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Crustal-scale shear zones and their significance to Archaean gold mineralization in Western Australia

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Abstract. Many large Archaean epigenetic gold deposits show a broad spatial relationship to regional lineaments in greenstone belts, although in detail they are sited in subsidiary brittle-ductile fault structures. Fluids, originating from a deep source, follow a complex path and re-equilibrate with different lithologies and with metamorphic fluid during migration to higher crustal levels. Temperature and pressure conditions at or below the amphibolite/greenschist metamorphic boundary, where most gold deposits are located, favour the establishment of brittle-ductile and brittle subsidiary structures, the preferred structural setting of gold deposits. Physical gradients between the regional ductile structures and more brittle subsidiary structures ensure transient, strongly localized, fluid flow into the latter, where lower temperatures and suitable host rocks with high Fe/(Fe + Mg) ratios favour gold-deposition. The multi-source origin and continuous re-equilibration of the fluid with crustal rock, which includes granitoid and greenstone-belt lithologies of different ages, is reflected in the diverse isotopic and geochemical signature of the gold deposits.

Distribution of gold deposits

Archaean gold deposits in the Western Australian Shield, as in other cratons, are heterogeneously distributed, with both poorly and well mineralized greenstone belts occurring in individual cratons (Groves and Batt 1984, Groves et al. 1987). At the broadest scale, the best-mineralized terranes are markedly linear greenstone belts (Figs. 1 and 2), whose structure is dominated by regional (> 100 km long) lineaments (e.g. Norseman-Wiluna Belt, West Australian Shield; Abitibi Belt, Canadian Shield). Recent work in both Western Australia and Canada indicates that these regional lineaments are the traces of ancient fault systems (Eisenlohr 1987; Mueller and Harris 1987; Partington 1987a; Hodgson 1986; Kerrich 1986a).

On a greenstone-scale, many of the largest Archaean gold deposits are spatially related to the regional lineaments (referred to as first-order structures), although in detail they are sited in subsidiary brittle-ductile and brittle faults (second-order structures) with generally < 10 km strike length that commonly splay off, or are associated with, the regional structures (Figs. 3 and 4; e.g. Hodgson 1986, Kerrich 1986a); several papers describing such relationships are presented in Macdonald (1986) and Ho and Groves (1987).

The controls on preferential gold concentration in linear greenstone belts, particularly in Western Australia, have been addressed by Groves and Batt (1984) and Groves and Phillips (1987) and are not repeated. The objects of this paper are to examine the reasons for the structural distribution of Archaean gold deposits in these linear belts, and, in particular, to consider why it is the second-order structures that are mineralized: this question has not been addressed in the literature. In addition, the paper examines the implications of such structural controls and discusses the constraints that structures of different scales impose on source regions for auriferous fluids and ore components.

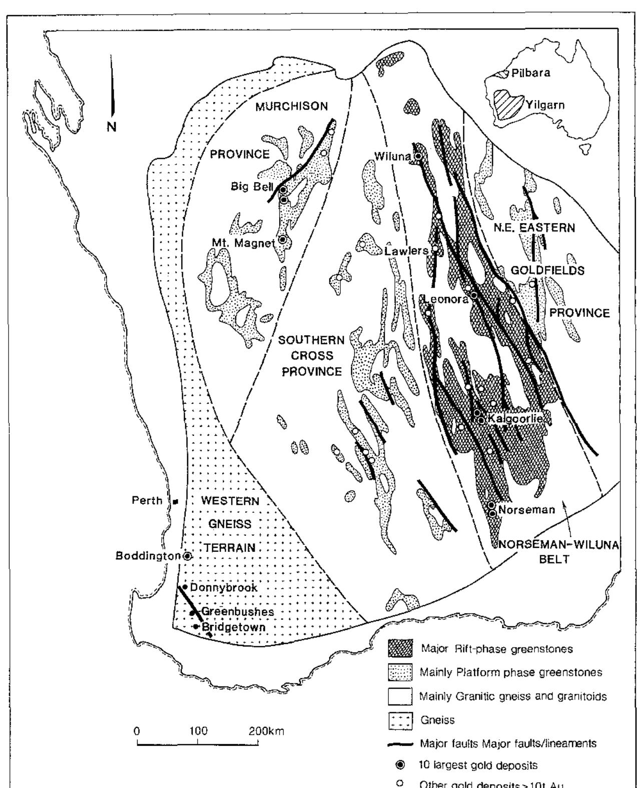

Fig. 1. Regional map of the Yilgarn Block showing types of greenstone belt, lineaments, and locations of major gold deposits (modified from Groves et al. 1987)

