering fluids and the lack of refinement of the secondary electrum precipitate (Webster, *op.cit.* and Webster and Mann, 1984).

The distribution of base metals in the secondary environment is a function of affinity for manganese oxide. Silver and base metal enrichments are ascribed to the adsorption of the metals onto oxides such as todorokite to form species like $(Ag_2, K_2, Ca, Ba, Na_2, Cu, Pb)Mn_4O_9 \cdot 5H_2O$, for example. Secondary gold as electrum, appears to be either precipitated immediately by manganese oxide wad development or further down the profile, at the water table by iron oxyhydroxides. Arsenic is not fixed by manganese oxides and has proved a poor pathfinder element in this environment (Webster, 1985).

The oxidised ore body at Mt. Muro in Kalimantan, Indonesia, exhibits many similarities to the weathered ore zone at the Upper Ridges mine (Simmons and Browne, 1990).

3. Fiji

The Vunda Prospect, is associated with a sparsely mineralised belt of Miocene to Pliocene shoshonitic volcanics, volcanoclastics, reworked sediments and comagmatic subvolcanic intrusions. Primary mineralisation is Au(Cu) porphyry and epithermal related and has been weathered in the surficial environment by Pliocene and present day lateritisation (Lawrence, 1984). In the past, the upper weathered portion of the latosol, a mottled red, brown, orange clay, was mistaken for hypogene alteration. Laterite or ferricrete is developed in places at the top of the profile that has a maximum thickness of 20 m (Lawrence, *op.cit.*). Epeirogenic uplift and peneplanation appears to be an essential component of the geomorphological processes required for the latosol to develop to a "mature" stage.

The mineralisation at Vunda is hosted by a middle unit of volcanics that underwent weathering prior to the deposition of an upper unit of extrusives. Remnants of a flat surface occupied by ferricrete occurs at the top of the middle unit. It is on this surface that the present drainage and undulatory topography have been superimposed. Weathering during Recent times has etched into the relatively older surfaces (Lawrence, *op.cit.*). Particulate gold as minute cubo-octahedral crystals, may be found in small isolated patches and lenses throughout the oxidised zone. The precipitation of secondary gold appears to be controlled by the water table with no preferential association with either pyrolusite, iron oxyhydroxides or clays. The slightly higher fineness of the secondary gold may suggest a minor component of transport by chloride complexing in a system dominated by thiosulphate complexation (Webster, 1985). Supergene gold is

also associated with oxidised mylonite zones below the latosol.

D. Africa

1. Introduction

Grubb (1973) observed that the late Mesozoic to mid-Tertiary period was globally a time of bauxitisation. Likewise, the first major phase of lateritisation in Africa is of Tertiary age (Maignien, 1966). Deep lateritic profiles up to 100 m thick are common in West Africa (Freyssinet *et al.*, 1989a). Perhaps the preservation of the laterite profiles can be related tectonically to the development of Tertiary basins described in Millot (1970). The Tertiary basins in West Africa are products of transgressions that appear to be related to epeirogenic processes that are also important phenomena in the evolution of lateritic development in Australasia. A model that perhaps can be envisaged is epeirogenic subsidence for Tertiary basin formation and contemporaneous stabilisation along the margins to the basins to accommodate maturation of lateritic profiles. These basins have a distribution that is crudely coincident with the areas of primary gold deposition of Precambrian age (Fig. 37 and Appendix I). Between Guinea and the Ivory Coast, the principle surface is deeply lateritised and appears to be after the African (late Cretaceous to mid-Cainozoic) planation event (King, 1962). This surface is at an elevation of approximately 600 m and does not appear to be preserved in the west toward Senegal and Mauritania. Laterites of a similar age are described in Zaire and Uganda (McFarlane, 1976) but do not appear to be economically significant.

Soils containing relatively old, poorly developed ferruginous incrustations are found throughout intertropical Africa, especially on old plateaus and Tertiary and early Quaternary

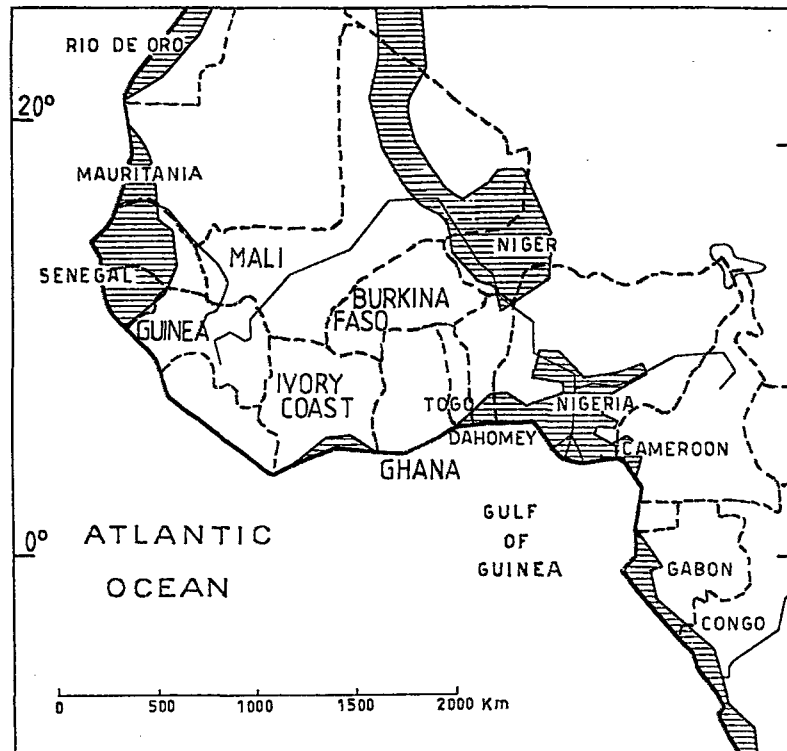


Figure 37

Cretaceous and Tertiary basins of Western Africa (modified after Millot, 1970).

outliers. Recent cuirasses appear to be restricted to ferruginous tropical soils where they span the continent from west to east in the northern hemisphere, between the 750 mm and 1500 mm isohyets. They occur as significant patches in the southern hemisphere in Angola, southern Zaire and Mozambique (Maignien, 1966).

2. Southern Mali

Freyssinet *et al.* (1989a) have described the effects of lateritisation upon gold mineralisation in the Kangaba area, southern Mali. Day temperatures range normally from 22° to 32°C and the annual rainfall is approximately 1300 mm. The Kangaba area is characterised by deep lateritic cover that is "millions of years" in age. Ferruginous cuirasses form large slightly undulating plateaus that are interrupted by lateral erosion proceeding from stream drainages. Southern Mali is

known for its historical gold placer production from the Birrimian basement that consists of volcano-sedimentary sequences 2300 to 1950 Ma in age. Shear zone, quartz veinlet-related gold occurs accompanied by sericite-chlorite alteration and pyrite-arsenopyrite mineralisation within the basement rocks (Freyssinet *et al.*, *op.cit.*).

The ore body at the Syama gold mine is effected by lateritisation with minimal dispersion from the primary lode system with the exception of what appears to be low grade secondary ore developed in the mottled zone (Olson *et al.*, 1991) (Fig. 38). The "mottled zone ore" appears to be controlled by biological activity including root holes and termite burrows that may be coincident with the water table.

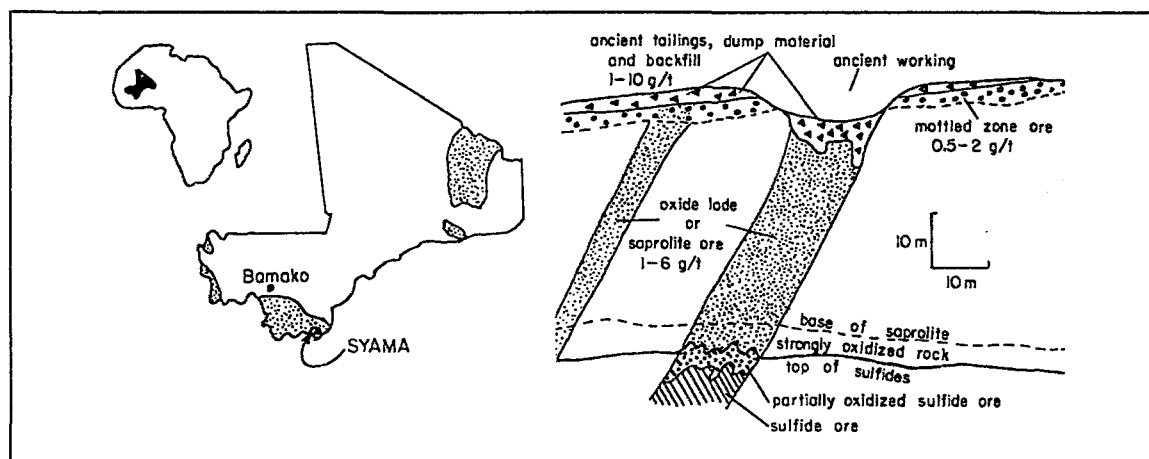


Figure 38

Location of Birrimian shield areas (stippled), the Syama Gold mine and a geological section viewed to the north (after Olson *et al.*, 1991).

3. Gabon

Gabon is located on the equator in West Africa (Fig. 39). In the Dondo Mobi area in southern Gabon, the landscape consists of convexo-concave hills covered with evergreen forest. The altitude ranges from 500 to 800 m with an annual average temperature of approximately 26°C and a mean annual rainfall of about 2000 mm. The Dondo Mobi deposit occurs within early

Proterozoic schists (or lisvenites) that are interpreted as metamorphosed komatiites associated with a package of amphibolites and talc schists. Gold mineralisation is associated with carbonate-rich quartz veins which contain rare bismutotelluride and pyrite (Colin and Vieillard, 1991).

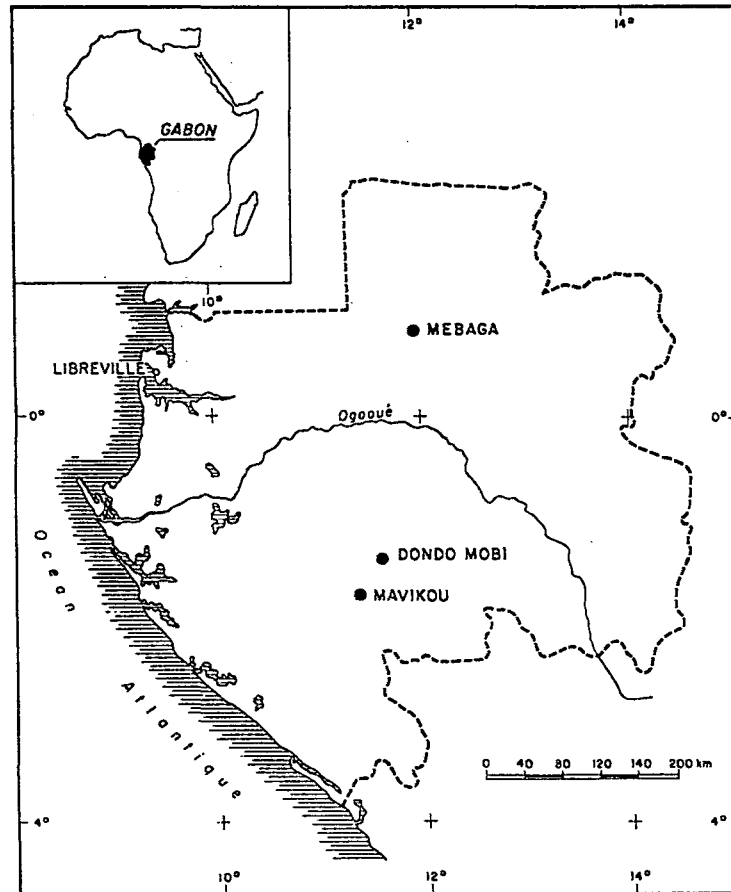


Figure 39
Locality of Dondo Mobi, Gabon (after Lecomte, 1988).

Stone lines are typically present everywhere in Gabon and are also observed in surrounding countries like Cameroun, Central African Republic, Congo and Zaire, i.e., the African equatorial depression. They have been observed in other parts of Africa, formed under slightly drier tropical conditions and in other parts of the world including, Madagascar, the Amazonian basin, on the Guiana shield and rarely in Australia. The typical stone line profile consists of (Lecomte, 1988):

- i) basal saprolite (H3)
- ii) the stone line (H2)
- iii) an upper loose clay horizon (H1).

