AGSO Journal of Australian Geology & Geophysics, 17(4), 253–258

Archaean lode-gold deposits

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EXPLORATION MODEL

Examples

Golden Mile, Norseman, Sons of Gwalia, Mt Charlotte, Hill 50, Wiluna, Victory-Defiance, New Celebration, Jundee, Kanowna Belle, Bronzewing, (Australia); Hollinger-McIntyre, Dome, Hemlo (Canada)

Target

- Typical size: 0.5–1600 t Au.
- Most common size: 1–20 t Au.
- Grade: >1g/t (open cut); >5g/t (underground).
- Low Cu/Au; low–medium Ag/Au; low–medium Te/Au; rare high Sb/Au ratio.

Mining and treatment

- Deep surface weathering allows low-cost open-cut mining of otherwise uneconomic deposits.
- Mineralisation generally free milling, but can be refractory where gold is associated with fine-grained pyrite or arsenopyrite.
- Low Cu content allows optimum treatment of ore.

Regional geological criteria

- Generally hosted in greenstone part of Archaean granite–greenstone terrane, particularly in linear belts.
- Structurally late, syn- to post-peak metamorphic timing.
- In areas of sub-greenschist to granulite-facies metamorphism, although most significant deposits are in areas of greenschist facies.
- Diverse structural settings, but common near major regional shear zones in secondary faults and near hinge areas of gently plunging upright antiforms.

Local geological criteria

- Potentially in any host rock, but noticeably common in competent lithologies with high Fe/(Fe+Mg), such as BIF and granophyric gabbro.
- Sheared margins of competent lithologies, such as granitoid, feldspar-porphyry, or dolerite.
- Jogs or splays in brittle–ductile shear zones.
- Intersection of shear zone with favourable host rock (see above) or other structures.
- Competent rock unit in less-competent rock sequence; exact host depends on lithostratigraphy.

Mineralisation features

- Epigenetic, structurally controlled, late-tectonic.
- Quartz–carbonate gangue with typically 1–6% sulphide.
- Mineralisation may be present in veins and/or distinct wallrock alteration zones.
- Broad correlation between temperature of mineralisation and regional metamorphic facies.
- Pyrite (±arsenopyrite) main sulphide species at low metamorphic grades with pyrrhotite (±arsenopyrite) prominent at medium–high grades.

Alteration

- Zoned alteration halo 0.2–200 m wide; smaller, poorly zoned halos near high-T deposits.
- Alteration related to K_2O, S and CO_2 metasomatism
- Low-T deposits in mafic host: sericite–carbonate (proximal); chlorite–carbonate (distal).

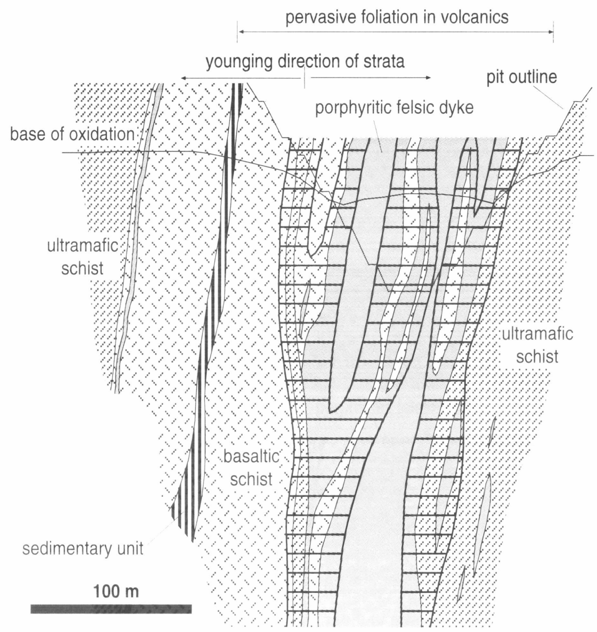

Figure 1. Hampton-Boulder (New Caledonia) deposit, cross-section 3440 mN. Alteration and mineralisation (hatched pattern) are hosted in a brittle–ductile shear zone (Boulder-Lefroy Fault) and localised near the margins of competent felsic dykes which intruded parallel to the shear, but predate Au mineralisation (modified from Vanderhor & Groves 1995)

- Medium-T deposits in mafic host: biotite–amphibole–plagioclase ± carbonate (proximal); biotite–chlorite–hornblende ± carbonate (distal).
- High-T deposit in mafic host: diopside–Kfeldspar–garnet–hornblende ± biotite.