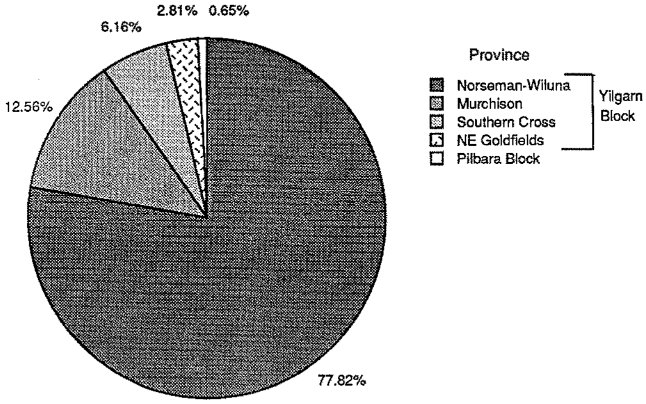

Fig. 2. Relative contributions of gold from the greenstone belts in the Yilgarn Block and the Pilbara Block. Production and reserves from the West Australian Archaean (total to 1983 = 2365 tonnes)

First-order structures

In the poorly-exposed terranes of Western Australia, large gold deposits are spatially associated with regional lineaments which are largely defined by photo-lineaments and aeromagnetic anomalies. In many cases, the lineaments cut across the greenstone stratigraphy, but they may also be localized along stratigraphic contacts (Skwarnecki 1987). Where exposed, the lineaments comprise highly sheared rocks with structures that suggest ductile non-coaxial deformation. In the Yilgarn Block, the Waroonga Shear, segments of the Mt Keith-Kilkenny Tectonic Zone and the Donnybrook-Bridgetown Shear are shear zones between 1–15 km wide that are characterized by vertical S-C fabrics at their margins, C-C′ fabrics in their centres and a subhorizontal stretching lineation. The subvertical foliation and subhorizontal stretching lineation of the first-order shear zones are indicative of strike-slip movements during the late-stage history of the terrane. Strike-slip movement has also been described from other Archaean terranes such as the Abitibi Belt, Canada (Hubert et al. 1986) and the Ikertôq shear belt, western Greenland (Grocott 1977).

The >100 km strike length of the lineaments and their apparent control on the distribution of deep crustal or upper mantle felsic magmas (porphyries) and mantle-derived lamprophyres (McNeil and Kerrich 1986; Perring et al. 1987), together with regional carbonation zones dominated by juvenile (mantle-derived) carbon (Golding et al. 1987; Groves et al. 1988), all suggest that they are transcrustal structures extending into the lower crust and mantle: at least some appear to be reactivated synvolcanic faults (Groves and Batt 1984). The nature of the lineaments at depths below those usually exposed in the greenstone-granitoid terranes can be gauged from observations of the Donnybrook-Bridgetown Shear, which is of approximately the same age (ca. 2.6 Ma, Partington 1987b) but located in the higher-grade metamorphic rocks of the Western Gneiss Terrain in the south-western Yilgarn Block (Fig. 1). The shear zone is a ductile structure intruded by synkinematic granitoids and rare-metal pegmatites, and contains rocks of higher metamorphic grade than the surrounding, lower-strain terrane (Partington 1987b). Modern lineaments of a similar scale, such as the active strike-slip systems in California (San Andreas fault system) and New Zealand (Alpine fault system), are deep-seated structures which separate continental plates.