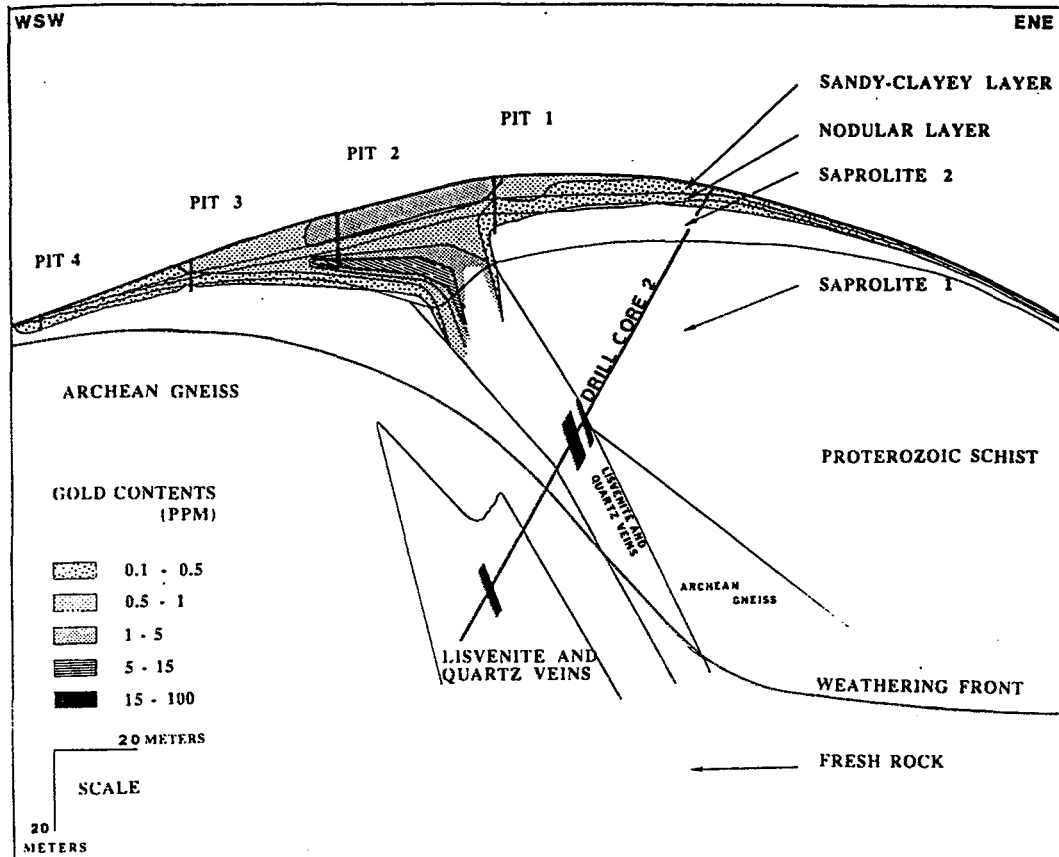


Figure 40
Cross-section illustrating the distribution of gold at the Dondo Mobi deposit (Colin and Vieillard, 1991).

At Dondo Mobi, the lateritic profile is divided into a lower and upper saprolite containing and void of smectite, respectively. The saprolite horizons are overlain by a stone line of lithorelics, haematitic and goethitic or gibbsitic nodules. A sandy-clayey layer occurs at the top of the profile and is overlain by a thin organic soil. Secondary gold distribution is confined largely to the profile above the saprolite producing a symmetrical "mushroom" shape (Fig. 40). The present slope upon which the lateritic profile is preserved is probably a function of post-lateritisation draping associated with river channel incision (Colin and

Vieillard, 1991). All gold appears to be residual, with the most dispersed particles being relatively fine grained (< 63 µm) and depleted in silver. The lithorelics within the stone line appear to be derived from an older laterite horizon by relatively rapid vertical degradation. This mechanism produces relatively greater dispersion of the gold and associated elements but with a commensurate decrease in concentrations. An approximately 200 m wide halo over the Dondo Mobi deposit contains up to 150 ppb Au in the H2 and H1 horizons (Lecomte, 1988, p.57) (Fig. 40).

The Western Australian, Lady Bountiful Extended deposit is also an example of stone line related gold that is underlain by saprolite and overlain by ferruginous transported material (Devlin and Crimeen, 1990, p.408).

4. Cameroun

The Mborquéné deposit in eastern Cameroun displays a similar dispersion pattern to the Dondo Mobi occurrence (Freyssinet *et al.*, 1989b). The relief is low. The weathered profile is developed upon Proterozoic (Birrimian) volcano-sedimentary rocks consisting of biotite schists, shales and sericitic schists. The base of the lateritic regolith is a pale ochre saprolite that is overlain by a pisolithic horizon that contains nodules of iron and clay. Ferricrete, several decimetres in thickness, is overlain by a ferrallitic soil. The geochemistry of mobility appears to be very similar to that of Monti (1987) for the Boddington laterite. Phosphorus pentoxide is enriched in the "laterite" unlike the situation at Boddington.

The dispersion index (Freyssinet *et al.*, 1989b):

$$I_{(i)} = \log x_{(i)} / [(1/n)(\Sigma \log x_{m(i)})]$$

relates the metal content of each sample from the lateritic profile to the mean content of metals in the mineralised structures and defines different halo sizes for different

elements.

- i) $I_{(i)} > 0,95$ represents the fresh and oxidised mineralisation.
- ii) $0,70 < I_{(i)} < 0,95$ represents strongly anomalous haloes which are primarily in fresh rock and secondarily in lateritic horizons.
- iii) $0,30 < I_{(i)} < 0,70$ represents the low grade zones in the weathered profile (Fig. 41).

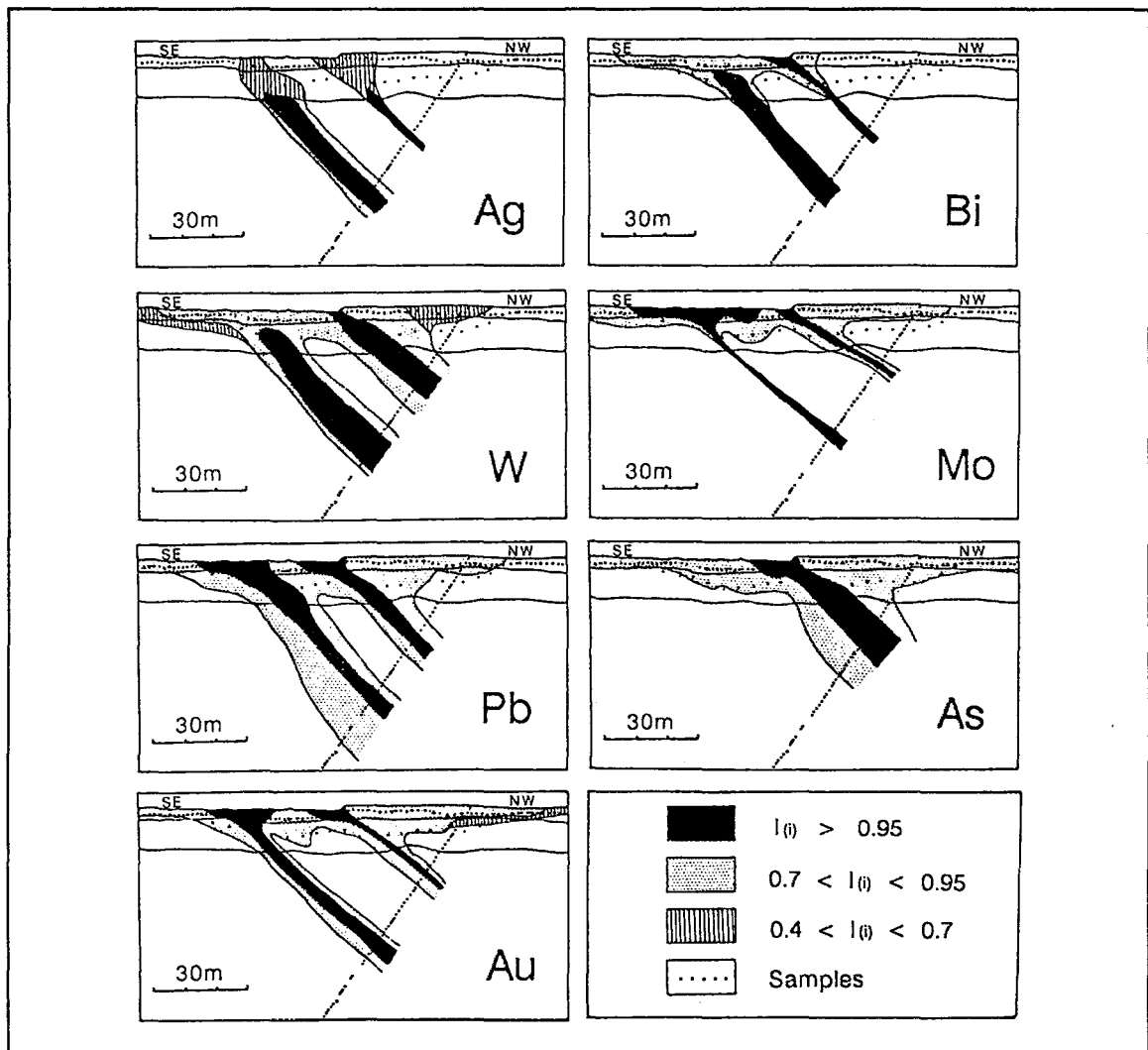


Figure 41

Trace element haloes in the lateritic profile at Mborguéné using the dispersion index (after Freyssinet et al., 1989b).

The size of the haloes range from 30 m for Bi and up to more

than 100 m for As. The elements can be ranked according to their halo size (Freyssinet *et al.*, *op.cit.*):

Ag < Bi < W < Mo-Pb < Au < As.

Bismuth appears to be the most residual element. It is little leached and is dispersed for only a few metres at the top of the profile. Tungsten, Mo, Pb and Au have a similar behaviour. They are partially dispersed but their haloes in the pisolithic horizon are of different sizes. Arsenic is the most dispersed in both the soils and the pisolithic horizon. It appears to have a greater correlation with iron than with the mineralisation. Silver is the most mobile element and is completely leached near the top of the profile. Silver displays a similar halo to Bi but has quite a different mobility. The thorough leaching of Ag will allow its detection only in close proximity to the source.

5. Ghana

Bowell *et al.* (1991) have investigated the mineralogical and chemical characteristics of the tropical weathering profile that mantles the Ashanti concession area in Ghana. Much of the concession area is covered by dense semi-deciduous forest. The regional shear zone system that controls auriferous quartz vein and disseminated sulphide mineralisation in altered phyllite and metabasalt, forms a prominent dissected ridge. The shear zone system occurs along the contact zone between Birrimian metavolcanics and metasediments. A true lateritic profile does not appear to be evident with bedrock overlain by saprolite and capped by an ochrosol soil horizon. The saprolite is in the order of tens of metres in thickness and the soil is less than ten metres thick. The mineralisation and sericitic wallrock alteration is evident as Au-Ag-As-Cu-Pb-Zn and K-Rb-Al signatures within the soils, respectively. Ferruginous cuirasses and "mushroom"-shaped dispersion patterns are not developed apparently due either to the relatively high

topographic slope or in the case of gold, unfavourable chemical conditions for complexing and secondary deposition (Bowell *et al.*, *op.cit.*).

E. South America

1. Introduction

The equatorial region of South America experienced a tropical climate throughout the Cainozoic (Gill, 1961). The continent of South America presents a gigantic cordillera flanked upon the east by a trough that has been partially filled by Cainozoic and Recent sediments derived from uplifted ranges. A number of planation events have been identified including early to late Cainozoic features. A pronounced Plio-Pleistocene cymatogeny and repeated cycles of subsequent uplift have produced the incision of the landscape that is evident today (King, 1962). The most distinct manifestations of ferruginous incrustation are found in Brazil and the Guianas (Maignien, 1966). The surficial secondary redistribution of gold has been investigated largely in Brazil in the Carajas region, in the states of Bahia and Goias. Laterites of Tertiary age are presently undergoing degradation under a semi-arid environment in the state of Bahia.

2. Brazil

The Carajas Mineral Province is located about 400 km south south-west of the mouth of the Amazon River in the Para Province of Brazil. The Salobo 3A Cu-Au and Bahia Au-Cu deposits are located along the southern margin to the Amazonian basin, on the interfluves to tributaries to the Amazon River (Fig. 42). The climate is tropical and vegetation is rainforest except for "iron clearings" on plateau tops. Average annual precipitation is approximately 2000 mm with mean daily temperatures of about 26°C. During

the "dry" season, measurements at Salobo show an excess of evaporation over precipitation. The more resistant rocks of the area are iron formations and quartzites that form plateaus at an elevation of ± 600 m, approximately 250 to 350 m above the surrounding lowlands. The ores are associated with late Archean to early Proterozoic metasedimentary-metavolcanic rocks (Andrade *et al.*, 1991).

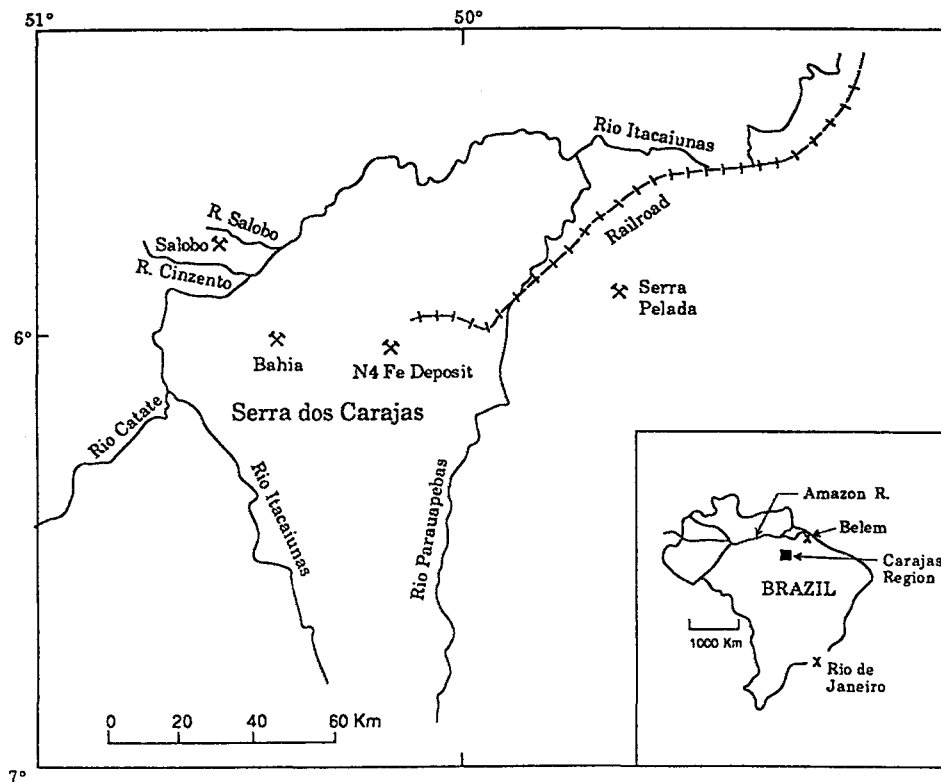


Figure 42
Map of the Carajas region, Para Province, Brazil (after Andrade et al., 1991).