Deposit geochemical criteria

- Subtle distal $K–CO_2$ metasomatism can be explored using alteration indices (3K/Al; CO_2/Ca; CO_2/Ca+Mg+Fe) and trace-element distribution.
- Trace elements include Ag, As, B, Bi, Mo, Pb, Sb, Te, W.
- S isotopes –5.7 to 5.0‰ (Yilgarn Craton).
- C isotopes –8.1 to –2.7‰ (Yilgarn Craton).
- Pb isotopes (zircon) give ages of ca. 2630–2600 Ma in the Yilgarn Craton.
- Typically, very low base-metal content, but some unusual deposits (e.g. Boddington—Cu, Mt Gibson—Cu, Zn, Pb) contain anomalous base-metal contents.

Surficial geochemical criteria

- Exploration relies heavily on geochemical methods because of widespread deep weathering profiles (20–100 m deep) and the presence of lateritic horizons in the Yilgarn.
- Depletion of Au in soil profile is common to up to 40 m depth, but redox fronts and in-situ lateritic horizons can retain the mineralisation signature.
- Soil, rock-chip, and regolith geochemistry surveys are the most widely used regional exploration tools.
- Au, As, Bi, Sb, Pb, W and Mo are the main pathfinder elements.

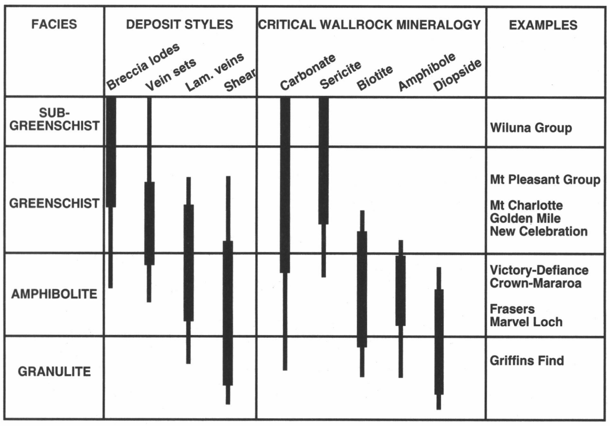

Figure 2. Variation of deposit style, critical wall-rock alteration assemblages, and examples of lode-Au deposits at metamorphic conditions ranging from sub-greenschist facies, near surface (<1 km depth) deposits to granulite facies, lower crustal (approx. 25 km depth) mineralisation (modified from Groves et al. 1992).

Fluid chemistry and source

- Low–to moderate salinity.
- Near neutral fluids: H_2O–CO_2 ± CH_4.
- XCO_2 = 0.1–0.2.
- T = 200–740°C; P = 0.5–5 kbar.
- Reduced to slightly oxidised primary fluids; late-stage fluids can be highly oxidised (e.g. Lawlers).
- Au generally transported as bisulphide complex; chloride complexes may be important for higher T deposits.
- Au precipitation due to one or more of desulphidation (reaction with Fe-rich host rock), phase separation, or fluid mixing.
- Metamorphic or magmatic origin postulated for hydrothermal fluids and Au. Isotopic data indicate deep crustal source for primary ore fluid, although the fluid has been modified by the wallrocks in hydrothermal conduits, and there is evidence of mixing with surface waters at high crustal levels.
- Magmatic fluids may be important for higher T deposits.

Geophysical criteria

- Orebodies normally have very weak (or absent) geophysical signature.
- Geophysical techniques mainly used to define host rocks and structural targets under cover.
- Airborne and ground magnetics most widely used geophysical exploration techniques.

Comments on genesis

- Archaean lode-gold deposits occur in a broad range of structural settings, and at different crustal levels, but they share a similarity in ore fluid characteristics and a relatively late-orogenic timing of mineralisation, which occurs after the main phases of regional thrusting and folding and after, or late-syn, peak metamorphism. Many deposits are related to the reactivation of earlier structures.