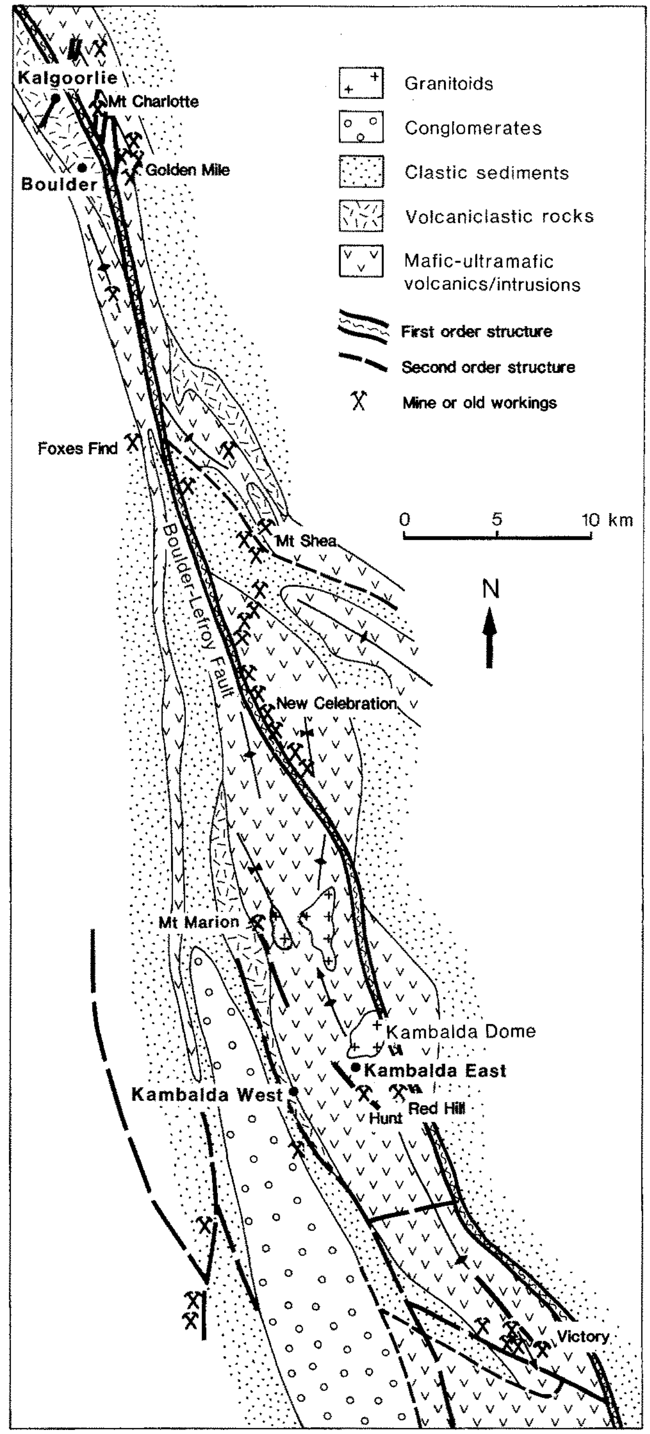

Fig. 3. Sketch map of Kalgoorlie-Kambalda area showing the location of major gold deposits in relation to first-order structures and second-order structures (see fig. 1 for location) (compiled from various sources)

The nature of the basement to the greenstone belts is also of importance to the form of the shear/fault zones at depth. Geological studies have indicated the presence of sialic basement in the Norseman-Wiluna Belt (Archibald et al. 1978; Gee et al. 1981). This has been recently confirmed by the discovery of ca. 3.4 Ga xenocrystic zircons, equivalent in age to some rocks in the Western Gneiss Terrain, in ca 2.7 Ga basalts at Kambalda in the centre of the belt (Compston et

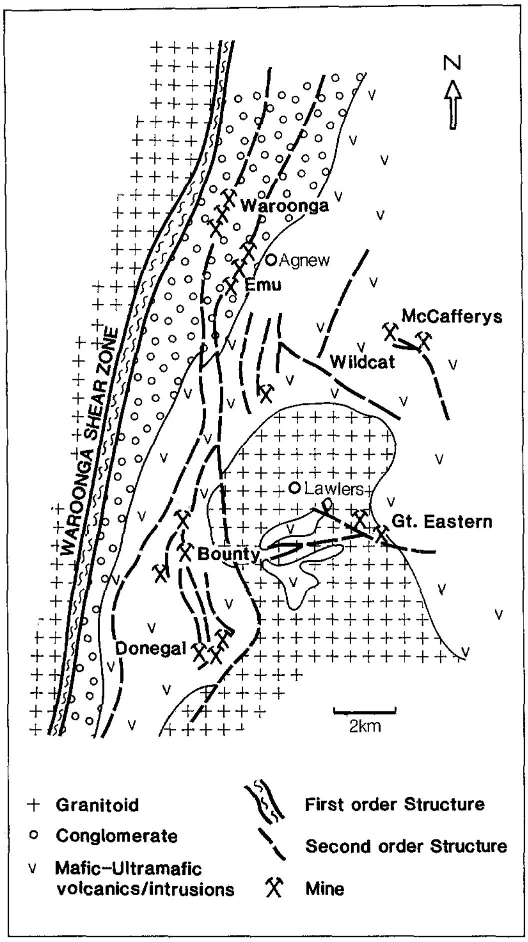

Fig. 4. Sketch map of Lawlers area showing the location of major gold deposits in relation to first-order structures and second-order structures (see fig. 1 for location)

al. 1986), and by indications of crustal contamination from basalt geochemistry (Barley 1986). Nowhere, however, has this crust been unequivocally identified at surface.

The movements on these fault/shear zones, which are associated with gold mineralization in the Norseman-Wiluna Belt, occurred late in greenstone-belt evolution (Gee et al. 1981), broadly coincident with regional metamorphism, synkinematic granitoid emplacement (Skwarnecki 1987) and intrusion of felsic porphyries (Mueller and Harris 1987).