The "lateritic" profile at the Salobo 3A deposit is similar to that found in the Ashanti situation in Ghana. It consists of a lower saprolite and an upper soil horizon developed on the side of a ridge. Lateritic dispersion does not appear to be evident and enrichment in the saprolite zone is probably inherited from down-slope transport. The topographic slope is approximately 20° (Andrade *et al.*, *op.cit.*, p.100). The Bahia deposit is located upon a plateau and exhibits lateritic dispersion in the classic "mushroom" shape within

the top 10 to 20 m of the profile. Secondary gold mineralisation appears to be distributed within both the "ferricrete" and the mottled zone. Lateritic weathering extends to 100 m depth. The dispersion of gold appears to be controlled by the scavenging capacity of vegetation and the assimilation of dead vegetation into the humus layer (Andrade *et al.*, *op.cit.*). Gold is subsequently mobilised from the humus layer by organic acids and transported to sites of deposition within the "laterite" below (Section III/B/2) (Fig. 43). A study of the morphology of this lateritic gold may reveal residual grains as recognised in some of the African examples above (Freyssinet *et al.*, 1989a, 1989b and Colin and Vieillard, 1991).

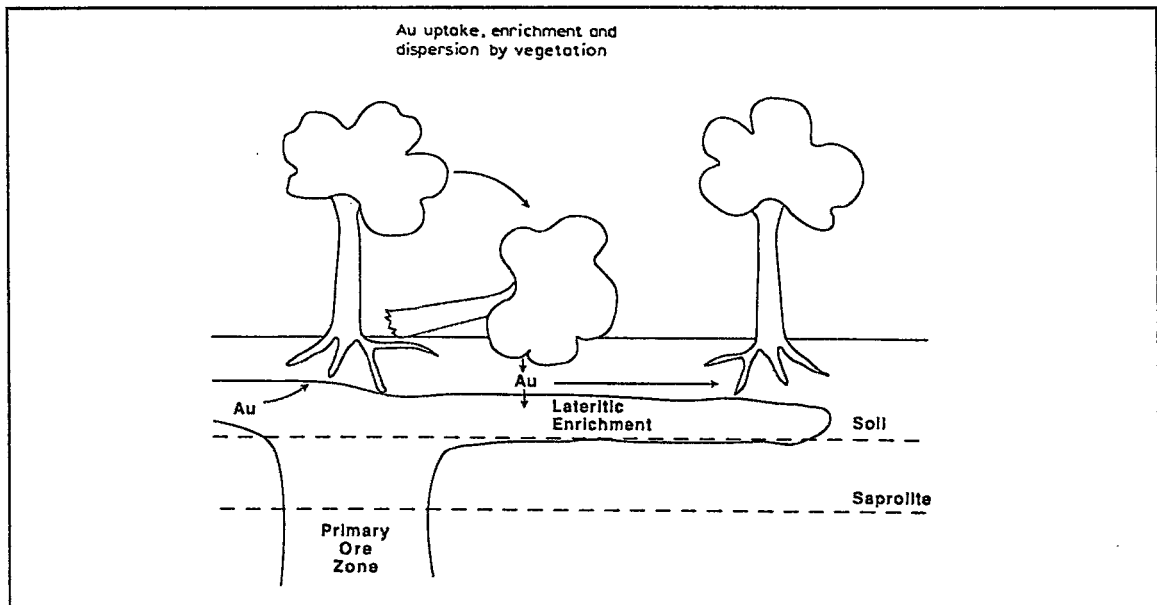


Figure 43

Conceptual representation of the role of vegetation in gold mobilisation, dispersion and enrichment (after Andrade *et al.*, 1991).

The Gentio de Ouro and Sento Sé Districts are located in the state of Bahia in Brazil (Fig. 44). The Gentio do Ouro district contains laterites that bear economic concentrations of secondary gold. The climate is semi-arid but the laterites are Tertiary in age and related to a tropical palaeoclimate (Carvalho *et al.*, 1991). The landscape of

Central Brazil is dominated by lateritised planation surfaces of lower Pleistocene age. At present, the profile is experiencing intense erosion as the Sao Francisco River incises deeper into the landscape to the immediate west of the district. Primary gold is associated with quartz lenses and sulphides developed at the contact between intrusive gabbro and ferruginous metapsammite. The metasediments are mid-Proterozoic in age. The overlying regolith has a relatively thin saprolite developed at the base with red latosols and ferruginous, pisolithic cuirasses at the top of the profile.

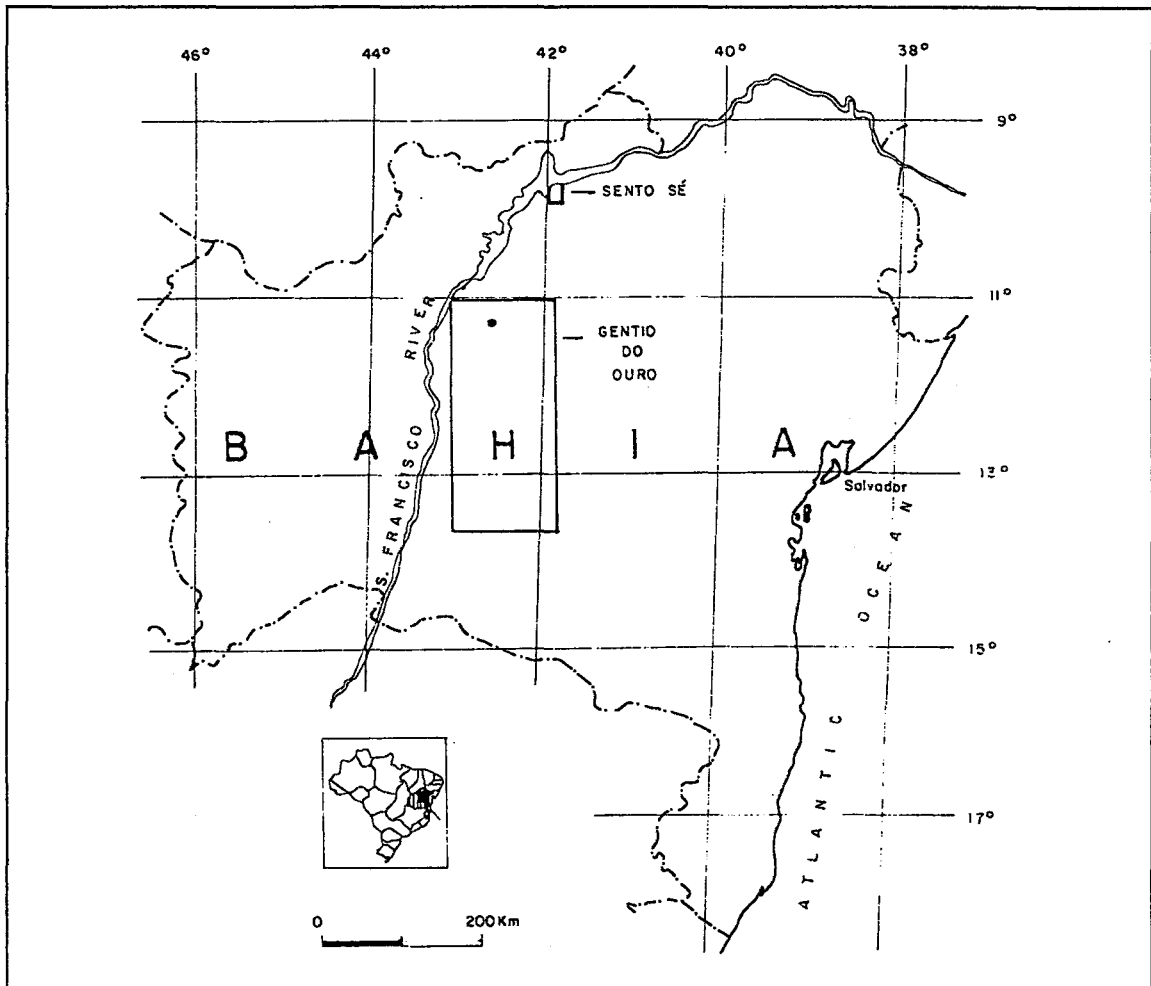


Figure 44
Location of the Gentio de Ouro and Sento Sé districts, Bahia, Brazil (after Carvalho et al., 1991).

Secondary enrichment in gold is characterised by an increase

in gold fineness and growth of gold nuggets in both the cuirasse and the latosol. Colloform, botryoidal, spherical and dendritic secondary gold is associated with the lateritic profile. Ancient prospectors reported the occurrence of gold nuggets weighing up to 1 kg in the red latosol (Carvalho *et al.*, *op.cit.*). Three generations of gold have been identified (Grimm and Friedrich, 1991):

- i) primary gold
- ii) weathered primary gold
- iii) chemically accreted gold

The formation of chemically accreted gold may be related to both the hydromorphous zone above the saprolite and to processes associated with the onset of aridity during the Quaternary. As in the Western Australian case, chloride complexing is suggested as a mechanism for this chemical redistribution and as a means of refinement of the gold (Grimm and Friedrich, *op.cit.*)

The trace element distribution through the profile is similar to that determined by Monti (1987) and Davy and El-Ansary (1986). In contrast to the Boddington example, these lateritic sections display enrichment in Cu and Mn upward through the profile. The Mn is believed to be after residual enrichment (Carvalho *et al.*, 1991) and the behaviour of Cu is possibly a function of adsorption onto secondary manganese oxyhydroxides.

Eluvial gold is associated with the stone line developed in the lateritic profile above the Posse deposit, Mara Rosa, in the Goias state of Brazil (Porto, 1991). Goias is contiguous with and immediately west of Bahia and has suffered the same climatic and geomorphological history. The present climate is tropical with an annual mean rainfall of 1800 mm. The Posse deposit is found within the Mara Rosa volcano-sedimentary sequence of probable Proterozoic age, confined to a finely banded felsic gneiss. Gold and tellurides are

disseminated in the silicate matrix.

The Posse profile is very similar to the profiles described in Gabon (Section V/D/3). The stone line consists of older, higher laterite, quartz and pisolite fragments. Gold grades are enriched in the stone line because of compaction and preferential downward physical migration of coarser grains. These grains have an irregular and rugged shape. The dispersion of gold is asymmetrical and downslope (5°) (Porto, *op.cit.*). Michel (1987) describes mechanically eluviated gold associated with what appears to be a "stone line" of iron oxyhydroxide-rich pebbles and quartz fragments in the Cuiaba area, Matto Grosso.

3. Guyana

The Omai property in Guyana is situated on the northern side of the watershed that drains into the Amazonian basin to the south. It is centred on coordinates $5^\circ 28'N$ and $58^\circ 45'W$ on the west bank of the Essequibo River approximately 225 km south-west of Georgetown (Fig. 45a) (Bertoni *et al.*, 1991).

Regionally, the area is underlain by late Archean to early Proterozoic volcano-sedimentary rocks that have been deformed by the Trans-Amazonian Orogeny (± 2 Ga). They have been intruded by orogenic calc-alkalic granitoids which includes the Omai Intrusive Complex. Gold mineralisation at Omai is associated with a quartz diorite phase of intrusion. The weathered zone above the intrusive was mined extensively by hydraulic means at the turn of the century. The West Lake Zone is located about 500 m south of the Omai pluton, overlying a sequence of silicified, carbonatised and sulphidised mafic to felsic volcanic rocks (Fig. 45b). Alteration is accompanied by abundant anastomosing quartz (carbonate) veining that contains relatively minor gold. Most of the gold is contained in the lateritic profile that is approximately 60 m thick. The laterite in Fig. 45b

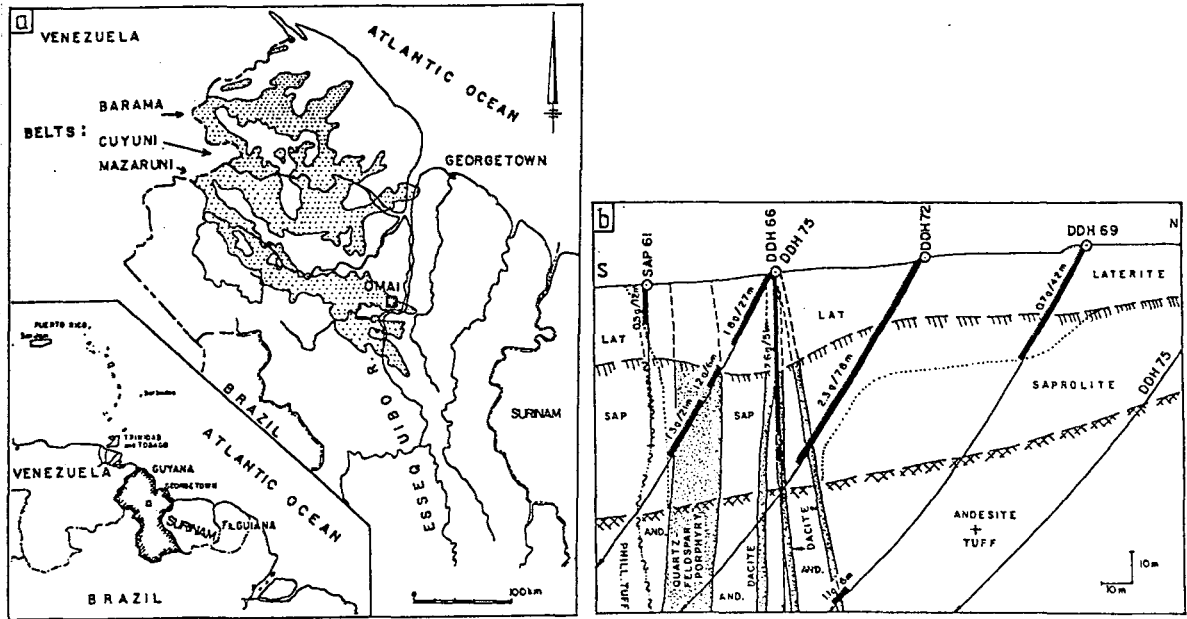


Figure 45
Location of the Omai property and the extent of greenstone belts in Guyana (a). Lateritic dispersion in the West Lake zone (b) (after Bertoni et al., 1991).

includes the mottled zone and the ferruginous pisolithic cuirasse. Gold is interpreted to have been mobilised from mineralised subjacent bedrock and its secondary distribution controlled by local hydrodynamic conditions (Bertoni *et al.*, *op.cit.*).

