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THE TECTONIC ENVIRONMENTS OF GOLD DEPOSITION AND INTRUSION OF RARE-METAL PEGMATITES: IMPLICATIONS FOR Au, Sn and Ta EXPLORATION IN THE YILGARN BLOCK, WESTERN AUSTRALIA

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ABSTRACT

The timing of intrusion and the tectonic environment of the Archaean Greenbushes rare-metal pegmatite group are similar in many respects to the timing of deposition and the tectonic environment of the Archaean epigenetic gold deposits of the Lawlers district. At a regional scale, the greenstone-scale shear zones control the location of gold deposits by being the locus of subsidiary shears and faults. The factor common to most gold occurrences in the Lawlers district is their location in structures formed in a wrench tectonic environment at the brittle–ductile interface. In all cases gold mineralization is located in small-scale structures which were active toward the end of deformation, when vertical movement was dominant. The Greenbushes pegmatite group (ca 2.54 Ga) is a NNW-trending, 400 m by 6 km, dyke-like body with subsidiary dykes and pods at its periphery . Recent exploration in the northern 1 km of its strike length indicates that it has the world's largest Ta and Li resource. The overriding control on the evolution of the Greenbushes pegmatite group has been its emplacement into the Donnybrook–Bridgetown shear zone. This shear zone is a regional NNW-trending, ductile, sinistral strike-slip shear zone approximately150 km long and 15 to 20 km wide. Sinistral movements along the Donnybrook–Bridgetown shear zone caused NNW–SSE anisotropies and secondary E–W anisotropies. Combined with the anastomosing character of the high strain zones, these anisotropies resulted in an irregular shear plane. Later movements caused the shear to "open", resulting in zones of intense pressure reduction. Any melts or fluids in the system at this time would have migrated towards this zone, initiating intrusion of the pegmatite.

Although the structures which control the deposition of gold and intrusion of rare-metal pegmatites are similar, the metamorphic grade and style of deformation associated with each type of mineralization are quite different. Gold deposits generally occur in structures within the brittle–ductile field associated with greenschist to low amphibolite facies metamorphism. In contrast, rare-metal pegmatites tend to occur in structures formed in the ductile field associated with mid–upper amphibolite facies metamorphism. Many of these differences can be explained in terms of the proposed metamorphic model for Archaean epigenetic gold deposits. Thus, it should te possible, using structural and metamorphic features in conjunction with detailed structural and metamorphic mapping, to identify the most prospective parts of these shear or fault systems for gold or rare-metal mineralization.

INTRODUCTION

The importance of structural features in controlling fluid flow and the location of mineral deposits has long been recognized (*e.g.*, Maitland, 1979; Newhouse, 1942; W.J. Phillips, 1972; Kerrich & Allison, 1978; Etheridge *et al.*, 1983; Guha *et al.*, 1983) and is accepted by most geologists. Workers are now recognizing the significance of structural control on many of the mineral deposits of the southern African, Western Australian and Canadian Archaean cratons. At a regional scale, Colvine *et al.* (1984) noted the importance of "breaks" in greenstone sequences of the Abitibi Belt in Canada, and suggested that these may exercise some control on gold siting. Major "breaks" or structural discontinuities (largely strike-slip faults) have also been recognized in the Norseman–Wiluna Belt (Gee *et al.*, 1981), the major gold-producing greenstone belt in the Archaean terranes of Western Australia. In a recent review of Archaean gold deposits, Groves *et al.* (1985) emphasized the importance of large faults and shears in localizing and channelling fluid flow. At a mine scale, detailed structural investigations of vein emplacement in some Canadian deposits have been recently published (*e.g.*, Guha *et al.*, 1983; Robert & Brown, 1986). Rare-metal pegmatites of Archaean age are also mainly confined to the linear synclinal greenstone belts of the Canadian, southern African and Western Australian cratons. The pegmatite fields tend to be particularly abundant along tectonic boundaries (Cerny, 1982), and are concentrated along shear zones similar to the Archaean epigenetic gold deposits.

Recent work on the Greenbushes pegmatite group (Fig. 1) and the gold deposits of the Lawlers district (Fig. 1) suggests that they were syn-tectonically deposited and intruded, respectively, into regional strike-slip shear systems which were active during the late Archaean (Partington, 1986; Bettenay *et al.*, in press; B. Eisenlohr & G.A. Partington, unpubl. ms., 1986). The aim of this

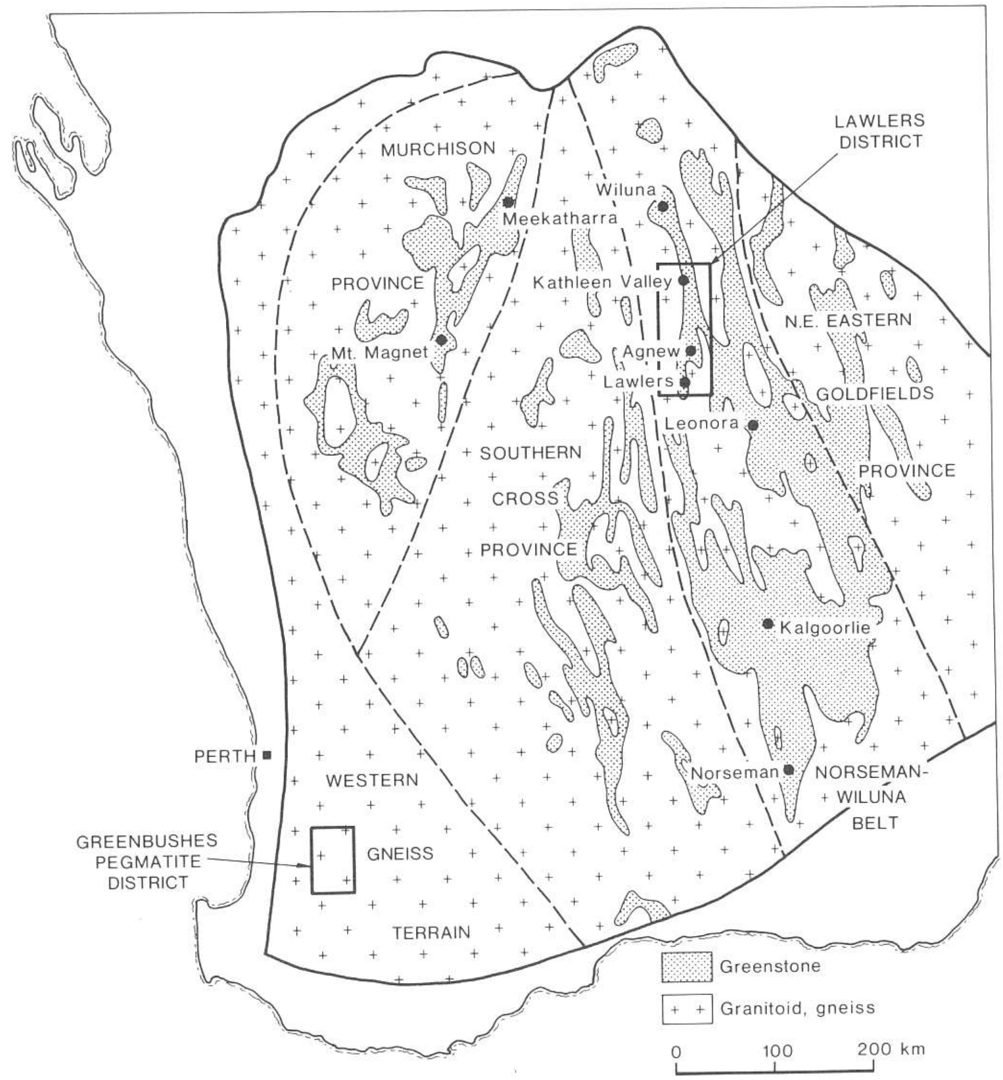


FIGURE 1 Map of the Yilgarn Block showing the location of the Lawlers and Greenbushes districts

paper is to describe the tectonic environments for both the gold deposits of the Lawlers district and the rare-metal pegmatites of the Greenbushes district, and to suggest possible criteria to aid exploration for both types of mineralization in Archaean terranes.