Second-order structures

Gold deposits in the Norseman-Wiluna Belt commonly occur in fault structures with lengths of 1 to 10 km and widths of centimetres to hundreds of metres. The form of these deposits varies considerably, depending on the detailed structural setting and host rock. Second-order structures may form as brittle-ductile faults, with the same sense of movement as the first-order structures (synthetic faults), or opposite movement directions, i.e. antithetic faults. Normal faults, and brittle quartz-vein arrays commonly strike at right angles to the extensional direction, and, in the case of reverse faults, the compressive direction. There is growing evidence that these structures reflect the regional stress orientations, and are subsidiary to the larger first-order structures. Ho (1984), for example, showed in the Kanowna area that mineralization in both steeply-dipping shear zones (Lost Chance) and in steeply-dipping laminated quartz reefs (Kanowna Main Reef) was geometrically related, and Boulter et al. (1987) show that several shear-zone and tensional-fracture orientations in the Golden Mile can be explained in terms of a single stress field. More recently, this has been demonstrated, both on a gold 'camp' (e.g. Kalgorlie; Mueller and Harris 1987) and more regional scale (Eisenlohr 1987; Partington 1987a). Correlation between vein formation and the regional stress field has also been described for the Sigma Mine in the Abitibi Belt, Canada (Robert and Brown 1986).

Host-rock lithology provides constraints on both the mechanical behaviour of the rocks during deformation, with more competent units fracturing more readily, and chemical control, with more iron-rich (more precisely high $Fe/[Fe+Mg]$) units being generally more favoured (Phillips and Groves 1983; Neall 1987; Wall 1987). Four types of deposits have been identified using the mineralized structure as the main criteria (Groves and Phillips 1987); these are: i) alteration haloes associated with near-vertical, brittle-ductile shear zones (e.g. Golden Mile, Sons of Gwalia, Harbour Lights), ii) laminated quartz veins in shear or fault zones (e.g. Norseman deposits), iii) brittle quartz-vein sets and surrounding alteration (e.g. Mt Charlotte, Paddington) adjacent to fault or shear zones, and iv) breccia ores in or adjacent to shallowly dipping faults or shear zones (e.g. Oroya Shoot, Kalgoorlie). More than one style may be present in a single mine/deposit. Where a stratigraphic succession has been well established (e.g. Kalgoorlie-Kambalda area), there is also a tendency for large gold deposits to be located towards the top of the volcanic-dominated part of the succession, near the contact with overlying volcaniclastic and clastic sedimentary sequences. This may reflect the tendency for most large gold deposits to be in sub-amphibolite facies metamorphic domains, the distribution of which grossly mirrors volcanic stratigraphy away from the greenstone belt margins (Binns et al. 1976). However, it may also reflect the regional change in the physical properties of the lithological sequence, with thick, massive, relatively isotropic, low tensile-strength (competent) volcanic sequences contrasting with thinner, more anisotropic, relatively ductile sedimentary sequences. This is almost certainly accentuated by the common occurrence of thick mafic sills intruded at or adjacent to this regional contact.

At the broadest scale, the geometrical relationships, combined with evidence for movement senses, suggest that the craton-scale ductile shear zones and associated secondary structures, at least in the Norseman-Wiluna Belt, are components of a regional shear system that varies from oblique-slip to strike-slip in character (Eisenlohr 1987, Mueller and Harris 1987; Partington 1987a). Locally, there appears to be interaction between these strike-slip shear systems (subhorizontal movement) and synchronous, synkinematic granitoid emplacement (subvertical movement) with gold deposits sited in zones with oblique movement between the two end-member structural domains (e.g. Leonora area; Skwarnecki 1987). In other cases, gold deposits occur in structures that are geometrically related to the major shear systems, but where late, largely vertical, normal movement has controlled gold depositional sites (e.g. Lawlers-Agnew area; Eisenlohr 1987; Partington 1987a), or where late reverse faulting is important in the control of late, breccia-style gold deposits (e.g. Oroya Shoot). Furthermore, at Kalgoorlie, gold deposits occur in structures interpreted to be related to both sinistral and dextral movement on major shears (Mueller and Harris 1987). Thus, although gold-hosting structures appear to be related on a gross scale to strike-slip shear systems, there are few deposits hosted in structures that are *purely* strike-slip. This appears to reflect not only the complex, long-lived nature of the shear systems but also the longevity of gold mineralization event(s) which show variable timing with respect to the peak of metamorphism, with many major deposits being retrograde with respect to peak metamorphism (e.g. Phillips 1986; Clark et al. 1986; Skwarnecki 1987), whereas some are overprinted by it (Golding and Wilson 1982; Phillips 1985).