F. India

1. Introduction

During Cainozoic times the changes in climate created by vast plate tectonic movements both horizontally and vertically, have had a greater effect upon the landscape than global climatic changes. The climates of southern or Peninsula India and Sri Lanka have been tropical throughout the Cainozoic while northern India, Pakistan and Burma have had their climates effected dramatically by tectonism (Gill, 1961). As in the cases of PNG and Indonesia, the potential energy associated with rugged fold belt terranes is not

conducive to the development or the preservation of laterites or their secondary ores. Those areas weakly effected by Mesozoic and Cainozoic orogeny are Central and southern India, Sri Lanka, south-eastern Thailand, Cambodia, Vietnam and southern China (Fig. 46). Laterites appear to poorly developed in this part of the globe (Maignien, 1966, p.56) and consequently, an apparent lack of economically important secondary gold is evident.

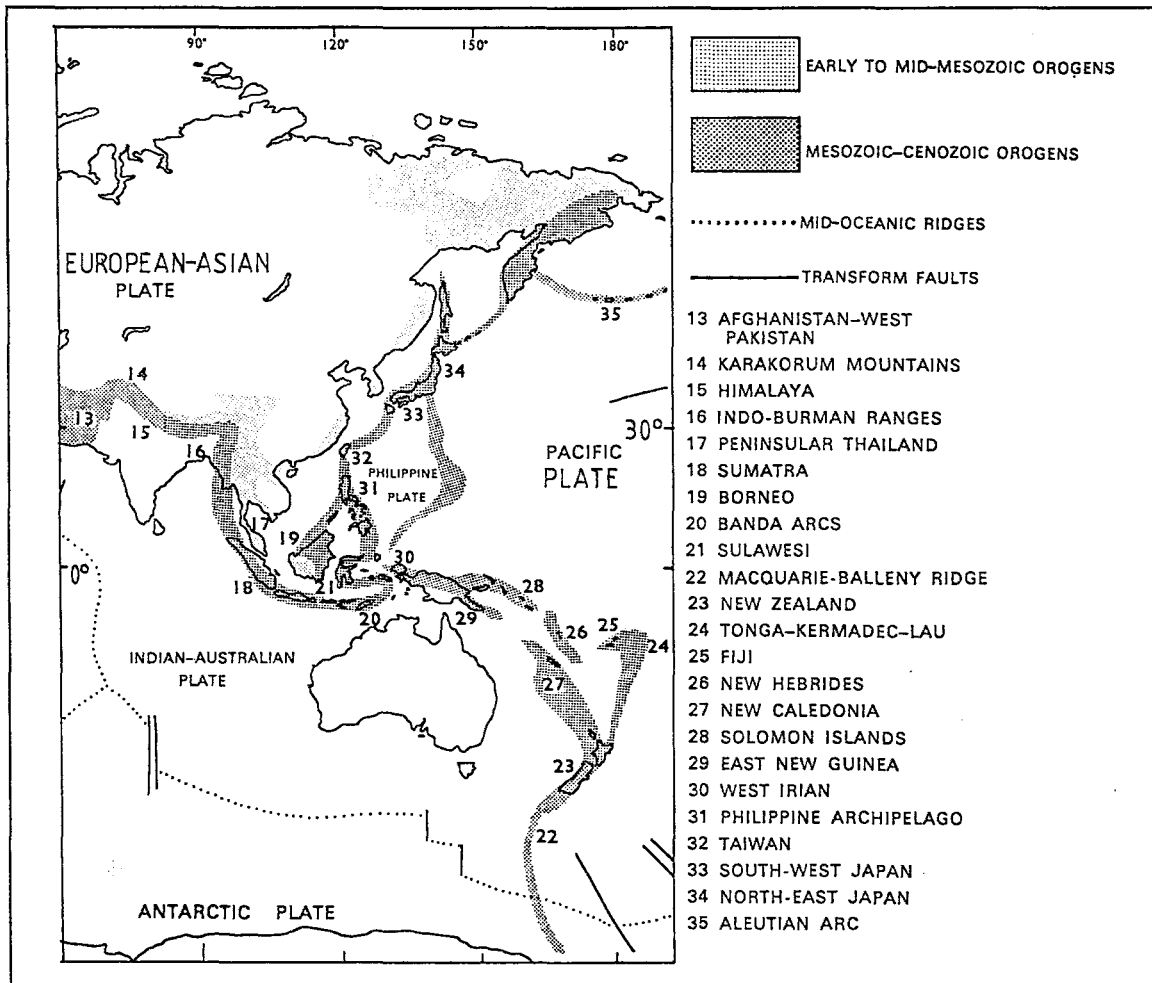


Figure 46

The distribution of Mesozoic-Cainozoic orogenic belts in India and south-east Asia (modified after Spencer, 1974).

2. Discussion

Considering the influence of tropical climate, relief and primary geology, the most likely environment for gold-bearing

laterite development is upon the Karnataka Craton within the Eastern Goldfield and Western Iron-manganese Archean Greenstone provinces of southern India (Fig. 47 and Appendix I). Rainforest is restricted to the west coast of India (Fig. 22). Outside the main valleys, most of Peninsula India is an undulating plateau of probably early Cainozoic age. The laterites can be divided into "high-level", *in situ* cuirasses associated with the plateau surface at elevations of greater than 600 m. The "low level" cuirasses occur in depressions and upon coastal lowlands and in many instances appear to be transported (King, 1962). On the western coast it is difficult to distinguish between these two types but on the eastern coast, the detrital facies is more apparent (Maignien, 1966).

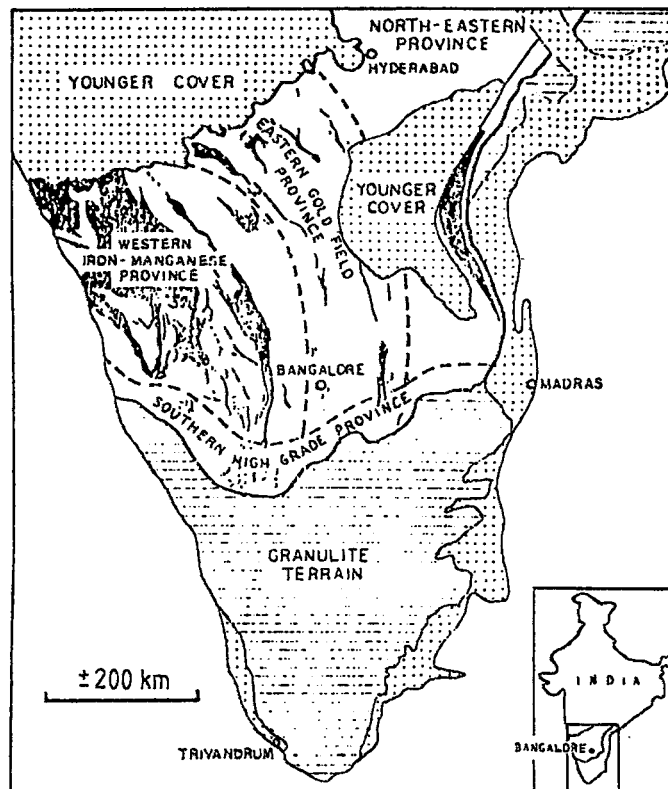


Figure 47
The Karnataka Craton (after Shashi Kumar, 1991).

Gold-bearing laterites occur overlying Precambrian ortho-amphibolites and felsic gneisses (metavolcanic) at Maruda in

the Kerala province (Narayanaswamy and Krishnakumar, 1991). The primary gold mineralisation is associated with quartz veining. These rocks appear to be part of the Southern High Grade Province of the Karnataka Craton (Shashi Kumar, 1991) approximately 100 km from the west coast. The laterite has a vermiform texture as a function of its close proximity to the Maruda River and the groundwater table (McFarlane, 1983, p.27). It is developed on a near flat surface and from its physiographic position, is of the "low level", probably *in situ* variety. Morphology of the lateritic gold grains suggest that both residual and hydromorphic effects contribute to the redistribution of gold in the weathered profile. Eh/pH considerations suggest that chloride complexing is the dominant agent responsible for secondary mobilisation of the gold (Narayanaswamy and Krishnakumar, 1991).

VI. DISCUSSION

A. Exploration

1. Introduction

The lateritic regolith may be viewed as either overburden of geochemical value that physically masks primary geology or a potential target as an easily exploitable resource. Laterites contain known reserves of Ni, Al, Fe, Mn, P and Au and are endowed with large resources of Ti and Nb in the Brazilian situation (Mariano, 1989, p.150). Potentially they may prove to be resources of resistate minerals containing V, Zr, Sn, Cr, Ga, REE and Th. A progressive philosophy perhaps may suggest the targeting of the laterite based on predictions of the prospective nature of basement geology. Should the regolith prove to be an economic proposition, this may provide additional means to explore and perhaps, develop the primary source.

Like all ore depositional processes, the formation of gold-bearing laterites is a product of the fortuitous coincidence of a number of natural phenomena. The most important requisite for laterite formation is a humid, warm, wet, tropical climate. Annual rainfall ought to be in excess of 1200 mm and mean temperatures greater than 21°C, approximately. The laterite requires preservation and ought not be disturbed tectonically by events more energetic than epeirogenesis. The economically important gold-bearing laterites are associated with a Cainozoic climate and tectonic events that provided placid uplift of cratonic landscapes. Lateritised land surfaces in central Africa have been interpreted as representing multiple peneplanation events dating back to the Jurassic-Cretaceous period (Gondwana surface) (McFarlane, 1976 and King, 1962). In Zaire, lateritic surfaces are preserved at elevations of greater than 2000 m but in general, mineralised laterites

tend to be developed and preserved at elevations less than 1000 m. Peneplanation slopes or the gradients of erosional surfaces control the style of secondary mineralisation within the laterite:

- i) less than 6°, hydromorphic processes predominate
- ii) 6° to 10°, residual/mechanical processes predominate
- iii) 10° to 20°, laterite development is severely impaired
- iv) greater than 20°, no laterite development.

The style of secondary mineralisation is also dependent on the rate of degradation, changes in climate, the consequent effect on the water table level and the intensity of gold mineralisation in the primary lodes. Lateritisation as an ore forming process requires a tropical climate in a tectonically stable environment of low relief that can accommodate sufficient uplift to ensure adequate drainage and degradation of the profile for accumulation of "resistate" material by hydromorphic and vertical mechanical processes. If the rate of tectonic uplift is too great, then lateral mechanical processes will dominate, leading to entire removal of materials from the source. The greater the source of primary gold, the greater the amount of metal available for distribution laterally. The product of dispersion halo size and tenor of secondary gold distribution may provide a semi-quantitative indication of the intensity of primary mineralisation. The examples analysed in the case studies are associated invariably with Archean and Proterozoic cratons, suggesting that Phanerozoic gold deposits, in general, remain associated with relatively high relief that is not conducive to lateritisation processes.

The above variables of climate, geomorphology and primary geology and their control on the distribution of gold-bearing laterites require conceptual modelling for planning and instigating effective geochemical exploration (Fortescue, 1975, Butt and Smith, 1980, Butt and Zeegers, 1989 and Zeegers and Leduc, 1991) (Section V/A and B). Murrel (1984)

suggests that this can be accomplished by a landscape analysis:

- i) determine current surface processes that control the transport and deposition of material
- ii) take stock of geological materials (regolithic) other than the target rocks
- iii) describe the regolith.

Based on the above analysis, the area under investigation may be divided into different domains that can be treated statistically as separate geochemical entities. A landscape and lateritic gold development model for the Western Australian situation is given by Smith (1987) and perhaps can be adapted for use elsewhere (Fig. 48).

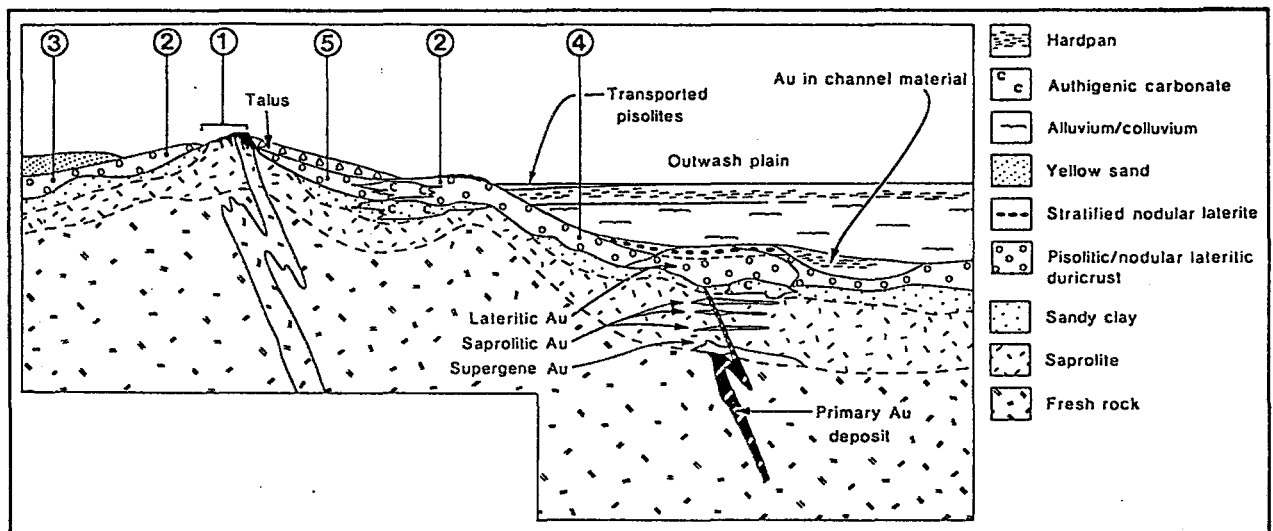


Figure 48

Cross-sectional synthesis of lateritic regolith stratigraphy typifying parts of the central Yilgarn Block, Western Australia (after Smith, 1987).