REGIONAL SETTING

Introduction

The regional setting and mineralization styles of both the Greenbushes pegmatite district and the gold deposits of the Lawlers district have been described in detail by a number of authors (Platt *et al.*, 1978; Platt, 1980; Wilde & Walker, 1982, 1984; Partington, 1986; Partington *et al.*, 1986; Bettenay *et al.*, in press; B. Eisenlohr & G.A. Partington, unpubl. ms., 1986). A brief summary of the setting of both deposit types is given below.

Lawlers

GEOLOGY

The rocks of the Lawlers district are affected by lower- to upper-grade greenschist facies metamorphism (Binns *et al.*,1976). Structures and textures are heterogeneously preserved such that precursor rocks can be recognized and, thus, the prefix "meta" is omitted, although implied, in the following discussion. The greenstones in this district consist of mafic volcanics, ultramafic rocks and interlayered gabbroic sills (Fig. 2). Overlying the sequence is a sedimentary unit consisting of conglomerates, arkoses and siltstones. The greenstone sequence is intruded by the following sequence of granitoids:

(i) A voluminous granitoid intruded to the west of the greenstone sequence. The eastern margin of this granitoid is incorporated in the Waroonga Shear and therefore intrusion is considered to be pre-shearing.

(ii) The Lawlers Tonalite intruded the axial region of the Lawlers Anticline (Fig. 2), either during or after folding. Numerous xenoliths of the greenstone sequence occur in the tonalite, suggesting that the exposed part of the intrusion is close to the roof zone.

(iii) East–west aplite dykes and pods of leucogranite intruded between the tonalite and the greenstone sequence.

Extensive Rb/Sr isotope data, mainly for the

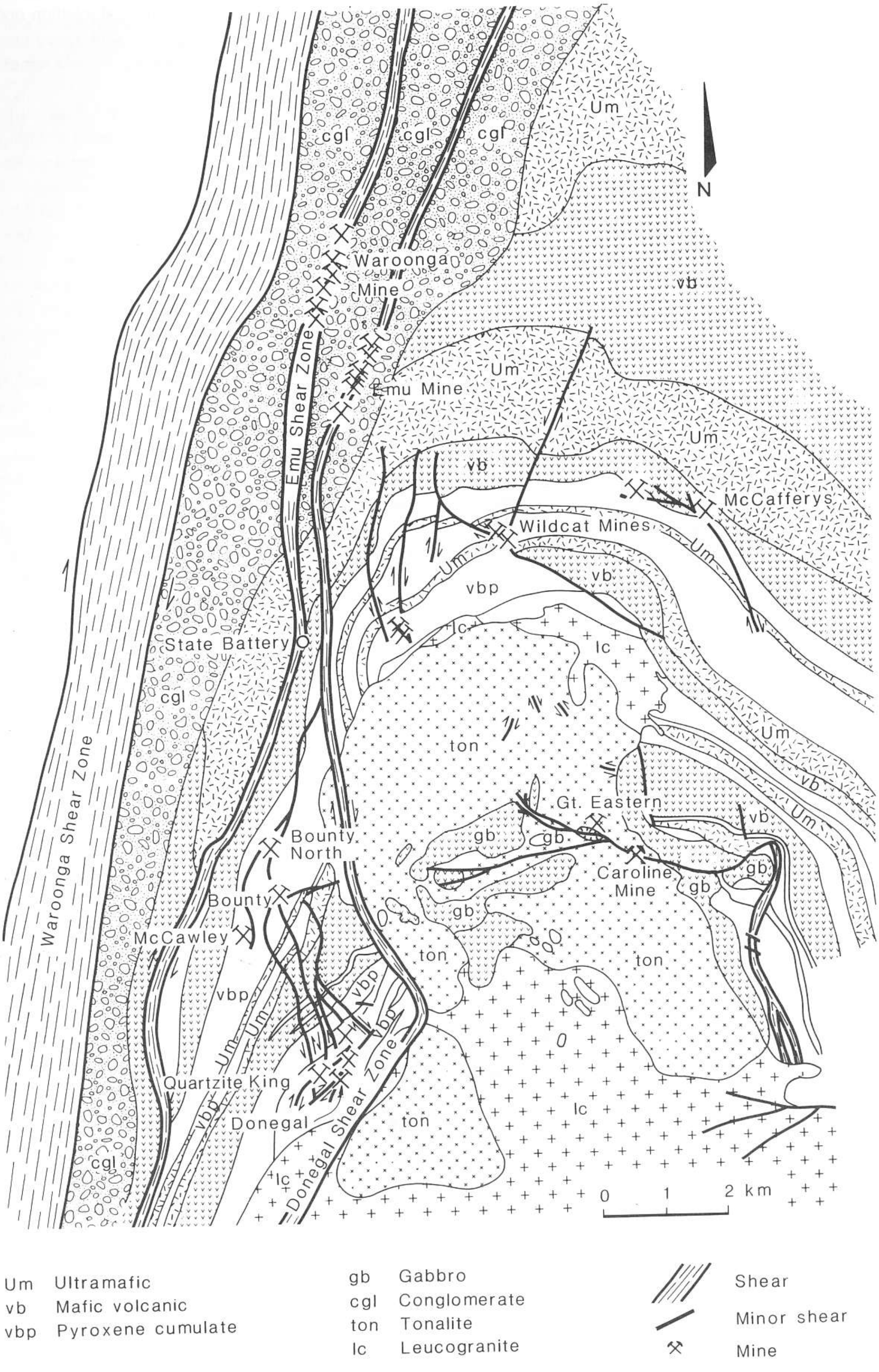


FIGURE 2 Geological map of the Lawlers district

surrounding granitoids and pegmatite dykes, are available for the region (Cooper *et al.*, 1978; Roddick *et al.*, 1976). Whole-rock Rb/Sr isochrons indicate ages ranging from 2.62 to 2.65 Ga for the bulk of the granitoids adjacent to the greenstones, with later pegmatite and aplite intrusions having ages between 2.58 and 2.47 Ga (Cooper *et al.*, 1978).

STRUCTURE

Regional setting

Recent regional and detailed mapping indicates that the structures in the district are the result of a greenstone-scale, non-coaxial deformation event (Eisenlohr, this volume; B. Eisenlohr & G.A. Partington, unpubl. ms., 1986). The major structural features of the region are large shear zones, kilometre-scale fold structures and a widespread north-northwest-trending foliation. Criteria used to recognize ductile shear zones are C–S mylonitic fabrics; asymmetric, refolded, and sheath folds; and pressure shadows (Berthé *et al.*,1979; Bell & Hammond, 1984; Lister & Snoke, 1984). Movement directions were deduced from criteria such as asymmetric pressure shadows and inclusion trails behind clasts in the conglomerates, and asymmetry of C–S fabrics (Simpson & Schmid, 1983).

Folds

The Lawlers Anticline (Fig. 2) is the most prominent of the regional fold structures, folding the greenstone sequence and clastic sediments of the Lawlers district. The Anticline plunges to the north at about 45° and the core region is intruded by tonalite (Platt *et al.*, 1978). The regional folds in the Lawlers district were probably formed by flexural slip: evidence includes the presence of asymmetric folds associated with prominent C–S fabrics in the hinge region of the Lawlers Anticline. The C–S fabric parallels stratigraphic layering, and is restricted to particular stratigraphic units. In addition the asymmetry of the folds is compatible with the regional folds. The similar orientation of the stretching lineation in the Waroonga Shear and plunge of the Lawlers Anticline further suggests that the shearing and folding are related.