Factors controlling siting of gold deposits

From a tectonic viewpoint, greenstone belts such as the Norseman-Wiluna Belt can be regarded as low-strain, low to medium metamorphic-grade domains with largely brittle, more rarely brittle-ductile, structures cut by transcrustal, high-strain, ductile to brittle-ductile shear zones: many of these zones, particularly those adjacent to synkinematic granitoids, are medium-high metamorphic-grade domains (Binns et al. 1976). On the greenstone-province scale, it might be expected that the first-order shear zones would be the domains of greatest fluid flow and highest fluid/rock ratios, yet they are largely unmineralized, whereas it is the second-order, but genetically-related, structures that host the major gold deposits. There appear to be two possibilities for this relationship, and both have genetic and exploration significance: i) there are physicochemical gradients between the first- and second-order structures which caused migration (infiltration) of fluid and/or selective transport (diffusion) of gold within fluids into second-order structures, or ii) the gold source was largely within greenstone belts (metamorphic model of Groves and Phillips 1987; Viljoen 1984), and was tapped by second-order faults/shears, whereas first-order shears primarily tapped a mantle and deep crustal source, as indicated by the coincidence of mantle-derived carbonation, porphyries and lamprophyres along them.

If i) is correct, the extent of the fault structure does not constrain fluid source, and metamorphic (see references above and references in Kerrich 1986a), magmatic (Burrows et al. 1986), or mantle (Golding et al. 1987) models can all be satisfied by observed structural control. On the other hand, if ii) is correct then the observed structural controls on gold deposits should favour the metamorphic model (cf. Groves and Phillips 1987) or models that invoke granitoid volatile phases (Viljoen 1984). Possibility ii) is virtually untestable, because there is no distinctive isotopic or geochemical signature of Au that can reveal its source, and accompanying Pb, which does have distinctive isotopic signatures, may not have precisely the same source or may have multiple sources (Dahl et al. 1987; Kerrich 1986b). Thus, it is important to examine possibility i) in the light of available, albeit reconnaissance, knowledge on the structural regimes hosting gold deposits. No only should this shed light on the major factors, other than host rocks, controlling siting of gold deposits, but it should also indicate fruitful areas of future research on shear-zone systems in major gold provinces.

If auriferous fluids were initially focussed in first-order structures, then their lack of gold deposits must relate both to physical gradients, which allow fluid flow into second-order structures, and pressure-temperature conditions that favour gold deposition in those structures. It is, therefore, pertinent to examine the nature of fluid flow in shear zones and faults under contrasting conditions of temperature and fluid pressure.

Ductile to brittle deformation and fluid flow

Large crustal-scale shear zones, such as those in the Yilgarn Block, deform dominantly by ductile processes as described by Mitra (1978). During ductile deformation, strain is taken up over a zone, and the process is continuous and aseismic. Evidence from both active and ancient shear-zone systems indicates that they are regions of high fluid flow. On the basis of isotopic criteria, Kerrich et al. (1984) and Kerrich (1986b) demonstrated fluid infiltration into shear zones at deep crustal levels. Examples of the importance of channelled fluids, even in deep crustal levels, include the occurrence of hydrothermally altered upper-mantle spinel lherzolites, altered by fluid phases preferentially localized in shear zones (Briqueu and Cabane 1987), and the eclogitization of lower crustal granulites, similarly attributed to fluid migration through shear zones (Austrheim 1987). Fluid movement within shear zones is heterogenous and localized as shown by the provincial character of metasomatic effects (McCaig 1984), and by detailed isotopic and microprobe investigations of Hickman and Glassley (1984) in West Greenland. Their work suggests an uneven distribution of fluid pathways within shear zones during deformation, and a strong preferred direction of fluid flow parallel to vertical lithologic boundaries and structures.

Shear zones are also zones of higher temperature than immediately surrounding rocks at the same structural level (Brun and Cobbold 1980; Scholz 1980). The higher temperatures are dominantly due to heat transport by fluids, rather than frictional heating, as calculations by Scholz (1980) have shown. Ferry (1980), in a study of heat and fluid distribution, also showed a correlation between zones of high fluid ratios and high heat flux, and schistosity and bedding trends. Although no detailed studies on the first-order structures in the Norseman-Wiluna Belt have been published, Spray (1987) suggests that they were at elevated temperatures with respect to surrounding rocks. Further, similarities with the Donnybrook-Bridgetown Shear, which is intruded by syntectonic granitoids, also suggest that the first-order shear zones were hotter than the surrounding rock (cf. Partington 1987b).