The numeric codes in Fig. 48 indicate:

- (1) outcropping bedrock
- (2) laterite at surface or near surface
- (3) lateritic blanket beneath sand plain
- (4 and 5) laterite masked by excessive cover

2. Geochemical sampling

The Yilgarn Block in Western Australia covers an area of approximately 650000 km², 80% of which is masked by the regolith. Most of the mines are located in the areas of exposed bedrock. Stony ferruginous material that accumulates commonly on arid land surfaces as a thin veneer, has been shown to be bedrock and laterite derived (Carver, *et al.*, 1987 and Ross, 1989). Problems associated with the sampling of this lag material include understanding the extent of transport from source. The lags show extensive lateral dispersion and have been used to advantage in regional exploration. Sampling of centimetre-sized lateritic pisolites or nodules at a spacing of less than 1 km x 3 km is suggested by Smith *et al.* (1989) for reconnaissance exploration of gold deposits. The above sample spacing parameters appear to be appropriate for base metal exploration in the region. Termite activity may provide a biological sampling mechanism for lateritic material masked by transported cover. In the Paterson Province, a Proterozoic cratonic area that hosts the Telfer gold deposit in Western Australia, termites appear to be responsible for the distribution of a fine grained lag that is almost universally present (Carver *et al.*, 1987)

A study conducted by Carver *et al.* (*op.cit.*, p.188) sampled the -6+2 mm lag fraction over gold mineralisation at a locality in the Eastern Goldfields Province of the Yilgarn Block. The samples returned values six-fold greater than -420+200 μ m and -200 μ m soil fractions. The area has low relief with well rounded hills rising no more than 20 m above the surrounding plain. Subcropping to outcropping oxidised rock is common on the hills together with remnants of a partly stripped lateritic profile. A thin veneer of unconsolidated soil overlies the weathered bedrock. In a similar area geomorphologically but influenced by aeolian dunes, responses to bedrock gold mineralisation for soils and the lag were found similar in intensity. This was ascribed to a considerable component of residual material contained

within the soils and not contamination of the lag by wind blown material. However, the lag sampling gave a broader spread of anomalous values than that of the soils.

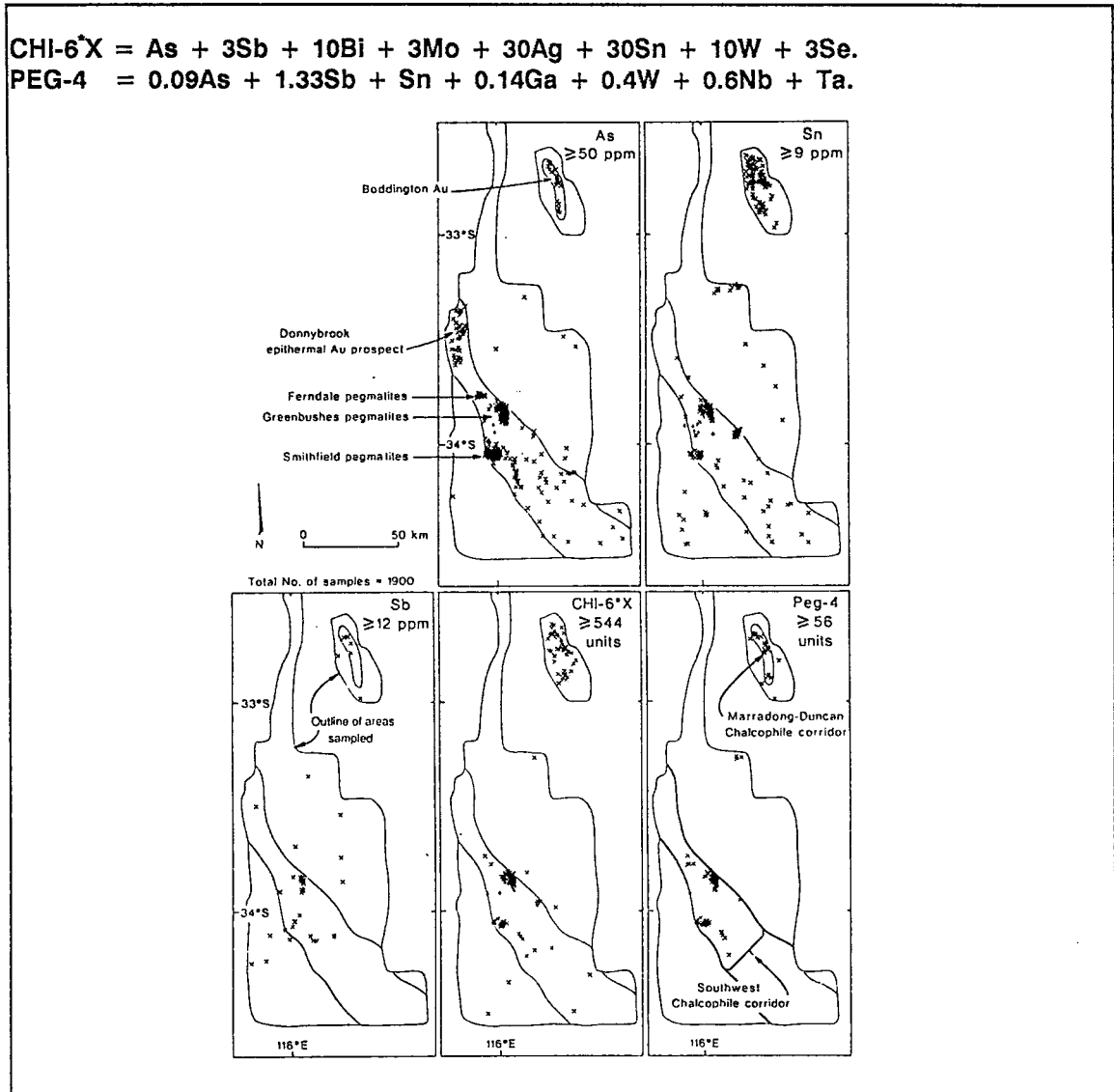


Figure 49

Chalcophile laterite geochemistry in the south-western part of the Yilgarn Block. "x" symbols indicate individual samples that exceed the threshold level (after Smith et al., 1989).

By generating one sample per 6 km², regional geochemical trends or "chalcophile corridors" were defined using multivariate statistical techniques on laterite As, Sb, Bi, Mo, Ag, Sn, W and Se geochemistry from the Western Gneiss

Terrane and the Murchison Province (Smith, *et al.*, 1989). Broad "corridors" defined by As and Sb appear to contain more discrete anomalies of Bi, Mo, Ag, Sn, W, Se or Au. Figure 49 illustrates the distribution of "chalcophile corridors" over the Western Gneiss Terrane including the Saddleback Greenstone belt. The CHI-6*X chalcophile index over the Boddington area on a prospect scale, shows a considerably greater dispersion halo than Au and other certain individual elements (Smith, 1987). The chemistry of the Mborguéné lateritic profile in Cameroun suggests that Pb may prove a useful pathfinder in combination with the above element suite (Freyssinet *et al.*, 1989a). These "corridors" are up to 30 km wide and 150 km long and appear to be the geochemical expression of the "physical" gold exploration tracts recognised in the past (Smith *et al.*, 1989, Groves *et al.*, 1989 and Coggan, 1984).

In the Gentio do Ouro district of Bahia, Brazil, Mn and Cu are associated with the mineralised laterites in some cases (Carvalho *et al.*, 1991).

B. Mining

Bliss (1992) has made an attempt to classify lateritic gold deposits as a discrete deposit type. The descriptive model for the deposit type demands the following qualifications:

- i) data on deposit sizes and grades are for unworked deposits
- ii) deposits may be underlain by unrecognised mineral deposits in the bedrocks
- iii) deposits may be placer deposits and not laterite-saprolite related.

Grade and tonnage curves have been drawn up for nine "Laterite-saprolite" gold deposits investigated in Guyana, Western Australia and Surinam (Fig. 50). The lack of data in general has led to a biased sample of deposits with nearly

60% of the data derived from Guyana examples. The grade and tonnage at the 50th percentile of deposits are 1,4 g/t Au and 3,9 Mt, respectively. Both the Boddington and Gibson deposits fall within the first 50th percentile range and by converting the above data into tons of contained gold, they are approximately 17 and 1,5 times larger than the 50th percentile deposit, respectively.

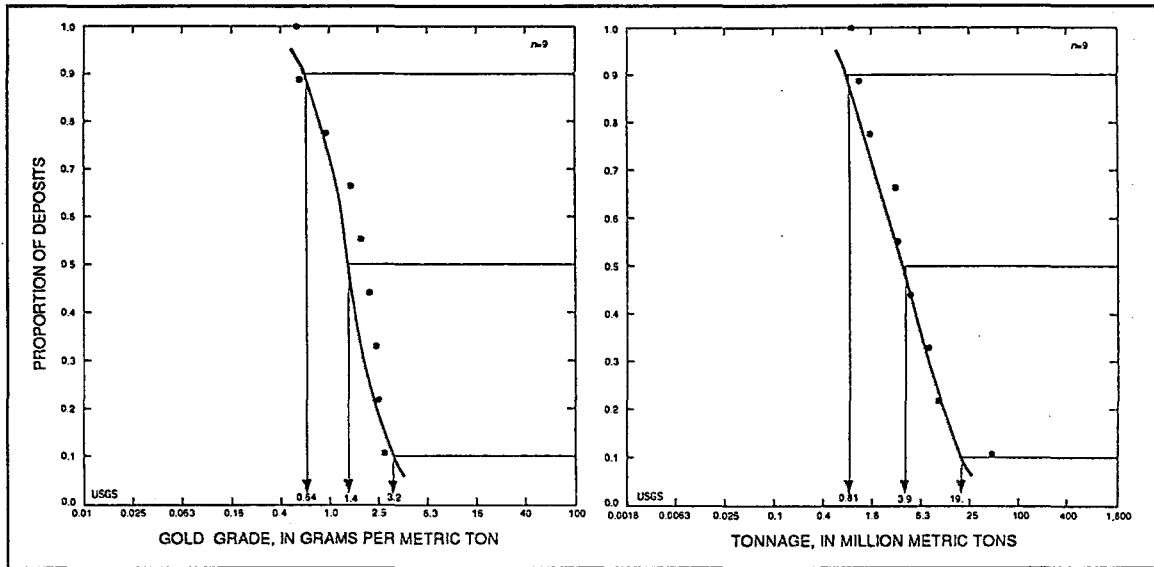


Figure 50

Percentile versus grade and tonnage curves for "Laterite-saprolite" gold deposits (after Bliss, 1992).

Supergene gold deposits associated with the lateritic profile are generally of a low grade nature. Since the early 1980's, advances in extractive technology have made ore bodies of deposits with a tenor of 1 to 2 ppm Au in the Western Australian open cut mining situation. Material in the 0,5 to 1,0 ppm Au range may be economically suitable for heap leaching operations (Smith, 1987). If infrastructural constraints will allow, relatively small deposits in the order of hundreds of thousands of tons can be mined profitably. Contractors may obviate initial high capital expenditure, by making mining and milling available at competitive rates.

The gold distribution in the PZ of the regolith at Westonia

has proved to be remarkably uniform and was mined using data from a 25 to 12,5 m x 25 m exploration/development drill hole grid. Mill reconciliations indicated that the exploration grade was understated by 3% (Drummond and Beilby, 1990). The Gibson mining operation blends its laterite, oxide and sulphide ore, presumably to boost revenues as grades in the basement are approximately three times greater than in the laterite. Grades also increase downward through the lateritic profile (Section V/B/3). Ore reserve drilling was conducted on a 25 m x 50 m grid in order to define ore blocks that were drilled subsequently on a 12,5 m x 12,5 m pattern for grade control purposes. Gold grades of the individual mining blocks vary laterally within the range of 0,75 g/t and 8 g/t Au over distances along strike, of up to 2 km (Gee, 1990, p.263). Gold is mined from the upper 8 m of the profile within pisolites, massive ironstone and in ferruginised material at the top of the zone (Davy *et al.*, 1988).

The South Junction Mine, located in the Meekatharra-Widgee Greenstone belt in the Murchison Province, produces much of its gold from weathered quartz lodes within the saprolite. It provides an example of grade control problems associated with coarse gold in the oxidised lodes and, to a lesser extent, in the laterite. The host rocks are an interfoliated, sheared and folded package of meta-ultramafic/mafic lavas, metapelites and intrusive felsic porphyries (Fiala, 1992). The overlying laterite is poorly developed laterally but appears to reflect to a limited extent, the behaviour of gold in the oxidised bedrock. The "Laterite deposit" was drilled on a 10 m x 10 m spaced grid, delineating a gold-bearing mantle approximately 6 ha in areal extent with a possible, initial reserve of 125000 t at 2 g/t Au. The "Laterite deposit" is restricted to the southern limits of the mine overlying jointed, felsic porphyry and is coincident with the confluence of two creeks (Fiala, *op.cit.* and W. Johnson, pers.comm., 1991) (Fig. 51). The laterite is

overlain by a 10 m thick transported horizon that has undergone ferruginisation, induration and in places, pedogenic calcretisation. The best gold grades are associated with pisolitic and nodular laterite but grades do persist into the base of the transported horizon above and into the top of the mottled zone below.