Shear zones

The dominant structure in the Lawlers district (Fig. 2) is the 2 km-wide north-northeast-trending Waroonga Shear described by Platt *et al.* (1978). The Waroonga Shear separates supracrustal rocks to the east and granitoid intrusions to the west, and extends to the north where it is obscured by Recent sediments. It has a vertical foliation and subhorizontal stretching lineation, and movement criteria indicate dextral strike-slip displacement (Fig. 3a).

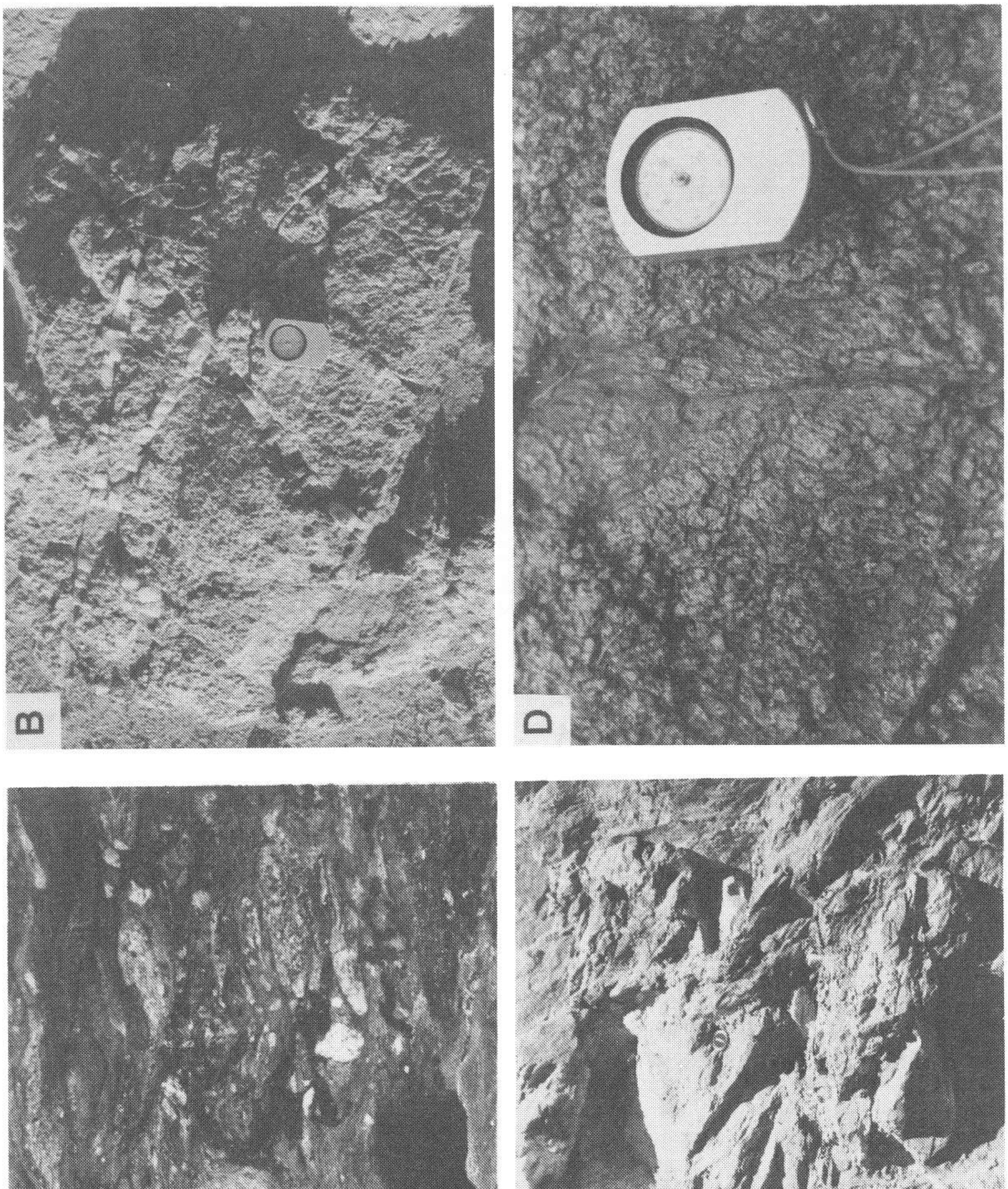
Numerous smaller, subsidiary shear-structures occur in the greenstone sequence marginal to the Waroonga Shear . These are impersistent high-strain zones, with two distinct orientations, and dimensions up to 100 m in width and 2 to 3 km in length. The first orientation varies from north–south to northeast–southwest and the shears have similar movement senses to the Waroonga Shear (*e.g.*, Emu and Donegal shear zones). They have a steep mylonitic fabric which is commonly folded by a series of upright non-cylindrical folds, with fold axes paralleling the trend of the Lawlers Anticline. Two sets of stretching lineations are developed. The early set parallels the fold axes, and is indicative of strike-slip movement, whereas the later set is steep, indicating dominantly vertical movement.

The second type of subsidiary shear (*e.g.*, the Caroline and McCafferys shear zones) has a dominantly west-northwest orientation with a vertical foliation and dip-slip lineation. In some zones, for example in the Great Eastern opencut, there is evidence for strike-slip movement which is overprinted by a late normal dip-slip movement. A feature common to all these subsidiary structures is the presence of some component of dip-slip movement late in the history of the structure.

MINERALIZATION

Gold occurrences in the Lawlers district are located in structures subsidiary to the major, regional shear zones. The latter are hundreds of metres wide, whereas the mineralized structures are metres to tens of metres wide. The formation and extent of subsidiary shears is also controlled by the mechanical properties of rocks. Compositional and competency contrasts dictate whether a rock deforms in a brittle or ductile manner (Fig. 3b-d). Curving of shear planes, feathering, and brecciation all tend to occur at lithologic contacts. In addition, the presence of prior weaknesses (*e.g.*, foliation planes) further constrains the orientation and termination of structural sites. It is important that, in many instances, the rocks are mechanically anisotropic and, therefore, do not fail along the theoretically predicted orientations (Donath, 1961). The tensile strength of foliated

FIGURE 3 (see opposite page) Examples of the fabrics observed in rocks of the Lawlers district. **A**: Ductile shear fabrics in the regional Waroonga Shear. Asymmetric pressure shadows on conglomerate clasts suggest a dextral strike-slip sense of movement on the shear zone (width of photograph is about 0.5 m). **B**: Evidence for brittle deformation in the Great Eastern gold mine. The conjugate fractures contain gold-bearing quartz veins (width of photograph is about 2 m). **C**: Evidence for brittle deformation in the Great Eastern gold mine. *En echelon* tension gashes are filled with gold-bearing quartz veins (width of photograph is about 2 m). **D**: Ductile–brittle subsidiary, sinistral, antithetic strike-slip shear zone in the Lawlers tonalite (width of photograph is about 0.5 m)


A
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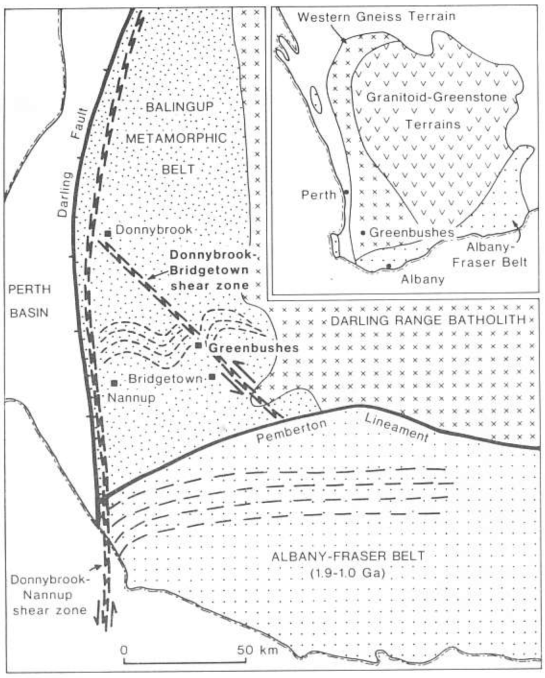