The importance and ubiquitous presence of fluids, even at deep levels in the Earth's crust, is described by Fyfe et al. (1978) and Wood and Walther (1986). Deep crustal electromagnetic soundings have revealed zones of relatively low electrical resistivity, interpreted to indicate layers with a continuous water phase (Nekut et al. 1977). Deep faults may decouple at the Moho or at horizontal decollements within the crust where, due to mineralogically controlled contrasts, variations in flow strength occur (White and Bretan 1985). Alternating brittle and ductile layers, leading to rheologic stratification in the lithosphere, have also been invoked by Ranalli and Murphy (1987). The presence of such horizontal layering could be an important feature in concentrating fluid flow at deep crustal levels into the large first-order structures, such as those broadly controlling gold-deposit location in granitoid-greenstone terranes.

In contrast to deformation in the ductile regime, brittle and brittle-ductile deformation is discontinuous and characterized by its periodicity and seismicity. The buildup and relaxation of stress are accompanied by large fluctuations in fluid pressure and porosity, and a seismic-pumping mechanism for hydrothermal fluid flow has been described by Sibson et al. (1975). Fractures, once initiated, are inherent weaknesses in the rock and are predisposed to repeated brittle failure. Vein formation itself is the result of repeated opening and filling of vein spaces, the crack-seal process of Ramsay (1980). Fluid circulation is dominantly constrained by such fracture-controlled channels, as indicated by calculated fluid pathways around cooling plutons (Norton and Knight 1977).

Relationship between first- and second-order structures and gold mineralization

The location of gold deposits suggests that contrasting fluid-pressure and/or temperature regimes within the first- and second-order structures may be responsible for fluid migration and gold deposition.

The transition from brittle to ductile deformation is dependent on i) the geometry and mode of faulting; ii) crustal composition; and iii) temperature. In addition, iv) fluid pressure is a critical factor in brittle deformation; and v) the water content of the rocks, and vi) strain-rate are factors which affect the onset of ductile deformation (Sibson 1984). In active fault systems, the limiting depth of microseismic activity is generally modelled as the transition from a frictional regime to a quasi-plastic deformation regime, and is located at the onset of greenschist metamorphic conditions, at approximately 15 km depth for quartzo-feldspathic rocks (Sibson 1984). Experimental evidence shows that quartz-bearing rocks more readily deform in a plastic manner than quartz-poor rocks at a given temperature, particularly when their water content is high. In addition, a lower strain rate and higher rock temperature will favour ductile deformation. At temperatures in excess of 300 °C quartz begins to flow plastically, whereas feldspar remains brittle until about 450 °C (Voll 1976). This temperature range is significant, as it encompasses the formation temperatures of most Archaean gold deposits (cf. Groves and Phillips 1987).

Brittle deformation is accompanied by a periodic fluctuation of fluid pressure, resulting in high fluid fluxes (i.e. seismic pumping mechanism of Sibson et al. 1975). Prior to brittle failure, fluid pressures increase and then drop to a minimum after failure. This establishes a transient pressure gradient between the first-order structures, with relatively constant fluid pressure, and the second-order structures with periodically varying fluid pressure, resulting in a net fluid flow into the latter. In addition, the restriction of fluid movement to fracture controlled channels accounts for the high fluid/rock ratios observed in gold-hosting veins (Kerrich 1986b; Neall 1987). Gold deposits are commonly located in mafic rock units, which, due to their lower tensile strength, are more prone to brittle fracturing than quartz-rich rocks (e.g. Groves and Phillips 1987). Due to their smaller scale, subsidiary structures show a greater geometric complexity induced by competence contrasts between rock types, and therefore favour the formation of dilational sites.

Thermodynamic calculations show that gold precipitation from a fluid is mainly dependent on the availability of compositionally suitable host-rocks and temperature; for example Neall (1987), Wall (1987) as discussed by Groves and Phillips (1987). As first-order structures are zones of higher temperature, with all other factors being equal gold will be more soluble in fluid within those zones than in the subsidiary structures. Further, if gold precipitation commences in cooler zones, then concentration (chemical potential) gradients will be set up and, irrespective of fluid flow, gold will diffuse down the gradient, provided there is a continuous fluid medium (Ewers 1969).