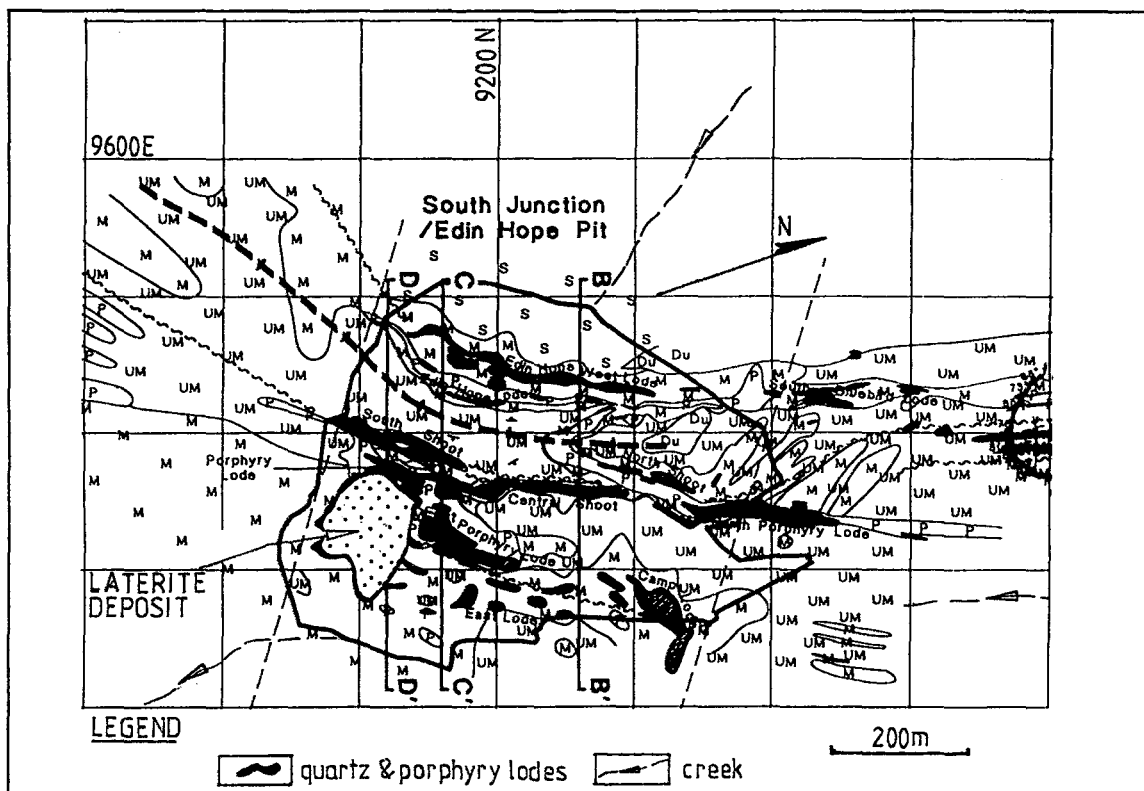


Figure 51

The position of the Laterite deposit relative to the primary lodes at the South Junction Mine (modified after Fiala, 1992).

Grade control is maintained by sampling of blast drill holes on a 3 to 6 m x 2,5 m spacing. In the lateritic areas, a cut-off of 0,5 g/t Au is used. High grade assays are not cut and arithmetic means are used to calculate the ore reserve. The presence of coarse gold associated with quartz lodes makes reconciliation with the grade control drilling and the ore reserve difficult. For the South Shoot Ore Zone, N Flitch, recovered gold was approximately 180% and 40% greater than that indicated by the ore reserve drilling and the mill feed assay, respectively (Fiala, 1992, p.95). Beyond the

bounds of the defined laterite ore body, high grade zones of mineralisation are developed patchily within the laterite and in many cases, have entirely eluded the 20 m x 20 m development drilling of the lode gold. The irregularity of the distribution of the gold in the laterite may be controlled by the influence of erosion and associated transported material that caps the profile. Transported material appears to have modified the chemistry of the underlying laterite at the Gibson deposit (Section V/B/3). If these irregularities in the laterite are attributable to erosional phenomena, the distribution of grades may become impossible to predict without very closely spaced drilling and mapping of erosional channel patterns. Geologically, the task is formidable for the paucity of cross-sectional exposure and the similarities between the physical nature of the ferruginised overburden and the laterite. Butt (1987, p.37) suggests that for the Yilgarn Block regolith in general:

"it is commonly very difficult to distinguish between transported overburden and the underlying weathered residuum".

A unique "conceptual ore body model" is required to deal with the problem (Carras, 1984, p.63) which should rely on geological interpretation that can only be formulated by greater data acquisition. This perhaps can be attained by establishing a database regarding the style of secondary distribution of gold within the lateritic profile prior to mining. If there is a suggestion of residual coarse gold in the laterite, this may help predict the nature of mineralisation in the primary lode system below.

VII. CONCLUSION

Lateritisation is a process that relies on a tropical climate, geomorphological slopes with gradients of less than 10° and a substrate that is associated with a stable cratonic environment. Lateritisation behaves as an ore forming process by the removal of mobile and concentration of the "immobile" components through the mechanisms of leaching, chemical precipitation and physical eluviation, respectively. Under conditions of slow degradation, gold is concentrated by transporting agents in the form of organic, thiosulphate and chloride complexes and deposition, controlled by ferrolysis at the water table. Residual concentration of gold may dominate and associated stone line profiles may develop under circumstances of relatively "rapid" vertical degradation. The morphology of secondary gold grains may give clues to their supergene history. In general, residual dispersion is evident by concentration in the laterite alone. Hydromorphic dispersion may distribute gold at all levels throughout the weathered profile.

In the Western Australian, Yilgarn Block environment, aridification has afforded the concentration of chloride in the regolith, providing sufficient potential solvent for gold to be remobilised and deposited in economic quantities at successively lower levels associated with the receding water table. A depleted zone within the oxidised portion of the primary gold lode is developed within the upper saprolite. Based on the Boddington model, the following potential "pathfinder" elements are associated with the laterite:

- i) Mo, Sb, W, Hg, Bi, and Au as mobile constituents
- ii) As and Pb as immobile constituents.

At the Mborguéne deposit, Cameroun, geochemical haloes indicate that the secondary dispersion of:

As > Au > Mo - Pb > W > Bi.

An upward, residual concentration of Mn and Cu in the laterite was recorded in the Gentio do Ouro district of Bahia, Brazil.

Ferruginous lag (after bedrock and laterite) found concentrated immediately above the lateritic regolith under the semi-arid conditions of Western Australia, has proved a useful sampling medium for its dispersed nature and in some cases, elevated geochemistry relative to the underlying soils. Sampling of pisoliths and nodules derived from the laterite on a regional scale has defined "chalcophile corridors" up to 150 km long. These geochemical "belts" are defined broadly by As and Sb but contain more discreet anomalies of Bi, Mo, Ag, Sn, W, Se or Au. Laterite ore bodies in Western Australia are larger than most others developed around the world, with Boddington being a veritable giant deposit. The advantageous infrastructural environment (largely influenced by the present climate and geomorphology) and present extractive technology allows low grade lateritic gold ores and oxidised primary lodes to be mined at relatively low cost. By considering the prevailing climate, post-lateritisation modifications to the landscape and the primary geology, the Western Australian model perhaps can be adapted and modified for exploration and mining elsewhere on the globe.

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REFERENCES

- Anand, R.R., Gilkes, R.J. and Roach, G.I.D. (1991). Geochemical and Mineralogical characteristics of Bauxites, Darling Range, Western Australia. *Appl. Geochem.*, 6, 233-248.
- Andrade, W.O., Machesky, M.L. and Rose, A.W. (1991). Gold Distribution and Mobility in the Surficial Environment, Carajas region, Brazil. *J. Geochem. Explor.*, 40, 95-114.
- Bagby, W.C. and Berger, B.R. (1985). Geological characteristics of sediment-hosted, disseminated Precious-metal Deposits in the western United States. 169-202. In: Berger, B.R. and Bethke, P.M., Eds., *Geology and Geochemistry of Epithermal Systems*. *Rev. Econ. Geol.*, 2, 298pp.
- Baker, W.E. (1973). The role of Humic acids from Tasmanian Podzolic soils in mineral Degradation and metal Mobilisation. *Geochim. Cosmochim. Acta*, 37, 269-281.
- Baker, G.F.U. (1975). Darling Range Bauxite Deposits, W.A. 980-986. In: Knight, C.L., Ed., *Economic Geology of Australia and Papua New Guinea 1: Metals*. Aus. Inst. Min. Metall., Melbourne, 1126pp.
- Baker, W.E. (1978). The role of Humic acids in the transport of Gold. *Geochim. Cosmochim. Acta*, 42, 645-649.
- Berger, B.R. and Bagby, W.C. (1991). The Geology and Origin of Carlin-type Gold Deposits. 210-248. In: Foster, R.P., Ed., *Gold Metallogeny and Exploration*. Blackie, Glasgow, 432pp.
- Bertoni, C.H., Shaw, R.P., Singh, Minamoto, J., Richards, J.M. and Belzile, E. (1991). Geology and gold

- mineralisation of the Omai property, Guyana. 767-771. In: Ladeira, E.A., Ed., *The Economics, Geology, Geochemistry and Genesis of Gold Deposits*. Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Bliss, J.D. (1992). Grade and Tonnage Model of Laterite-saprolite Au. 50-51. In: Bliss, J.D., Ed., *Developments in Mineral Deposit Modelling*. Bull. U.S. geol. Surv., 2004, 168pp.
- Bowell, R.J., Foster, R.P., Gize, A.P., Hoppis, H.A., Laffoley, N.d'A. and Rex, A.J. (1991). Mineralogical and Chemical characteristics of a Tropical Weathering Profile in Ghana: implications for gold exploration. 713-719. In: Ladeira, E.A., Ed., *The Economics, Geology, Geochemistry and Genesis of Gold Deposits*. Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Boyle, R.W. (1979). *The Geochemistry of Gold and its Deposits (together with a chapter on geochemical prospecting for the element)*. Bull. geol. Surv. Canada, 280, 584pp.
- ____ (1986). Gold Deposits in Turbidite Sequences: their geology, geochemistry and history of the theories of their origin. 1-13. In: Keppie, J.D., Boyle, R.W. and Haynes, S.J., Eds., *Turbidite-hosted Gold Deposits*. Spec. Paper geol. Assoc. Can., 32, 186pp.
- Büdel, J. (1973). The Climatic Geomorphic System. 104-130. In: Derbyshire, E., Ed., *Climatic Geomorphology*. MacMillan, London, 296pp.
- Butt, C.R.M. and Smith, R.E., Eds. (1980). Conceptual Models in Exploration Geochemistry. *J. Geochem. Explor.*, 12, 89-365.

- Butt, C.R.M. (1983). Aluminosilicate cementation of Saprolites, Grits and Silcretes in Western Australia. *J. geol. Soc. Aust.*, 30, 179-186.
- ____ (1985). Granite weathering and Silcrete formation on the Yilgarn Block, Western Australia. *J. Aust. Earth Sci.*, 32, 415-432.
- ____ (1987). The Dispersion of Gold in the Weathered Zone, Yilgarn Block, Western Australia. 27-54. In: *Meaningful Sampling in Gold Exploration*. Bull. Aust. Inst. Geoscien., 7, 182pp.
- ____ (1988). Gold Mobility in the Weathering Environment. In Smith, B.H., Stokes, C.A., Govey, A.L. and Oates, C.J., Eds., *The Second International Conference on Prospecting in Arid Terrain*, Excursion Guidebook, Boddington and Eastern Goldfields, Western Australia.
- ____ (1989). Genesis of Supergene Gold Deposits in the Lateritic Regolith of the Yilgarn Block, Western Australia. *Econ. Geol.*, Monograph 6, 460-470.
- Butt, C.R.M. and Zeegers, H. (1989). Classification of Geochemical Exploration Models for Tropically weathered terranes. *J. Geochem. Explor.*, 32, 65-74.
- Carras, S.N. (1984). Comparative Ore Reserve Methodologies for Gold Mine Evaluation. 59-70. *Reg. Conference, Gold Mining, Metallurgy and Geology*, Aus. Inst. Min. Metall., Perth/Kalgoorlie.
- Carvalho, I.G., Mestrinho, S.P., Fontes, V.M.S., Goel, O.P. and De A. Souza, F. (1991). Geochemical evolution of Laterites from two areas of the Semiarid region in Bahia State, Brazil. *J. Geochem. Explor.*, 40, 385-411.

- Carver, R.N., Chenoweth, L.M., Mazzucchelli, R.H., Oates, C.J. and Robbins, T.W. (1987). "Lag" - a Geochemical sampling medium for Arid regions. *J. Geochem. Explor.*, **28**, 183-199.
- Cloke, P.L. and Kelly, W.C. (1964). Solubility of Gold under Inorganic supergene conditions. *Econ. Geol.*, **59**, 259-270.
- Coggan, J.H. (1984). Geophysics as an Aid to Gold Exploration in the Yilgarn Block. 113-138. In: Doyle, H.A., Ed., *Geophysical Exploration for Precambrian Gold Deposits*. Publ. Univ. Ext., Univ. W. Aust., **10**, 182pp.
- Colin, F. and Vieillard, P. (1991). Behaviour of Gold in the Lateritic equatorial environment: weathering and surface dispersion of residual gold particles at Dondo Mobi, Gabon. *Appl. Geochem.*, **6**, 279-290.
- Curtin, G.C., Lakin, H.W. and Hubert, A.E. (1970). The mobility of Gold in Mull (forest humus layer). *Prof. paper U.S. geol. Surv.*, **700-C**, C127-C129.
- Davy, R. and El-Ansary, M. (1986). Geochemical patterns in the Laterite profile at the Boddington Gold Deposit, Western Australia. *J. Geochem. Explor.*, **26**, 119-144.
- Davy, R., Clarke, R., Sale, M. and Parker, M. (1988). The Nature and the Origin of the Gold-bearing Laterites at Mount Gibson, Western Australia. 45-48. In: *The Second International Conference on Prospecting in Arid Terrain*. Aus. Inst. Min. Metall., Melbourne.
- Deer, W.A., Howie, R.A. and Zussman, J. (1977). *An Introduction to the Rock-forming Minerals*. Longman, London, 528pp.