FIGURE 4 Regional map of southwestern Australia showing the location of the Greenbushes district with respect to major structures

rocks is weakest parallel to the foliation, thus predisposing the rocks to fail in a brittle manner in this orientation. Most deposits in the area are hosted by volcanic/intrusive rocks of sub-amphibolitic metamorphic grade. Within this class, two structural styles are recognized: (i) alteration haloes ± quartz vein systems in shear zones, and (ii) thick, persistent, laminated quartz veins in fractures or shear zones. In all cases gold deposition postdated peak metamorphism, as the alteration assemblages are not metamorphosed. While structure is an important factor in locating the alteration and gold deposition, the distribution of gold within a locality is also subject to host-rock chemical controls; the predominance of gold deposits in iron-rich host-rocks has previously been noted by Groves *et al.* (1985). An example of host-rock chemistry influencing the site of gold deposition occurs in the Donegal Mine, where stratabound oreshoots are located within a tholeiitic unit in the mine sequence, and at the Great Eastern mine, where the locations of high-grade oreshoots are influenced by mafic xenolith contacts in the tonalite.

Greenbushes

GEOLOGY

The Greenbushes pegmatite group (*ca* 2.54 Ga) is located on the Donnybrook–Bridgetown shear zone (Fig. 4). The pegmatite is a north-northwest-trending, 400 m by 6 km, dyke-like body with subsidiary dykes and pods at its periphery (Fig. 5). Recent exploration in the northern 1 km of its strike length indicates that it contains the world's largest resource of Ta and Li. The original orientation of the pegmatite, and the spatial relationships of zones within it, are equivocal because of intense heterogeneous deformation. The pegmatite varies internally from pod-like bodies of coarse pegmatite with igneous structure, such as large radiating tourmaline suns, through zones of fractured and aligned silicate minerals to ultramylonite. Even where igneous structures arepreserved, the pegmatite is characterized by granular, recrystallized aggregates or granular subgrains. Deformation is most intense along contacts, where there are complex relationships between pegmatite and country rocks similar to those present along the contact zones of some synkinematic granitoids (*e.g.*, Cowan Brook Dam pluton).

The Greenbushes pegmatite group is hosted by a sequence of dioritic gneisses, amphibolites and sediments, and occurs at or close to a contact between dominantly mafic–ultramafic amphibolites and sedimentary granofels (Bettenay *et al.*, in press). The occurrence of pillow-like, vesicular-like structures, and an association with banded iron-formations suggest that the amphibolites evolved in a deepwater-volcanic environment. The sediments resemble greywacke sequences which commonly occur in Archaean greenstone sequences and have a mixed granitoid–mafic provenance, as defined by geochemistry and zircon morphology. The sequence in the pegmatite hangingwall and footwall is dominated by dark green, tholeiitic, coarse- and fine-grained amphibolites after dolerite and basalt precursors, respectively. However, within the zone occupied by the pegmatite, there are a variety of pale-green amphibolites and ultramafic schists that have komatiitic affinities and, in this respect, they resemble greenstone sequences. All lithologies are deformed by narrow high-strain zones with associated biotite±phlogopite±quartz–carbonate alteration.

The metamorphic history of the district is complex, with geochronological evidence for three metamorphic episodes (Partington *et al.*, 1986). However, the metamorphic grade within the shear zone is mainly upper amphibolite facies, with temperatures of approximately 560°C being recorded, in contrast to low- to mid-amphibolite facies metamorphism on a regional scale. The higher-grade metamorphism along the shear zones appears to be related to migmatization and selective granitoid emplacement, although it is possible that viscous heating within these zones caused the coincidence of all these features. The occurrence of staurolite–kyanite assemblages near Bridgetown suggests relatively high-pressure conditions during metamorphism, as does the occurrence of spodumene rather than petalite as a primary phase in the pegmatite.

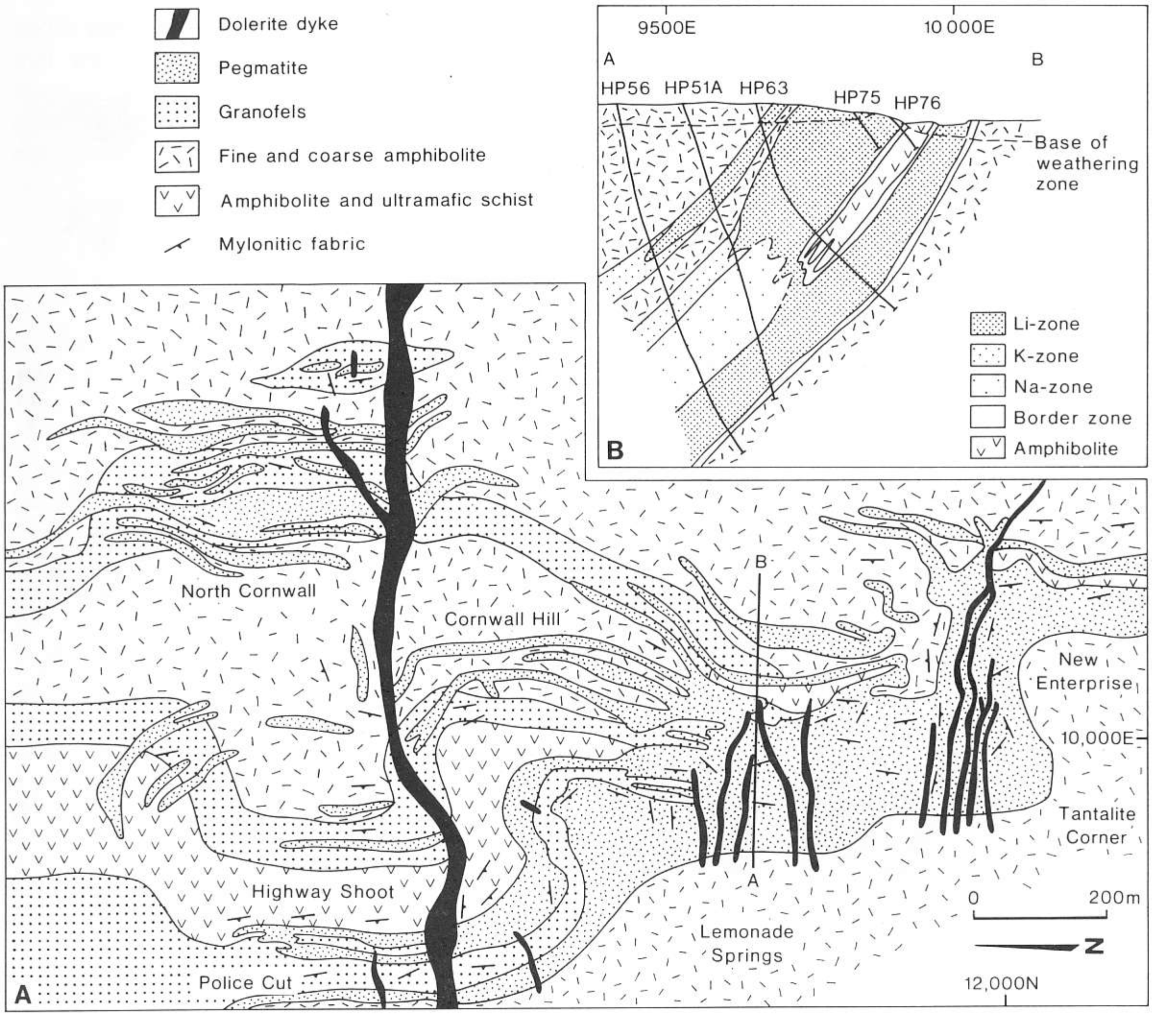


FIGURE 5 Geological map showing the distribution of the Greenbushes pegmatite group