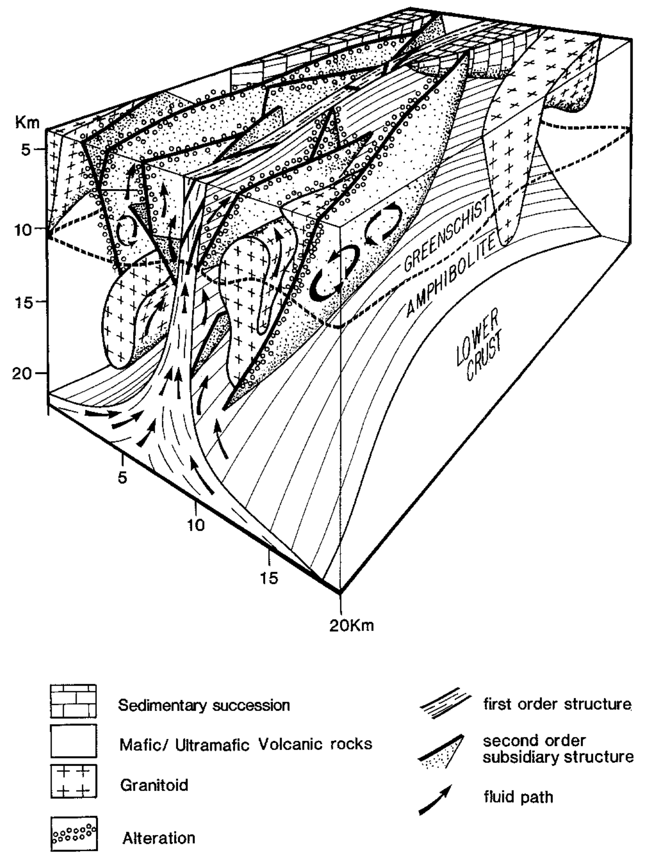

Fig. 5. Schematic block diagram illustrating fluid path through the crust via first-order fault zones into subsidiary structures. Note that first-order structures are also the site of porphyry and lamprophyre intrusions that are not shown in the figure

In summary, it appears that a number of factors can act in concert to induce both pressure and temperature gradients between first-order and subsidiary structures (Fig. 5). Gold concentration gradients may be set up between high- and low-temperature ends of the system, and dilational sites with high fluid/rock ratios should be common in the brittle-ductile to brittle subsidiary structures in sub-amphibolite facies domains.

The general lack of vertical zonation in alteration and the widespread chlorite and carbonate haloes surrounding gold deposits (Phillips 1986) suggest that the fluid involved was ubiquitous at a kilometric-scale, and that a combination of local (lode to deposit-scale) differences in fluid/rock ratios, pressure, temperature and rock chemistry were the more important factors contributing to gold precipitation at specific sites. Large amounts of volatiles were present in Archaean sequences prior to metamorphism, particularly in zones of regional carbonation that broadly coincide with first-order lineaments. The possibility of fluid mobility during metamorphism as a result of enhanced porosity and permeability induced by high fluid pressures has been pointed out by Etheridge et al. (1983, 1984). In particular, rocks around shear and fracture systems should be more permeable due to effects such as dilatency hardening. It appears likely, therefore, that fluids derived during metamorphism would mix with fluids from deep crustal sources such as those channelled by first-order structures.

High fluid-rock ratios may be obtained by convective circulation of fluid cells in the presence of suitable, impermeable, cap-rock (Etheridge et al. 1983, 1984). In the absence of an impermeable layer, fluid pressures higher than the hydrostatic head would result in an open system and fluid loss. Since Archaean supracrustal sequences were in a near vertical orientation prior to the gold mineralizing event, permeability contrasts due to juxtaposition of different rock types are considered unlikely, although the occurrence of many large gold deposits near the volcanic-sedimentary transition requires explanation. Syntectonic recrystallization could restrict permeability, resulting in a sealed system with significant convection within the shear zones, and leading in turn to higher fluid/rock ratios. Such a mechanism has been proposed to account for vein formation in the Connemara Schists, Ireland by Yardley (1986), and could possibly explain the frequent siting of gold deposits stratigraphically below quartz-rich volcanogenic sediments. The lack of evidence for meteoric water (Golding and Wilson 1982) in gold deposits, despite the known deep circulation of meteoric fluids in major fault zones (Norton and Taylor 1979), lends support to this argument.

From the above discussion, it is concluded that the gold mineralizing fluid could consist of two components: i) a mantle/lower crustal component introduced via first order-structures, and ii) a metamorphic component derived from higher-grade metamorphic domains in greenstone belts and granitoid basement (cf. Groves and Phillips 1987). This can potentially explain the provinciality and distinct isotopic signature of gold deposits. Fluids originally derived from the mantle/upper crust would re-equilibrate and mix with metamorphic fluids during fluid migration, and assume geochemical and isotopic compositions reflecting the nature of the traversed rocks. For example, Pb isotope studies suggest Pb sources from both older granitoid crust and local greenstone sequences (Dahl et al. 1987), and C and O isotope studies of carbonates suggest either direct mantle contribution of CO_2, metamorphic dissolution of mantle-derived carbonate alteration zones or both (Golding et al. 1987).