- De Martonne, E. (1973). Climate: Factor of Relief. 61-75. In: Derbyshire, E., Ed., *Climatic Geomorphology*. MacMillan, London, 296pp.
- Devlin, S.P. and Crimeen, J.D. (1990). Lady Bountiful Extended Gold Deposit. 405-410. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.
- Dimmock, G.M., Bettenay, E. and Mulcahy, M.J. (1974). Salt content of Lateritic profiles in the Darling Range, Western Australia. *Aust. J. Soil Res.*, 12, 63-69.
- Drummond, A.J. and Beilby, G.R. (1990). Westonia Gold Deposits. 289-295. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.
- Fedoseyeva, V.I., Fedoseyev, N.F. and Zvonareva, G.V. (1986). Interaction of some Gold Complexes with Humic and Fulvic acids. *Geochem. Internat.*, 23(3), 106-110.
- Fiala, J.D. (1992). South Junction Gold Deposit - Meekatharra. *Bull. Aust. Inst. Min. Metall.*, 3, 85-96.
- Fortescue, J.A.C. (1975). The use of Landscape Geochemistry to process Exploration Geochemical data. *J. Geochem. Explor.*, 4, 3-7.
- Freyssinet, Ph., Zeegers, H. and Tardy, Y. (1989a). Morphology and Geochemistry of Gold grains in Laterite profiles of southern Mali. *J. Geochem. Explor.*, 32, 17-31.
- Freyssinet, Ph., Lecomte, P. and Edimo, A. (1989b). Dispersion of Gold and Base metals in the Mborguéne Lateritic profile, east Cameroun. *J. Geochem. Explor.*,

32, 99-116.

- Gee, R.D. (1990). Gibson Lateritic Gold Deposit. 259-264. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.
- Gill, E.D. (1961). The Climates of Gondwanaland in Kainozoic Times. 332-353. In: Nairn, A.E.M., Ed., *Descriptive Palaeoclimatology*, Interscience Publishers, New York, 380pp.
- Goldhaber, M.B. (1983). Experimental study of Metastable Sulfur Oxyanion formation during Pyrite oxidation. *Amer. J. Sci.*, 283, 193-217.
- Goldman, M.I. and Tracy, J.I. (1946). Relations of Bauxite and Kaolin in the Arkansas Bauxite Deposits. *Econ. Geol.*, 41, 567-575.
- Goudie, A. (1973). *Duricrusts in Tropical and Subtropical Landscapes*. Oxford University Press, London, 174pp.
- Granger, H.C. and Warren, C.G. (1969). Unstable Sulfur compounds and the Origin of Roll-type Uranium Deposits. *Econ. Geol.*, 64, 160-171.
- Grimm, B. and Friedrich, G. (1991). Precipitation and concentration of gold in Colluvial soils in the Semiarid region of Gento do Ouro, Central Bahia, Brazil. 343-351. In: Ladeira, E.A., Ed., *The Economics, Geology, Geochemistry and Genesis of Gold Deposits*. Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Groves, D.I., Barley, M.E. and Ho, S.E. (1989). Nature, Genesis and Tectonic setting of Mesothermal Gold

mineralisation in the Yilgarn Block, Western Australia. *Econ. Geol., Monograph 6*, 71-85.

Groves, D.I. and Foster, R.P. (1991). Archaean Lode Gold Deposits. 63-103. In: Foster, R.P., Ed., *Gold Metallogeny and Exploration*. Blackie, Glasgow, 432pp.

Groves, D.I. and Ho, S.E. (1990). A short Review of Gold in the Yilgarn Block. 539-553. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.

Grubb, P.L.C. (1973). High-level and Low-level Bauxitisation: a criterion for classification. *Miner. Sci. Engng.*, 5(3), 219-231.

Heald, P., Foley, N.K. and Hayba, D.O. (1987). Comparative anatomy of Volcanic-hosted Epithermal deposits: Acid-sulphate and Adularia-sericite Types. *Econ. Geol.*, 82, 1-26.

Hedenquist, J.W., White, N.C. and Siddeley, G. (1990). Epithermal Gold Mineralisation of the Circum-Pacific; geology, geochemistry, origin and exploration, I. *J. Geochem. Explor.*, 35, vii-xii.

Henley, R.W. (1991). Epithermal Gold Deposits in Volcanic Terranes. 133-164. In: Foster, R.P., Ed., *Gold Metallogeny and Exploration*. Blackie, Glasgow, 432pp.

Hill, A.D. and Cranney, P.J. (1990). Fortnum Gold Deposit. 665-666. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.

Hilton, K. (1985). *Process and Pattern in Physical Geography*. University Tutorial Press, Slough, 219pp.

- Hingston, F. and Gailitis, V. (1976). The Geographic variation of Salt precipitated over Western Australia. *Aust. J. Soil Res.*, 14, 319-335.
- Horrocks, N.K. (1981). *Physical Geography & Climatology*. Longman, Burnt Mill, 370pp.
- Hynes, A. and Gee, R.D. (1986). Geological setting and Petrochemistry of the Narracoota Volcanics, Capricorn Orogen, Western Australia. *Precambrian Res.*, 31, 107-132.
- King, L.C. (1962). *The Morphology of the Earth*. Oliver and Boyd, Edinburgh, 699pp.
- Kolotov, B.A., Spasskaya, T.S., Vagner, B.B. and Minacheva, L.I. (1980). The Relationship between Colloidal and other forms of Migration of Gold in Water in the Supergene zones of Ore deposits. *Geochem. Internat.*, 17(4), 80-82.
- Krauskopf, K.B. (1951). The Solubility of Gold. *Econ. Geol.*, 46, 858-870.
- ____ (1979). *Introduction to Geochemistry*. McGraw-Hill Kogakusha, Tokyo, 617pp.
- Lakin, H.W., Curtin, G.C. Hubert, A.E., Shacklette, H.T. and Doxtader, K.G. (1974). *Geochemistry of Gold in the Weathering Cycle*. Bull. U.S. geol. Surv., 1330, 80pp.
- Lamb, H.H. (1977). *Climate, Present, Past and Future*. Methuen, London, Vol. 2, Climatic history and the future, 835pp.
- Lawrance, L.M. (1988). Behaviour of Gold within the Weathering profile in the Yilgarn Block, Western

- Australia. 335-351. In: Ho, S.E. and Groves, D.I., Eds., *Advances in Understanding Precambrian Gold Deposits*, 2(12), Univ. W. Australia, Perth.
- ____ (1990). Supergene Gold Mineralisation. 300-313. In: Ho, S.E., Groves, D.I. and Bennett, J.M., Eds., *Gold Deposits of the Archean Yilgarn Block, Western Australia: Nature, Genesis and Exploration Guides*. Univ. Western Australia, 20.
- Lawrence, L.J. (1984). Surface and near Surface Gold at Vunda, Fiji. 1-12. In: *Gold Mining, Metallurgy and Geology*. Proc. Aus. Inst. Min. Metall., Kalgoorlie.
- Lecomte, P. (1988). Stone-line profiles; importance in geochemical exploration. *J. Geochem. Explor.*, 30, 35-62.
- Leeming, P.M. (1985). *Turbidite-hosted gold deposits*. M.Sc. dissertation, (unpubl.), Rhodes Univ., Grahamstown, 104pp.
- Levinson, A.A. (1980). *Introduction to Exploration Geochemistry*. Applied Publishing, Wilmette, 924pp.
- ____ (1987). *Practical problems in Exploration Geochemistry*. Applied Publishing, Wilmette, 269pp.
- Mabbutt, J.A. (1980). Weathering history and Landform development. *J. Geochem. Explor.*, 12, 96-116.
- Maignien, R. (1966). *Review of Research on Laterites*. UNESCO, Paris, 148pp.
- Mann, A.W. (1984). Mobility of Gold and Silver in Lateritic weathering profiles: some observations from Western Australia. *Econ. Geol.*, 79, 38-49.

- Mann, A.W. and Webster, J.G. (1990). Gold in the Exogenic Environment. 119-126. *In: Hughes, F.E., Ed., Geology of the Mineral Deposits of Australia and Papua New Guinea.* Aus. Inst. Min. Metall., Melbourne, I, 982pp.
- Mariano, A.N. (1989). Nature of Economic Mineralisation in Carbonatites and related Rocks. 149-176. *In: Bell, K., Ed., Carbonatites Genesis and Evolution,* Unwin Hyman, London, 618pp.
- McFarlane, M.J. (1976). *Laterite and Landscape.* Academic Press, London, 151pp.
- McFarlane, M.J. (1983). Laterites. 7-58. *In: Goudie, A.S. and Pye, K., Eds., Chemical Sediments and Geomorphology: precipitates and residua in the near-surface environment.* Academic Press, London, 439pp.
- Michel, D. (1987). Concentration of Gold in in situ Laterites from Matto Grosso. *Mineral. Deposita*, 22, 185-189.
- Millot, G. (1970). *Geology of Clays.* Springer-Verlag, New York, 429pp.
- Minter, W.E.L. (1991). Ancient Placer Gold Deposits. 283-308. *In: Foster, R.P., Ed., Gold Metallogeny and Exploration.* Blackie, Glasgow, 432pp.
- Monti, R. (1987). The Boddington Lateritic Gold Deposit, Western Australia: a product of supergene enrichment processes. 355-368. *In: Ho, S.E. and Groves, D.I., Eds., Advances in Understanding Precambrian Gold Deposits*, 11, Univ. W. Australia, Perth.
- Murrel, B. (1984). The Landscape Inventory Approach - common sense in geochemical sampling. *J. Geochem. Explor.*, 22, 367-368.

- Narayanaswamy and Krishnakumar, N. (1991). Concentration of Gold in in situ laterites at Maruda, Nilambur Valley, Kerala, India. 743-750. *In: Ladeira, E.A., Ed., The Economics, Geology, Geochemistry and Genesis of Gold Deposits*. Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Needham, R.S. and De Ross, G.J. (1990). Pine Creek Inlier - Regional Geology and Mineralisation. 727-737. *In: Hughes, F.E., Ed., Geology of the Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.
- Nesbitt, B.E. (1991). Phanerozoic Gold Deposits in tectonically active Continental Margins. 104-132. *In: Foster, R.P., Ed., Gold Metallogeny and Exploration*. Blackie, Glasgow, 432pp.
- Olson, S.F., Diakite, K., Guindo, A., Ford, C.R.B., Winer, N., Hansen, E., Lay, N. and Bradley, R. (1991). Geology of the Syama Gold Mine, Mali, West Africa. 593-599. *In: Ladeira, E.A., Ed., The Economics, Geology, Geochemistry and Genesis of Gold Deposits*. Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Ong, H.L. and Swanson, V.E. (1969). Natural Organic acids in the Transportation, Deposition and Concentration of Gold. *Colorado School of Mines Quart.*, 64, 395-425.
- Ong, H.L., Swanson, V.E. and Bisque, R.E. (1970). Natural Organic Acids as agents of Chemical Weathering. *Prof. paper, U.S. geol. Surv.*, 700-C, C130-C137.
- Owen, H.B. and Hargreaves, M.R. (1975). Mount Saddleback Bauxite area, W.A. 987-991. *In: Knight, C.L., Ed., Economic Geology of Australia and Papua New Guinea 1: Metals*. Aus. Inst. Min. Metall., Melbourne, 1126pp.

- Panteleyev, A. (1988). A Canadian Cordilleran Model for Epithermal Gold-Silver Deposits. 31-44. In: Roberts, R.G. and Sheahan, P.A., Eds., *Ore Deposit Models*. Geosci. Can. Reprint Ser., 3, 194pp.
- Polynov, B.B. (1937). *The Cycle of Weathering*. Murby, London, 220pp.
- Porto, C.G. (1991). Grade distribution and Morphology of Gold grains in the Stone line Lateritic profile of the Posse deposit, Mara Rosa, Goias, Brazil. 721-728. In: Ladeira, E.A., Ed., *The Economics, Geology, Geochemistry and Genesis of Gold Deposits*. Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Roberts, R.G. (1988). Archean Lode Gold Deposits. 1-20. In: Roberts, R.G. and Sheahan, P.A., Eds., *Ore Deposit Models*. Geosci. Can. Reprint Ser., 3, 194pp.
- Rogerson, R. and McKee, C. (1990). Geology, Volcanism and Mineral Deposits of Papua New Guinea. 1689-1701. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, II, 1828pp.
- Rose, A.W., Hawkes, H.E. and Webb, J.S. (1979). *Geochemistry in Mineral Exploration*. Academic Press, London, 657pp.
- Ross, J.R. (1989). Prospecting in Arid terrain - geological problems and opportunities. *Bull. Aus. Inst. Min. Metall.*, 294(7), 52-53.
- Rossiter, R.D. (1984). *Epithermal Gold Deposits : their Geology and Genesis*. M.Sc. dissertation, (unpubl.), Rhodes Univ., Grahamstown, 132pp.
- Roth, E., Groves, D., Anderson, G., Daley, L. and Staley, R.