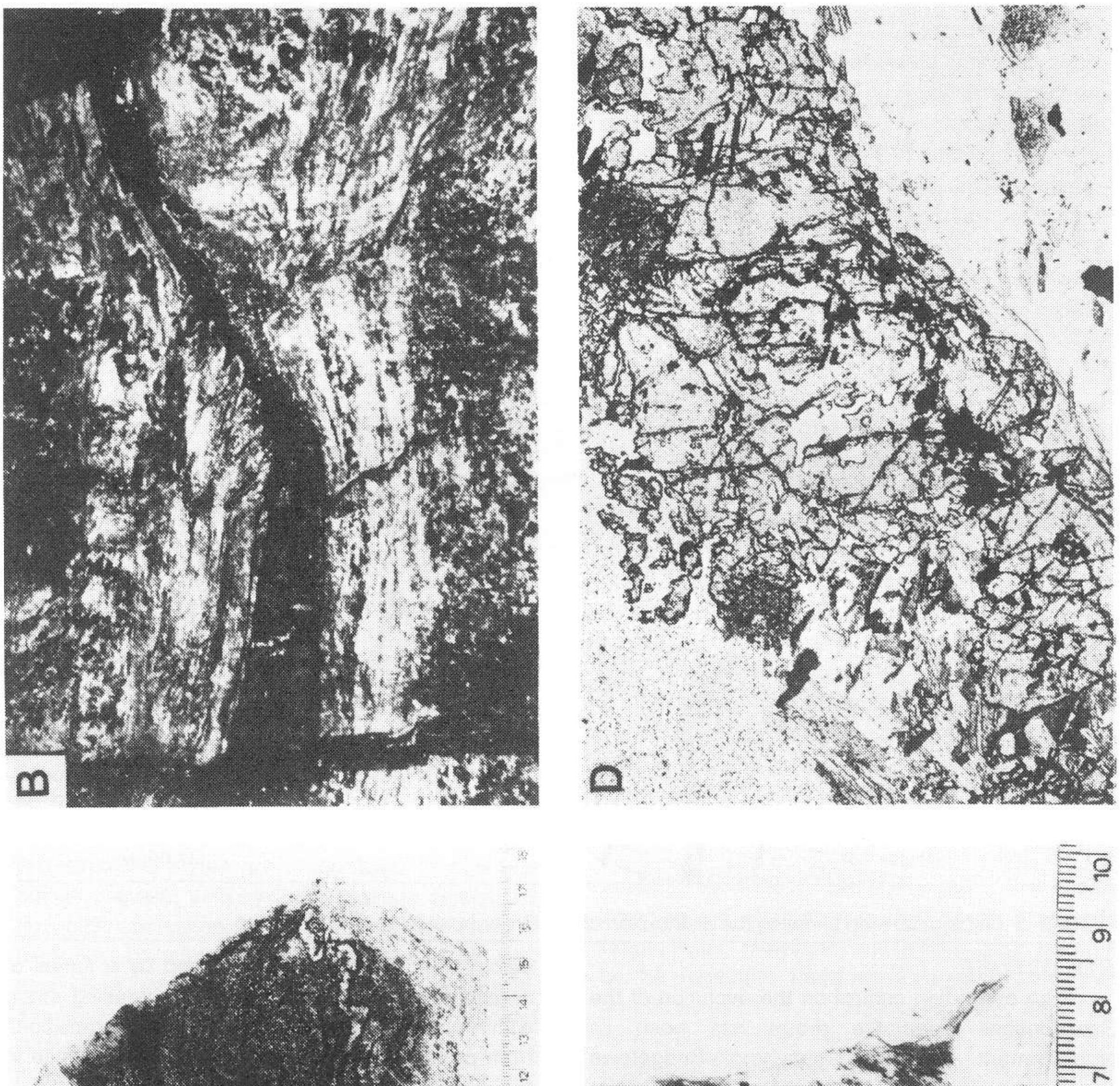
STRUCTURE

The overriding control on the evolution of the Greenbushes pegmatite group has been its emplacement into the Donnybrook–Bridgetown shear zone (Fig. 4). This shear zone is a major north-northwest-trending linear feature, approximately 150 km long and 15 to 20 km wide, that is best defined on the basis of NOAA imagery and aeromagnetic maps. Displacement and rotation of aeromagnetic features, combined with mesoscopic and microscopic structures, indicate a sinistral strike-slip component of movement (Partington, 1986). White *et al.* (1986) have confirmed the sinistral movement and identified a later reactivated dip-slip movement in the shear zone further to the north.

The gneisses contain evidence for an earlier deformational event (D1), and are interpreted to be *ca* 3.1 Ga basement (Fletcher *et al.*, 1983; Partington *et al.*, 1986) to the supercrustal rocks. However, the D2 deformation is regionally dominant, producing gross parallelism of all lithologies to the north-northwest trend of the Donnybrook–Bridgetown shear zone (Partington, 1986). Vertical north-northwest-striking planar structures, north-northwest-trending horizontal linear structures and asymmetric fold structures are associated with D2 deformation, which is characterized by a series of anastomosing high-strain zones. Increasing strain within shear zones is characterized by transitions from protomylonite to ultramylonite or phyllonite in their centres.

The gross regional distribution of a series of tonalites–leucogranites–pegmatites (*ca* 2.6–2.59 Ga) along major tectonic contacts, the nature of their marginal zones and the migmatitic layering within the gneisses all indicate emplacement during syn-D2 shearing. Commonly, these granitoids were progressively deformed to orthogneiss during later progressive deformation along the shear zone. They disrupt the normally sub-horizontal attitude of stretching lineations related to sinistral strike-slip displacement, producing an array of orientations, the end-members of which are a flat-lying lineation and a vertical down-dip lineation.

The Greenbushes pegmatite group contains most of the criteria for non-coaxial deformation recorded from the country rocks, suggesting that it was deformed by later sinistral shearing associated with movements along the Donnybrook–Bridgetown shear zone (Fig. 6a-c). Furthermore, the preservation of rare, relict igneous structures and its gross form, in part parallel to shear bands



and in part parallel to shear zone margins, suggest that the pegmatite was emplaced during the shearing event. Microstructures from the less deformed domains also indicate that the pegmatite crystallized during the shearing (Fig. 6d).

STRUCTURAL ENVIRONMENTS OF THE LAWLERS GOLD DEPOSITS AND GREENBUSHES PEGMATITE GROUP

Introduction

Wrench tectonic regimes and their geometry have been described in detail by Wilcox *et al.* (1973) and Lowell (1985). The geometry of the structures described from the Lawlers district, both on a regional and local scale, suggests that this type of deformation operated at a greenstone scale. Wrench tectonic regimes, such as the San Andreas Fault in California (Harding, 1976), and the Caledonide deformation in Spitzbergen (Harland, 1971), have been previously recognized and described. More recently, a wrench tectonic mode of deformation has been proposed for part of the Abitibi Belt in Canada (Hubert *et al.*, 1985), a greenstone belt whose characteristics have been likened to those of the Norseman–Wiluna Belt (Groves & Batt, 1984).

In a wrench tectonic regime, the maximum and minimum principal compressive stresses lie in a horizontal plane. Regional-scale folds perpendicular to the principal compression direction are among the first structures to develop. Principal displacement shears with the same movement sense as the originating couple develop, and numerous subsidiary structures, such as those depicted in Figure 7a, develop during progressive deformation. The dominant movement in wrench tectonic zones is strike-slip along approximately vertical boundaries (Lowell, 1985).