Discussion

The tectonic controls outlined above: i) provide a coherent explanation of the observed siting of gold deposits in greenstone belts, ii) bear on constraints used in previous genetic discussions, and iii) have exploration significance.

In the Norseman-Wiluna Belt, first-order ductile shear zones appear to be reactivated transcrustal structures forming discrete portions of regional shear systems that developed during the latter stages of the evolution of granitoid-greenstone terranes. These deformation zones may have marked the positions of mantle thermal activity which resulted in the intrusion of granitoids, porphyries and lamprophyres (Perring et al. 1987) and the development of regional-scale mantle-derived carbonate alteration zones (Groves et al. 1988) in, and in close proximity to, the first-order shear zones. Granitoid emplacement influenced shear zone geometry in some areas. An extended history of magma emplacement and channeled fluid infiltration is evidenced by complex, commonly contradictory, relationships between intrusions, alteration and deformation fabrics related to shearing. It is also suggested by the recognition of both dextral and sinistral strike-slip movements on different shear zones in different parts of the terrane and on the same shear systems at Kalgoorlie. Basically, the first-order structures represent major zones of hot fluid infiltration into cooler crust. Rheologic/lithologic boundaries would have provided a focussing mechanism for fluid at lower crustal levels, with transcrustal discontinuities providing regions of higher permeability thus allowing fluid to migrate upward through the crust. Second-order subsidiary shear zones are brittle-ductile or brittle structures that are smaller scale and therefore subject to greater influence by lithological heterogeneities in the greenstone successions than first-order structures; more complex geometries thus develop. Such structures host most of the gold deposits in Archaean granitoid-greenstone belts.

Fluid movement from first-order ductile shear zones into brittle-ductile to brittle secondary structures at high crustal levels can account for the observed siting of gold deposits. Fracture-controlled vein formation by crack-seal processes would ensure high fluid/rock ratios around gold lodes. Complementary temperature gradients between first- and second-order structures would have resulted in selective gold deposition in the cooler environments, and induced concentration gradients within a continuous fluid system. The long-lived nature of the first-order shear zones and the late (relaxation) movement of second-order structures can explain the variable timing of gold deposition with respect to igneous intrusions and peak metamorphism, and the considerable length and depth of each of the subsidiary structures, combined with their development in heated wall-rocks, can explain the lack of marked zonation in the deposits.

This structural model is capable of explaining most of the available, albeit reconnaissance, stable and radiogenic isotope data on the gold deposits. For example, there is evidence that C in gold-related carbonate alteration has an ultimate mantle origin (Golding et al. 1987), whereas Pb in ore-related sulphides was derived both from greenstone sequences and older granitic basement of lower crust (Dahl et al. 1987), implying a mantle-crustal fluid path. Despite these generalities, there is growing evidence for the provinciality of isotope data, with differences between gold districts or even between deposits in the same district (Perring et al. 1987). In terms of the model discussed above, this suggests that fluid pathways within subsidiary structures were important in controlling the geochemical and isotopic characteristics of gold mineralization and/or that ore-fluid characteristics changed during the development of fault systems.

If the above structural model is valid the scale of the subsidiary structures cannot be used to imply a greenstone source for ore fluid, and ore components, therefore, cannot be used to support a purely metamorphic model for gold genesis (cf. Groves and Phillips 1987). However, the variability of both stable and radiogenic isotope compositions for gold deposits negates an exclusive mantle origin for ore fluid and ore components; mantle-derived carbonation so far sampled has a more constant isotopic composition than that related to gold deposits (Golding et al. 1987). It seems most likely, both in terms of isotopic composition and the structural considerations discussed above that a multi-source ore system, comprising mantle, lower crust and greenstone components was involved in gold genesis: similar conclusions have been presented by Golding et al. (1987) and Perring et al. (1987), and Kerrich (1986b) has discussed a similar model.

From an exploration viewpoint, the present distribution of gold deposits in subsidiary structures that are related to transcrustal shear zones appears consistent with theoretical considerations. Thus, mapping and documentation of movement vectors for the first-order shear zones is vital to prediction of the nature and orientation of subsidiary structures likely to host gold deposits. This, combined with identification and mapping of suitable (normally high Fe/[Fe+Mg]) host rocks, should provide a powerful tool in exploration not only in mineralized areas where some, but not all, mineralized structures have been discovered, but also in virgin ground.

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