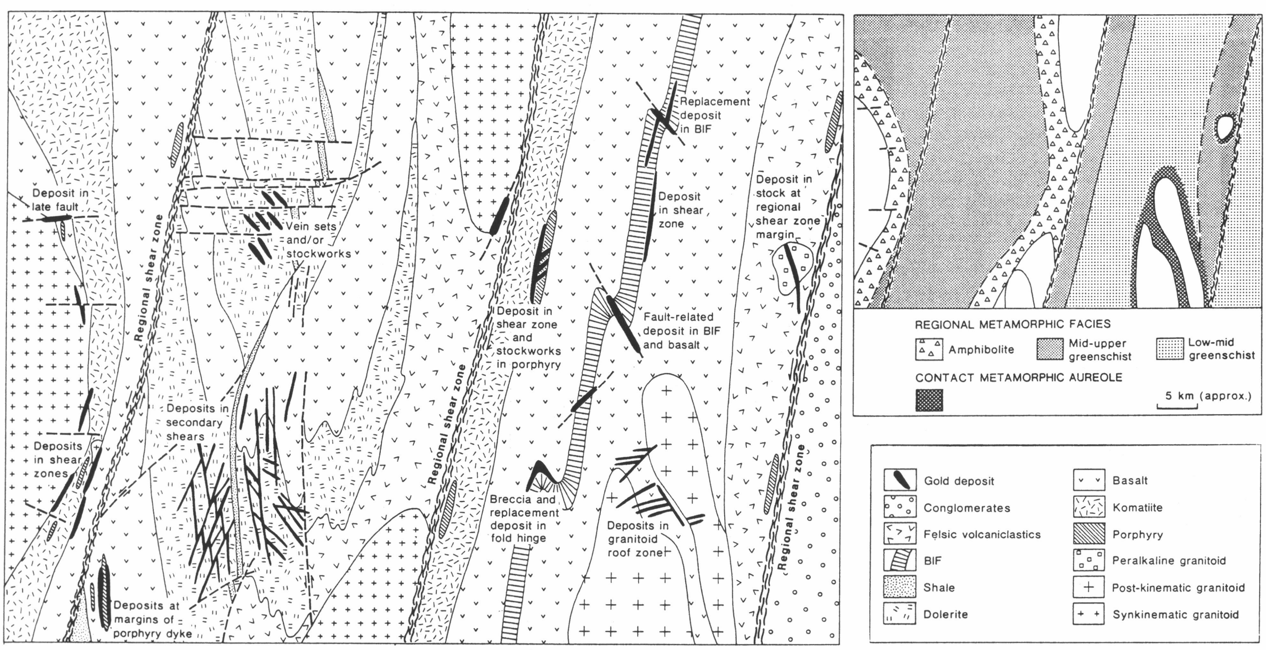

Figure 3. Schematic representation of the nature of Archaean lode-Au mineralisation, illustrating variable structural styles, host rocks and metamorphic settings (from Groves et al. 1990).

Introduction

Archaean lode-Au deposits are sited in the greenstone belts of all Archaean shield areas, and account for almost 20% of cumulative world Au production (Roberts, 1987). In Australia, this style of mineralisation is the single most important source of Au, with annual production in 1994 close to 180 t from approximately 100 mines. The majority of Australian deposits are located in the Yilgarn Craton of Western Australia. However, a small but significant number of deposits also occur in the Pilbara Craton and in small Archaean outliers between the Yilgarn and Pilbara Cratons. Given the focus of mining (and exploration) on the Yilgarn Craton, much of the following discussion is biased to lode-Au mineralisation in that craton. However, references are made to other areas where appropriate.

Size and grade

The giant Golden Mile deposit at Kalgoorlie in the Norseman–Wiluna Belt of the Yilgarn Craton is the best-known Archaean lode-Au deposit in Australia. The deposit has an estimated content (mined and resources) of 1600 t Au, making it one of the largest Au deposits in the world. The size of the Golden Mile, however, is somewhat anomalous in the Australian context, and the average Au content of currently mined Western Australian Archaean lode-Au deposits is approximately 2 t (Vanderhor & Groves 1995).

Since the first discovery of Au hosted by Archaean rocks in the late 19th century, the average grade of the deposits has fallen steadily, from more than 40 g/t in the 1890s to less than 5 g/t Au in 1988 (Groves et al. 1990). Current major underground mines typically have head grades of 4–9 g/t, with the noticeable exception of the Mt Charlotte mine at Kalgoorlie, which operates economically at an average head grade of 2.7 g/t Au. The majority of near-surface deposits that can be exploited by open-cut mining have grades below 5 g/t Au and the economic cut-off may be as low as 0.5 g/t in strongly oxidised surface material.