Lawlers

Maximum shear stress in a north-trending wrench tectonic environment with dextral movement is developed when the maximum compressive stress is oriented northeast–southwest and the minimum stress is oriented northwest–southeast. Regional folds, such as the Lawlers Anticline, are formed early in the deformation, and principal strike-slip zones, such as the Waroonga Shear and Donnybrook–Bridgetown shear zone, are subsequently developed. All northerly trending shears in the Lawlers district have a dextral movement direction, and form part of a greenstone-wide anastomosing and splaying shear system which appears to continue north to Wiluna (Eisenlohr, this volume). During progressive deformation, minor shears develop at both low and high angles to the principal shears. The Donegal and Wildcat shear systems, for example, consist of minor shears which are oriented at 330° and 060°, and have a dextral displacement. The shears passing through the Great Eastern mine are oriented at 110° and have a sinistral displacement, as predicted (Fig. 7). These subsidiary structures are of great importance in the Lawlers district as they host the main gold-bearing lodes and quartz veins.

Greenbushes

The structures present in the Greenbushes pegmatite district are similar to those described from other major transcurrent shear zones. Brittle deformation is characteristic of the upper parts of shear systems (*e.g.*, the Lawlers district), while at lower levels (*i.e.*, below 10–15 km; Sibson, 1977) deformation occurs in a predominantly ductile fashion. In the Greenbushes pegmatite district, the ubiquitous presence of structures characteristic of ductile deformation indicates that deformation occurred deep in the crust in response to movements along the Donnybrook–Bridgetown shear zone. Ductile deformation in transcurrent shear zones usually produces intense linear fabrics with an horizontal orientation associated with two vertical foliations at 30° to each other (Nicolas *et al.*, 1977; Fig. 8). As strain increases, these fabrics become parallel and form a distinctive braided S-shaped texture (Berthé *et al.*, 1979). This type of ductile deformation is believed to be comparable to deformation in the deeper parts of currently active fault systems, such as the San Andreas and Alpine fault systems in California and New Zealand, respectively (Grocott, 1977).

The coincidence of high-grade metamorphism, including anatexis and intrusion of granitoid magmas, in shear zones elsewhere has been documented by Nicolas *et al.* (1977), Berthé *et al.* (1979), Ramsay and Allison (1979), and Brun and Choukroune (1981). A comparison of the Greenbushes pegmatite district with these previously documented examples highlights many

FIGURE 6 (see opposite page) Examples of the fabrics observed in rocks of the Greenbushes district. **A**: Evidence for ductile deformation in the Donnybrook–Bridgetown shear zone. Metamorphic layering in a granofels has been ptygmatically folded. **B**: Evidence for ductile deformation in a shear zone crosscutting the Greenbushes pegmatite. Note the refolding of isoclinal folds localized at a kink in the shear band (width of photograph is about 10 m). **C**: Evidence for ductile deformation in a shear zone crosscutting the Greenbushes pegmatite. Note the brittle deformation of the albite (white) and tourmaline (black) in comparison to the ductile deformation of the quartz and K-feldspar. Asymmetric pressure shadows indicate a sinistral sense of movement on the shear zone. **D**: Evidence for syntectonic crystallization in the Greenbushes pegmatite. The helicitic garnet has an inner spiral of tantalite inclusions and an outer spiral of microlite inclusions (width of photograph is about 4 cm)

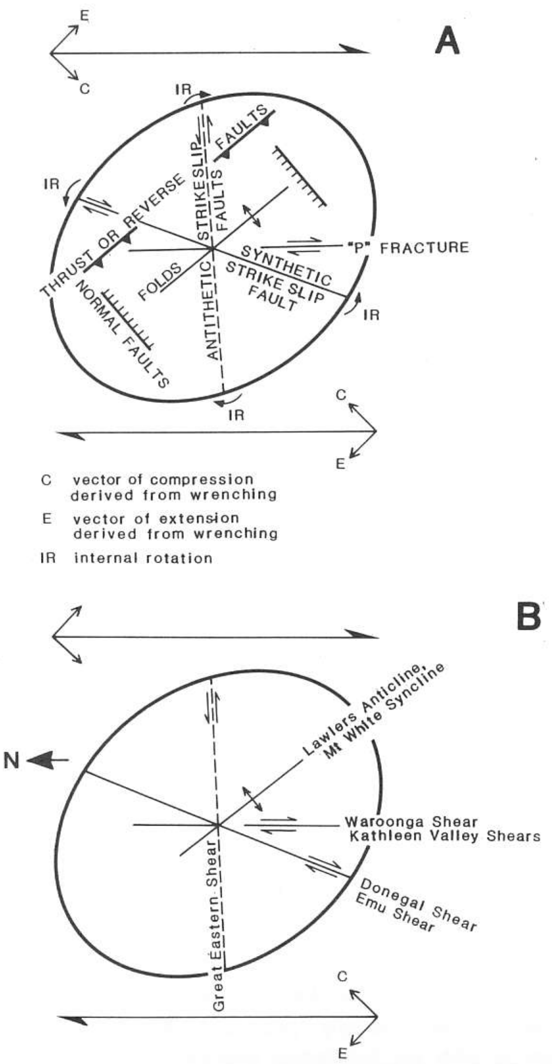


FIGURE 7 Diagram comparing structures in a wrench tectonic regime with those of the Kathleen Valley–Lawlers region (Eisenlohr, this volume, fig. 6). **A**: Predicted orientation of structures in a wrench tectonic regime. **B**: Measured orientation of structures in the Kathleen Valley–Lawlers region

similarities. The dominant structures in the Anger–Lanvaux shear zone, France, are a horizontal stretching lineation which parallels fold axes and a foliation or slaty cleavage which wraps the axis of the shear zone. As in the Greenbushes pegmatite district, the folds in this shear zone have axes parallel to the general trend of the shear zone (Fig. 8). This is attributed to crustal shortening in a direction oblique to the boundaries of the shear zone. In the Montagne Noire shear zone, France, high-grade metamorphism is centred on the axial region of the shear zone, and lower-grade assemblages occur symmetrically away from the axial region. A similar metamorphic bilateral symmetry seems to be present in the major shear zones in the Greenbushes pegmatite district: zones of migmatization and anatexis are present only in the areas of highest strain (Fig. 8), whereas lower-grade assemblages without migmatization occur in lower-strain zones. A major sequence of orthogneiss and late- to post-tectonic granitoid intrusions occurs in the core of the Donnybrook–Bridgetown shear zone. The axial regions of these shear zones display clear evidence for partial melting at various scales within the deformed gneisses, and a general association of pegmatite and granitoid intrusion. Similar variations in plunge and trend of the linear structures in the Greenbushes pegmatite district are described from the Mayadan, Lanvaux–Angers and Montagne Noire shear zones. In some areas, the lineations completely encircle the main axial orthogneiss region, suggesting diapirism was synchronous with transcurrent shearing (Den Tex, 1975). Such a relationship would explain the haloes of down-dip plunging lineations that are present along the margins of all the granitoids in the district and also along the intrusive contacts of the Greenbushes pegmatite group.