- (1991). Primary mineralisation at the Boddington Gold Mine, Western Australia: an Archean porphyry Cu-Au-Mo deposit. 481-488. *In: Ladeira, E.A., Ed., The Economics, Geology, Geochemistry and Genesis of Gold Deposits.* Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Sato, M. (1960). Oxidation of Sulphide Ore bodies. 1: geochemical environments in terms of Eh and pH. *Econ. Geol.*, 55, 928-961.
- Shashi Kumar, K.T. (1991). Karnataka Craton - Peninsula India: a potential major gold habitat. 209-216. *In: Ladeira, E.A., Ed., The Economics, Geology, Geochemistry and Genesis of Gold Deposits.* Proc. Symp. Brazil Gold '91, Belo Horizonte. Balkema, Rotterdam, 823pp.
- Silberman, M.L. and Berger, B.R. (1985). Relationship of Trace Element Patterns to Alteration and Morphology in Epithermal Precious-metal Deposits. 203-232. *In: Berger, B.R. and Bethke, P.M., Eds., Geology and Geochemistry of Epithermal Systems.* Rev. Econ. Geol., 2, 298pp.
- Sillitoe, R.H. (1991). Intrusion-related Gold Deposits. 165-209. *In: Foster, R.P., Ed., Gold Metallogeny and Exploration.* Blackie, Glasgow, 432pp.
- Simmons, S.F. and Browne, P.R.L. (1990). Mineralogic, Alteration and Fluid-inclusion studies of Epithermal Gold-bearing veins at the Mt. Muro Prospect, Central Kalimantan (Borneo), Indonesia. *J. Geochem. Explor.*, 35, 63-103.
- Smith, R.E. (1987). Using Lateritic Surfaces to Advantage in Mineral Exploration. 312-321. *In: Geochemical Methods: their application to Ore Exploration.* Exploration '87 Proceedings.

- Smith, R.E., Birrel, R.D. and Brigden, J.F. (1989). The implications to Exploration of Chalcophile Corridors in the Archean Yilgarn Block, Western Australia, as revealed by Laterite Geochemistry. *J. Geochem. Explor.*, 32, 169-184.
- Spencer, A.M. (1974). Index Map showing Orogenic segments described. xi-xiii. In: Spencer, A.M., Ed., *Mesozoic-Cenozoic Orogenic Belts - Data for orogenic studies*. Geol. Soc. London, Scottish Academic Press, Edinburgh, 809pp.
- Stoffregan, R. (1986). Observations on the Behaviour of Gold during Supergene oxidation at Summitville, Colorado, U.S.A. and the implications for Electrum stability in the Weathering environment. *Appl. Geochem.*, 1, 549-558.
- Symons, P.M., Anderson, G., Beard, T.J., Hamilton, L.M., Reynolds, G.D., Robinson, J.M., Staley, R.W. and Thompson, C.M. (1990). Boddington Gold Deposit. 165-169. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.
- Tardy, Y. and Nahon, D. (1985). Geochemistry of Laterites, stability of Al-goethite, Al-haematite, and Fe₃₊-kaolinite in Bauxites and Ferricretes: an approach to the mechanism of Concretion formation. *Amer. J. Sci.*, 285, 865-903.
- Veselinovic, M. (1992). *Genetic Models for Epithermal Gold Deposits and Applications to Exploration*. M.Sc. dissertation, (unpubl.), Rhodes Univ., Grahamstown, 122pp.
- Webster, J.G. and Mann, A.W. (1984). The influence of Climate, Geomorphology and Primary Geology on the

supergene migration of Gold and Silver. *J. Geochem. Explor.*, 22, 21-42.

Webster, J.G. (1985). *Supergene migration of Gold and Silver, and the influence of Primary Geology, Climate and Geomorphology*. Ph.D. thesis, (unpubl.), Univ. Western Australia, Perth, 148pp.

____ (1986). The Solubility of Gold and Silver in the system Au-Ag-S-O₂-H₂O at 25°C and 1 atm. *Geochim. cosmochim. Acta*, 50, 1837-1845.

Wedepohl, K.H. (1978). *Handbook of Geochemistry*. Springer-Verlag, Berlin, II-4.

Welsh, T.C. (1990). The Mineral Industry in Papua New Guinea. 1681-1688. In: Hughes, F.E., Ed., *Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, II, 1828pp.


Westra, G. and Keith, S.B. (1981). Classification and Genesis of Stockwork Molybdenum Deposits. *Econ. Geol.*, 76, 844-873.


Wilson, A.F. (1984). Origin of Quartz-free Gold Nuggets and Supergene Gold in Laterites and Soils - a Review and some new observations. *Aust. J. Earth Sci.*, 31, 303-316.

Woodall, R. (1990). Gold in Australia. 45-67. In: Hughes, F.E., Ed., *Geology of the Mineral Deposits of Australia and Papua New Guinea*. Aus. Inst. Min. Metall., Melbourne, I, 982pp.

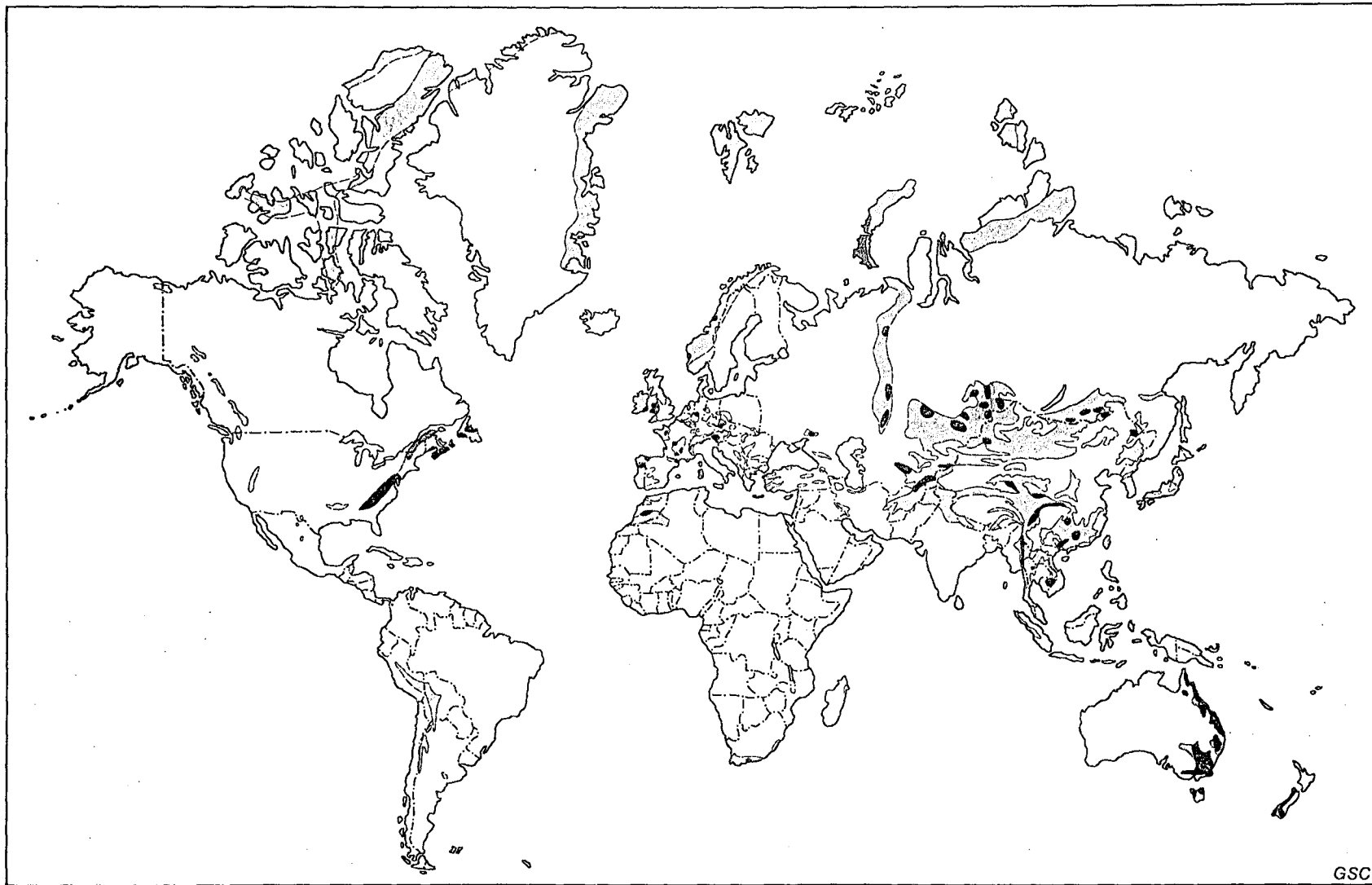
Zeegers, H. and Leduc, C. (1991). Geochemical Exploration for Gold in Temperate, Arid, Semi-arid and Rain-forest Terrains. 309-335. In: Foster, R.P., Ed., *Gold Metallogeny and Exploration*. Blackie, Glasgow, 432pp.





 Exposures of Precambrian shields and outliers
(includes minor cover rocks; also crystallines and
intrusives of uncertain, probably Precambrian age)


 Areas of primary gold deposits
and gold mines

APPENDIX I
(after Boyle, 1979)




 Exposures of Paleozoic rocks affected by Paleozoic orogenies (Caledonian, Hercynian, Variscan, etc.) (includes some Precambrian and younger rocks in places)


 Areas of primary gold deposits and gold mines


 Areas of primary gold occurrences (some contain commercial placers)

World distribution of primary gold deposits and occurrences of Paleozoic age.



 Exposures of Mesozoic and older rocks affected by Mesozoic orogenies (Nevadian, Palisade, Cimmerian, Laramide, Columbian, Yen Shanian, etc.) (includes some rocks affected by Cenozoic orogenies)

 Areas of primary gold deposits and gold mines

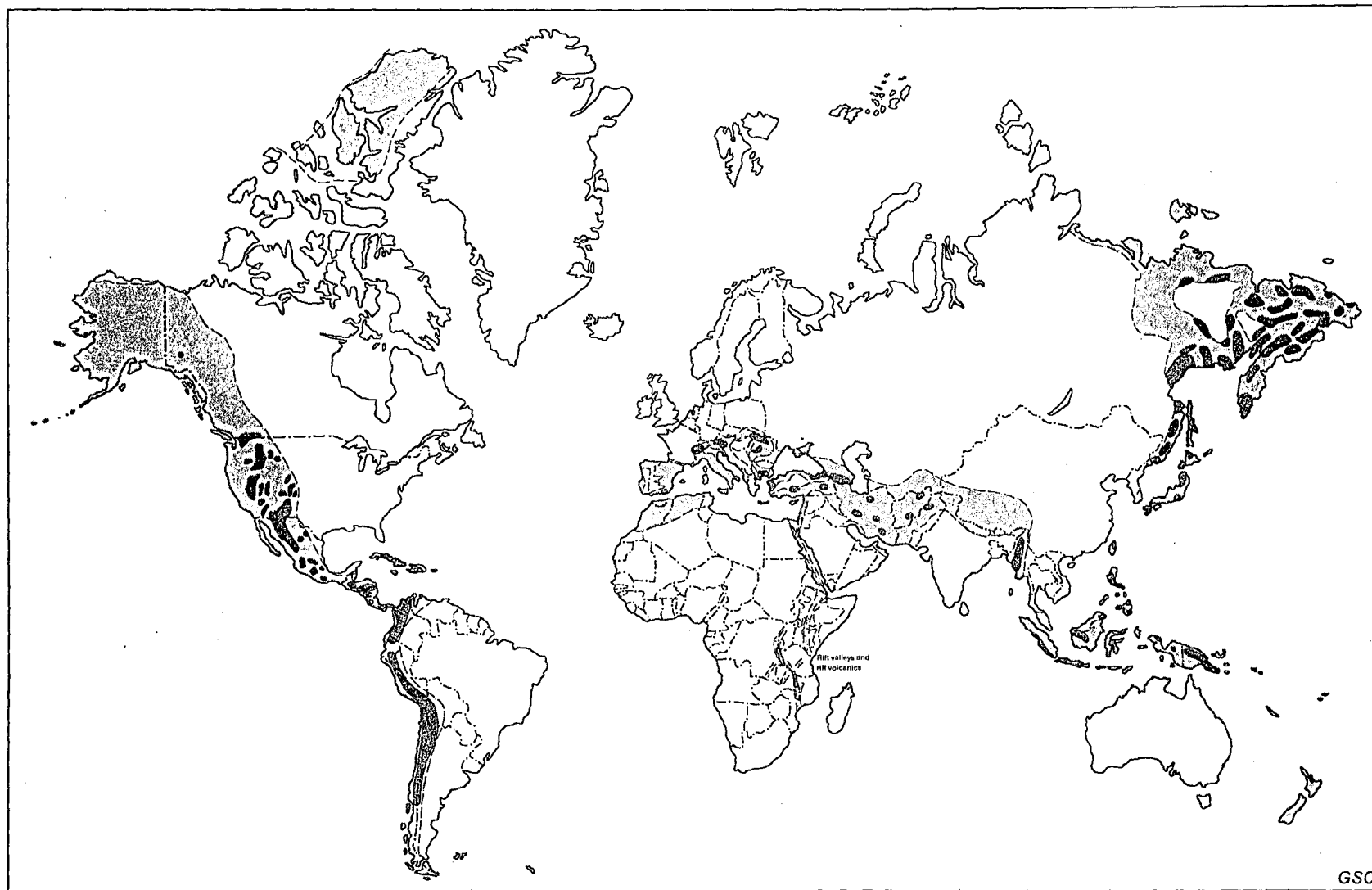
 Areas of primary gold occurrences (some contain commercial placers)

GSC


World distribution of primary gold deposits and occurrences of Mesozoic age.


(after Boyle, 1979)

APPENDIX I



GSC

 Exposures of Cenozoic and older rocks affected by Cenozoic orogenies (Alpine, Laramide, etc.)

 Areas of primary gold occurrences, deposits and gold mines

World distribution of primary gold deposits and occurrences of Cenozoic age (may include some deposits older than Tertiary).