Classification and general characteristics

As a direct result of the surge in Au exploration in the 1980s, the understanding of Archaean lode-Au deposits has increased dramatically in the last decade. The Archaean lode-Au style of mineralisation has traditionally been associated with Au-only, brittle–ductile shear-related 'mesothermal' deposits that formed at mid-crustal levels, typically at greenschist-facies metamorphic conditions (e.g. Groves et al. 1989). Although correct for the majority of lode-Au deposits, recent studies (e.g. Hagemann et al. 1992, Knight et al. 1993, Neumayr et al. 1993, Bloem et al. 1994) have described an increasing number of deposits from a wider range of crustal conditions, varying from sub-greenschist to granulite facies. Less commonly, Au deposits have been described with genetic affinities to other styles of mineralisation, such as volcanic-hosted massive sulphide (VHMS) deposits and porphyry deposits.

Based on Canadian examples, Robert (1996) recognised two broad groups of deposits, based on the composition of their ore: Ag-rich deposits, in which the concentration of Ag exceeds that of Au, and Au-rich deposits, in which the concentration of Au exceeds that of Ag. Ag-rich deposits are further subdivided into three styles of mineralisation which can be regarded as auriferous end-members of other deposit types: VHMS, Cu–Ag–Au veins, and porphyry deposits (Robert 1996). All these three styles are generally rich in sulphides, particularly chalcopyrite, which further sets them apart from the typically Cu-poor Au-rich (or Au-only) deposits, which Robert (1996) subdivided into two styles: quartz–carbonate veins and disseminated–replacement deposits.

The Ag-rich styles of mineralisation are rare among the known Australian Archaean lode-Au deposits. The Boddington deposit in the SW Yilgarn is possibly an Australian example of a porphyry-style Ag-rich deposit (Roth et al. 1990), but a post-deformational timing has been suggested (Allibone et al. 1996). Golden Grove and Mount Gibson in the Murchison Province of the Yilgarn Craton are the only known significant Australian Archaean Au-rich VHMS deposits. However, textural studies at Mount Gibson (Yeats & Groves 1998) have shown that the majority of the Au was introduced late in the tectonic history of the greenstone belt and that the syngenetic massive sulphides only provided a rheologically favourable horizon for later Au deposition.

The vast majority of known Australian Archaean lode-Au deposits fall into the category of quartz–carbonate vein-style Au-rich deposits and, consequently, much of the following discussion relates to this group. In the Yilgarn Craton, the deposits are interpreted to represent a coherent genetic group deposited late in the tectonic and structural history of the craton under metamorphic conditions which range from sub-greenschist to granulite facies (Groves et al. 1995). The deposits are structurally controlled and generally occur in or adjacent to late or reactivated structures. They are consistently enriched in Au, Ag, As, and W, variably enriched in Bi, Sb, Te, and B and, typically, only slightly enriched (if at all) in Cu, Pb and Zn (Perring et al. 1991). Lateral zonation of hydrothermal alteration is characteristically present on the scale of centimetres to tens of metres. However, vertical zonation, where recognised, is normally more subtle and on a scale of hundreds of metres (e.g. Mikucki et al. 1990). In addition, as determined from fluid-inclusion studies, a low-salinity, H_2O–CO_2 ± CH_4 fluid is important at most of these deposits. Although H_2O:CO_2:CH_4 ratios are variable for different deposits, most have a calculated XCO_2 of 0.1–0.2 before phase separation or mixing with other fluids (cf. Groves et al. 1992). Alteration assemblages vary in mineralogy with host rock and metamorphic setting, but enrichment in CO_2, S and K(±Na), plus the ore metals, is characteristic.

Structural setting and timing

There is a gross relationship between the location of Archaean lode-Au deposits and crustal-scale deformation zones in the Yilgarn Craton. A similar relationship has been noted in the Superior Province of Canada, where lode-Au mineralisation is associated with the so-called 'breaks' (Robert 1990). Despite this large-scale association, Au mineralisation is rarely hosted in first-order structures, and deposits are instead hosted in second and lower order structures, which may or may not show a direct geometric relationship to the large-scale deformation zones (e.g. Eisenlohr et al. 1987, Witt 1993). The general lack of mineralisation within the major structures suggests that, if the structures are interlinked and the major structures acted as fluid conduits, they did so at deeper crustal levels than those currently exposed in most Au deposits.