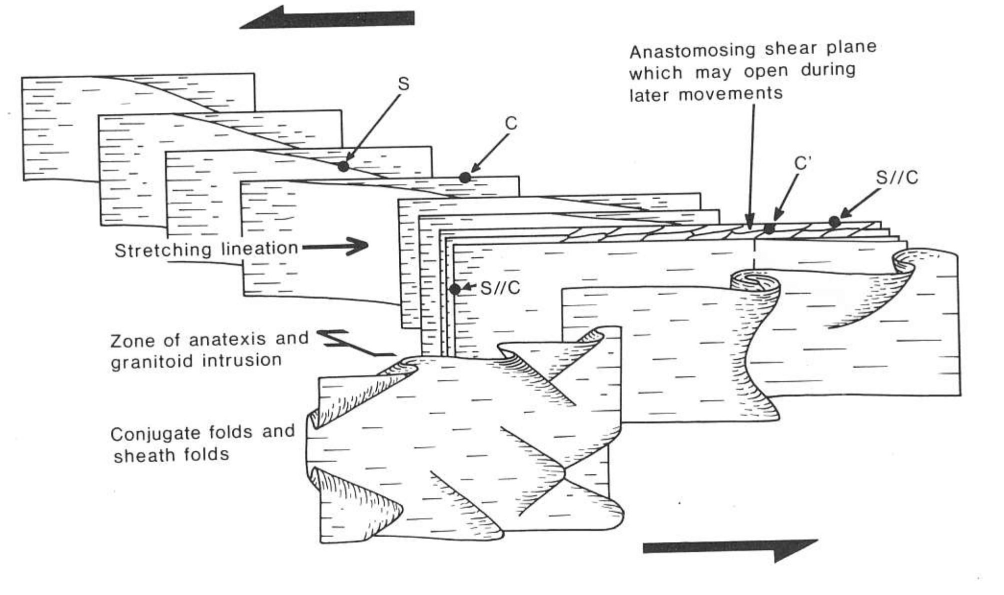


FIGURE 8 Schematic representation showing structures in the Donnybrook-Bridgetown shear zone

STRUCTURAL CONTROL ON MINERALIZATION

Controls on gold mineralization

At a regional scale, the greenstone-scale shear zones control the location of gold deposits by being the locus of subsidiary shears and faults. The factor common to most gold occurrences in the Lawlers district is that they are located in structures formed in a wrench tectonic environment at the brittle-ductile interface. In all cases, gold mineralization is located in small-scale structures which were active toward the end of deformation, when vertical movement was dominant (B. Eisenlohr & G.A. Partington, unpubl. ms., 1986).

The major principal shears are not mineralized and generally lack evidence for late vertical tectonic movement. In the Lawlers district this is exemplified by the Waroonga Shear, which is unmineralized. Specific structural sites identified to be favourable for gold deposition are: (i) subsidiary shear structures, (ii) feather structures at the termination of shear zones, and (iii) sites along curved shear planes. The Great Eastern deposit is hosted in a series of subparallel subsidiary shear structures where sinistral movement is overprinted by late vertical movements. The location of the shear in the south of the pit is controlled by a mafic xenolith (Fig. 9). Deposits such as Emu developed where contrasting rock competence resulted in differential movement rates which opened up spaces, allowing increased fluid flow and subsequent wallrock alteration and gold deposition. More massive quartz veins parallel to foliation and with a steeply plunging lineation, strongly suggest development during the tensional stress regime and utilization of pre-existing weaknesses in the rocks. These shears provided discontinuities in the host rock which were reactivated during the later vertical tectonic movement, allowing quartz and gold deposition. The extent of the quartz reef is largely controlled by the extent of the shear. Structural sites for the lenticular and discontinuous types of deposits are numerous. Quartz localization may be controlled by irregularities in shear planes, resulting in the formation of a small, local, tensional-stress environment. Curvatures in shears where displacement creates "voids" is another structural trap (*e.g.*, workings southwest of Wildcat, Fig. 2). Lenticular pods of quartz may also form simply as the result of fracturing of the host rock in a subhorizontal plane during vertical movement under brittle conditions.

Controls on the intrusion of the Greenbushes pegmatite group

Intrusion of pegmatites is characteristically associated with increased hydrostatic pressure. Thus, intrusion will only occur when the fluid pressure of the melt exceeds the ambient pressure condition within the host rocks. During intrusion the melt pressure will decrease to the ambient pressure in the host rocks, and the intrusion will expand within the intrusive site until external and internal pressures are equalized. The host rocks had to be structurally prepared for the intrusion of the pegmatitic melts which formed the Greenbushes pegmatite group. For initial intrusion to occur in the ductile field (where hydrostatic

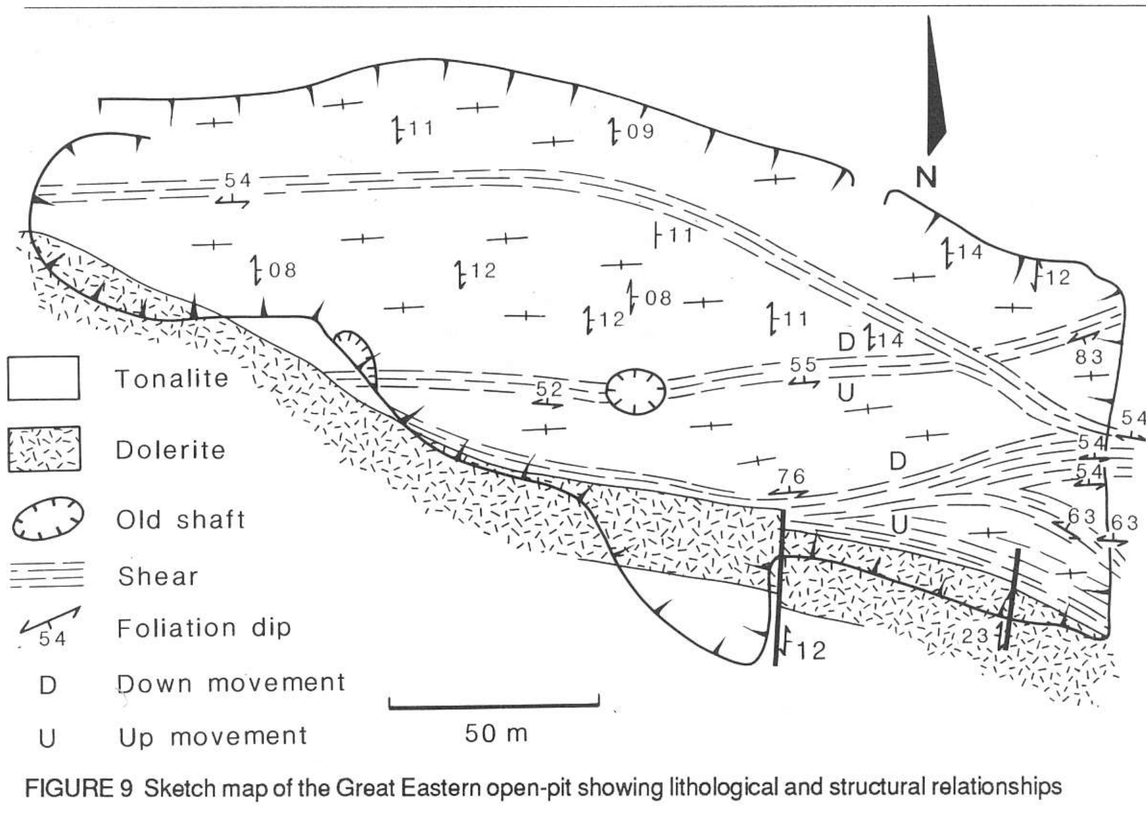


FIGURE 9 Sketch map of the Great Eastern open-pit showing lithological and structural relationships