The structural styles of individual Au deposits broadly reflect the metamorphic conditions under which they formed. At low metamorphic grades, brittle tensional quartz veins and breccias dominate (e.g. Wiluna: Hagemann et al. 1992). These give way to brittle–ductile laminated quartz veins at mid to upper greenschist-facies conditions (e.g. Kalgoorlie: Phillips 1986) and ductile shear-zone-hosted mineralisation at amphibolite and granulite-facies conditions (e.g. Southern Cross: Bloem et al. 1994). Au mineralisation occurs syn- to post-peak regional metamorphism and is synchronous with major fault or shear-zone movement. Importantly, however, it is commonly associated with the last significant movement on these structures (Groves et al. 1995), meaning that the geometry of the host sequences has not changed significantly since the time of mineralisation.

The majority of published geochronological data for the Yilgarn (summarised in Yeats & McNaughton 1997) is consistent with ~2640–2630 Ma Au mineralisation. Several studies, however, suggest that Au may have been introduced at other times. Yeats & McNaughton (1997) presented new data for the Jundee and Mount McClure deposits in the Yandal greenstone belt, which require Au mineralisation to have occurred prior to ~2660

Ma. Mueller et al. (1996) dated the main Au mineralising event at Big Bell in the Murchison Province at 2662±5 Ma, using U–Pb in garnet thought to have formed during Au mineralisation, and a later, secondary event (±Au) has been dated at 2614±2 Ma, using titanite. However, the structural timing of mineralisation at the Big Bell Au deposit remains controversial and the textural relationship between the minerals used for the geochronology and the Au mineralisation is equivocal. At Lawlers, a SHRIMP U–Pb titanite study by Fletcher et al. (submitted) has dated the later of two Au mineralising events at 2592±9 Ma, distinctly younger than any other mineralisation reliably dated elsewhere in the Yilgarn. A number of ^{39}Ar–^{40}Ar plateau ages for hydrothermal muscovite from the eastern part of the craton also give younger ages for Au mineralisation. However, given the uncertain cooling history of the Yilgarn, the validity of this method remains a matter of debate. Nevertheless, clear evidence is emerging that lode-Au mineralisation occurred in the Yilgarn Craton at times other than ~2640–2630 Ma. At this early stage of research, pre- and post- ~2640–2630 Ma mineralisation appears to be much less widespread than the main event. However, further work is needed to confirm this.

At Mount York in the Pilbara Craton, Neumayr et al. (1993) recorded similar general structural and relative temporal relationships to those observed for lode-Au mineralisation in the Yilgarn. However, no research has been done on the absolute timing of Au mineralisation in the Pilbara.

Host rocks

Any lithology may host lode-Au mineralisation within an individual greenstone sequence, but spatial analysis of Au mineralisation on a district or craton scale reveals that specific rock types are preferential hosts (Groves et al. 1990). Two factors are considered to be important in the mineralising process. The rheological properties of the host rock may physically localise fluid flow, with relatively brittle lithologies more prone to fracturing and veining and, consequently, mineralisation. The chemical properties of the rock may also play an important role. For example, Fe-rich rocks and/or rocks with a high Fe/Fe+Mg ratio are capable of destabilising Au bisulphide complexes, causing the formation of Fe sulphides and coprecipitation of Au. Not surprisingly, the contribution to total Au production from deposits in relatively Fe-rich mafic volcanic and intrusive rocks is by far the most significant in the Yilgarn Craton, although this figure is strongly influenced by the giant mafic-hosted deposits at Kalgoorlie and, to a lesser extent, Kambalda. In these districts, granophyric zones in thick layered gabbroic intrusions combine a high degree of competency with a high Fe/Fe+Mg, providing a physically and chemically ideal site for Au mineralisation. BIF and other Fe-rich sedimentary units are also relatively important contributors as host rocks (e.g. the Hill 50 deposit at Mount Magnet), particularly when their low overall abundance in greenstone belts is taken into account.

In contrast to the Yilgarn Craton, sedimentary and ultramafic rocks are the major hosts to known Au mineralisation in the Pilbara Craton (Groves et al. 1990). However, as stated earlier, Au mineralisation in the Pilbara is minor, when compared to that in the Yilgarn Craton.

Wallrock alteration

Wallrock alteration associated with Archaean lode-Au mineralisation, as stated above, varies according to host rock and metamorphic grade. However, mineral assemblages indicative of carbonation, K±Na metasomatism and sulphidation are common across a broad range of metamorphic conditions, ranging from sub-greenschist to granulite facies.

In lode-Au deposits in sub-amphibolite-facies domains, laterally zoned alteration assemblages may be split into chlorite–muscovite and biotite–muscovite stable sequences, broadly reflecting formation at the chlorite and biotite subzones of the greenschist facies, respectively (Mikucki et al. 1990). In tholeiitic mafic rocks (by far the dominant hosts to Au mineralisation), chlorite–muscovite stable alteration is typically characterised by distal chloritic alteration which grades into proximal carbonate (ankerite ± siderite)–sericite–pyrite ± pyrrhotite alteration adjacent to mineralisation. Alteration patterns in mafic-hosted biotite–muscovite stable alteration zones broadly parallel those in the lower temperature types, with the notable differences that up to 40% biotite may be developed in intermediate alteration zones (cf. Phillips & Groves 1984, Clark et al. 1989) and that sericite is much less extensively developed. Deposits which are hosted in ultramafic, intermediate, felsic or metasedimentary rocks show alteration assemblages that reflect the same chemical changes as those noted for the mafic-hosted examples. However, mineral species and absolute abundances reflect the nature of the host rock. For example, highly magnesian phases, such as talc and tremolite, are commonly present in alteration assemblages in ultramafic rocks (Mikucki et al. 1990).

Lode-Au deposits hosted in amphibolite and granulite-facies domains exhibit wall-rock alteration assemblages which are geochemically consistent with those in lower metamorphic grade deposits, although alteration is less extensive and lateral zonation is generally poorly developed or absent. Carbonate species are not major alteration minerals under these conditions, reflecting the instability of ankerite–quartz-bearing assemblages at higher temperatures and pressures (Ridley & Barnicoat 1990). In the Southern Cross greenstone belt, mafic-hosted Au mineralisation in an amphibolite-facies domain is associated with quartz–pyrite–pyrrhotite ± plagioclase veins with diopside–calcite or fibrous tremolite ± chlorite rims, which are surrounded by biotite–pyrrhotite ± amphibole ± chlorite alteration haloes, several centimetres wide, in the wall rock (Bloem et al. 1994). The deposits of the Coolgardie Goldfield display similar alteration assemblages, with the addition of garnet (Knight et al. 1993). Au mineralisation in a granulite-facies domain at Griffins Find is associated with a quartz–diopside–microcline–pyrrhotite–arsenopyrite-loellengite assemblage (Barnicoat et al. 1991), again reflecting similar chemical changes to those seen at lower metamorphic grades.

Exploration strategies

Exploration for Archaean lode-Au deposits relies heavily on geochemical methods in Western Australia (in particular the Yilgarn Craton), owing to widespread deep weathering (generally 20–100 m deep) and the presence of surficial laterite. Lode-Au mineralisation generally has a poor geophysical signature. Airborne and ground magnetics have been used extensively as a mapping tool, to define exploration targets such as Fe-rich host rocks and favourable structures by designating areas of prospective geology beneath residual or transported cover. In addition, at some localities, there may be positive magnetic anomalies associated with Au mineralisation (owing to the presence of magnetite as an alteration phase), or negative anomalies due to sulphidation of primary magnetite in strongly magnetic host rocks (e.g. BIF).

Soil, rock-chip, and regolith geochemistry are the most widely used regional exploration tools, followed by shallow RAB drilling of surface targets (cf. AMF 1995). In areas overlain by transported regolith, exploration may proceed directly from regional magnetic target generation to RAB drilling. Au itself, analysed to low (ppb) levels, is generally the most effective pathfinder element. However, As, Bi, Sb, W and Mo have also been utilised in exploration. Au is commonly depleted within the saprolitic profile up to 40 m depth, but both in-situ and transported lateritic material may retain the signature of primary mineralisation (Butt et al. 1993, Lawrance 1993). Consequently, an understanding of regolith evolution and chemistry is of vital importance to lode-Au exploration in Western Australia. More sophisticated geochemical techniques, such as the mobile metal ion (MMI) method (cf. Mann et al. 1993), are beginning to be applied to Au exploration, but their effectiveness is yet to be proven.

The late tectonic timing of Archaean lode-Au mineralisation allows the possibility of geomechanical modelling (or 'stress mapping') as a targeting tool in camp-scale lode-Au exploration. Au mineralisation is associated with areas of high fluid flow, which is focussed in areas of low mean stress (Ridley 1993). Geomechanical modelling at Kalgoorlie (Holyland 1990), Granny Smith (Ojala et al. 1993) and Coolgardie (Knight et al. 1993) has illustrated a good correlation between known lode-Au mineralisation and modelled areas of low mean stress. This method could be used to define drill targets in camps where the basement geology is well understood.

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Received 5 November 1996; accepted 11 June 1998