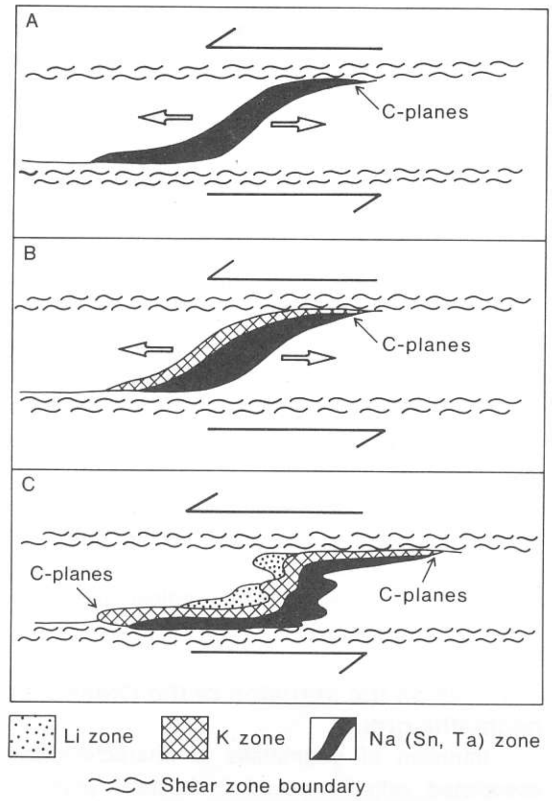


FIGURE 10 Schematic diagram showing the intrusion sequence of the Greenbushes pegmatite group. **A** to **C** indicate progressive shearing during pegmatite intrusion

pressure = lithostatic pressure) the containing stress in the host rocks must decrease to allow the magmatic pressures contained within the pegmatite melt to exceed the host-rock confining pressures. Experimental work and computer modelling indicate that during movements in ductile shear zones, high strains build which eventually result in strain hardening (White *et al.*,1980). This process continues until failure occurs and movement is initiated within the shear zone. Spaces will not actually open in the ductile field but, as predicted by computer modelling (McIntyre, 1985), major pressure reduction occurs in certain sites, such as in the lee of ridged bodies or along curved shear planes. Sinistral movements along the Donnybrook–Bridgetown shear zone created major north-northwest–south-southeast anisotropies and secondary east–west anisotropies which, combined with the anastomosing character of the high strain zones, resulted in irregular shear planes within the regional shear zone. Later movements caused the shear to "open", resulting in zones of intense pressure reduction. Any melts or fluids in the system at this time would have migrated towards this zone, thus initiating intrusion of the pegmatite (Fig. 10). Then the hydrostatic pressure in the pegmatite magma would have increased, forcing further failure and associated zones of intense pressure reduction, and permitting intrusion of pegmatite magma along the shear zone. Further movement in the shear zone was triggered by the intrusion of the hot magma, which would have lubricated the shear system and aided further ductile deformation. This, in turn, attracts more melt into the system, allowing the pegmatite to increase in size until the site cools sufficiently and further movement ceases.

This type of tectonism tapped large expanses of the lower crust, mixing melts, hydrothermal fluids and/or metamorphic fluids. Such processes may account for the large size of the Greenbushes pegmatite group and explain the obvious controls that the Donnybrook–Bridgetown shear zone exerts on the intrusion of not only pegmatite, but also associated granitoids and later mafic dykes. The structural control on igneous activity in the district is emphasized by the similar intrusion some 2.1 Ga later of the Ferndale (Kepert, 1985) and Malulyup (Seet, 1986) pegmatite groups.

GUIDES TO EXPLORATION

A comparison of the structural and metamorphic features of the two types of mineralization is given in Table 1, and is shown schematically in Figure 11. The presence of rare-metal pegmatites in similar structures to gold mineralization suggests that these magmatic fluids utilized similar structural channelways to the Au-bearing ore fluids. This similarity emphasizes the importance of greenstone-scale shear zones in localizing fluid flow in Archaean terranes. However, although the structures which control the deposition of Au and intrusion of rare-metal pegmatites are the same, the metamorphic grade and style of deformation associated with each type of mineralization are quite different. Gold deposits generally occur in structures within the brittle–ductile field associated with greenschist to low amphibolite facies metamorphism (Fig. 11). In contrast, rare-metal pegmatites tend to occur in structures formed in the ductile field associated with mid- to upper amphibolite facies metamorphism (Fig. 11).

Preliminary data suggest that strike-slip movement occurred both prior to and during peak metamorphism between *ca* 2.8 Ga and 2.5 Ga across the Western Australian craton. The tectonism would have allowed fluids or melts to become mineralized because of: (i) access to large volumes of rock through craton-wide fault systems, (ii) increased solubility of Au at higher P–T conditions, and (iii) the concentration of rare-metals by anatexis deep in the crust (*cf.* Groves *et al.*, 1985). Lower metamorphic conditions prevalent within the subsidiary structures outside the major shear structures (Fig. 11) allowed fluid localization and Au deposition under a suitable temperature regime (*e.g.*, Seward, 1984). In contrast, rare-metal pegmatites generally intruded into areas of the crust where higher temperatures and pressures were present (Fig. 11), associated

TABLE 1 Comparison between Archaean gold and rare-metal pegmatite mineralization. Data sources: * Ho (this volume); ** Perring *et al.* (this volume)

	LAWLERS DISTRICT	GREENBUSHES PEGMATITE GROUP
METAMOPHIC GRADE	Mid-greenschist to low-amphibolite	Low-amphibolite to upper-amphibolite
P-T AND DEPTH OF FORMATION	* 2–3 kb, 250–350°C, 5-8 km	5–7 kb, 450–650°C, 12–15 km
STRUCTURE	Brittle fracture zones and tension fractures Some evidence for recrystallization and helicitic garnets Recrystallization Stretching lineation is subhorizontal in the shear zones and sub-vertical in granitoid contact zones	C–S fabrics with evidence for sheath folds, asymmetric pressure shadows, pull-apart and asymmetric augen structures Sheath folds occur in the ultramafic units Stretching lineation is sub-horizontal
TECTONIC ENVIRONMENT	Gold mineralization occurred in the brittle–ductile regime of the crust Associated with a regional dextral strike-slip shear zone	Pegmatite intruded into a regional sinistral N–S shear zone in the ductile regime of the crust
STRUCTURAL CONTROL	Subsidiary faults and shear zones parallel and oblique to the Waroonga Shear Mineralization occurs at shear intersections, horse-tail structures and curved shear zones Formed laminated veins, sheeted vein systems and tension fractures	Pegmatite intruded parallel to the mylonitic fabric Associated with curves in the shear zone and shear-band structures Formed pods and dykes
AGE	Post granitoid intrusion, syn-deformation and syn-metamorphism *circa* 2.6 Ga	Post granitoid intrusion, syn-deformation and syn-metamorphism Probably crystallized syn-deformation *circa* 2.54 Ga
SOURCE	** Metamorphic ± mantle ± magmatic fluids	Fractionated crustal melts
HOST ROCKS	Granitoids, mafic/ultramafic volcanic rocks and sills, and conglomerates	Granitoids, mafic/ultramafic volcanic rocks and sills, greywackes, BIFs, and quartzites

with either syntectonic granitoids or zones of anatexis in the axial regions of regional shear zones.

Many of these differences can be explained in terms of the metamorphic model proposed by Groves *et al.* (1984). Low- to medium-grade metamorphism is conducive for gold deposition, and these conditions appear to exist in parts of the crust outside the influence of regional shear zones or associated granitoid intrusions. In contrast, the higher-grade metamorphic conditions within granitoid contact zones and in the axial regions of the major shear zones cause migmitization and anatexis which, according to Groves and G.N. Phillips (in press), precluded gold deposits from these areas by increasing the solubility of Au and removing free H_2O from the system. The structural and metamorphic features given in Tables 2 and 3 may be used in regional gold and rare-metal exploration, respectively, as guides to the most prospective areas in a greenstone sequence.

TABLE 2 Structural and metamorphic features indicative of brittle–ductile regimes

Metamorphic minerals	Structures
serpentine	faults
talc	tension fractures
tremolite	*en échelon* fractures
chlorite	stylolites
quartz	slickenslides
prehnite	cleavages
pumpellyite	pinnate joints
epidote	Riedel shears
albite	conjugate fractures
biotite	solution hollows
calcite	lineations
actinolite	accretion steps
sericite	breccias
andalusite	syntaxial and antitaxial growth fibres
chloritoid	asymmetric kinks
	chevron kinks
	non-cylindrical kinks

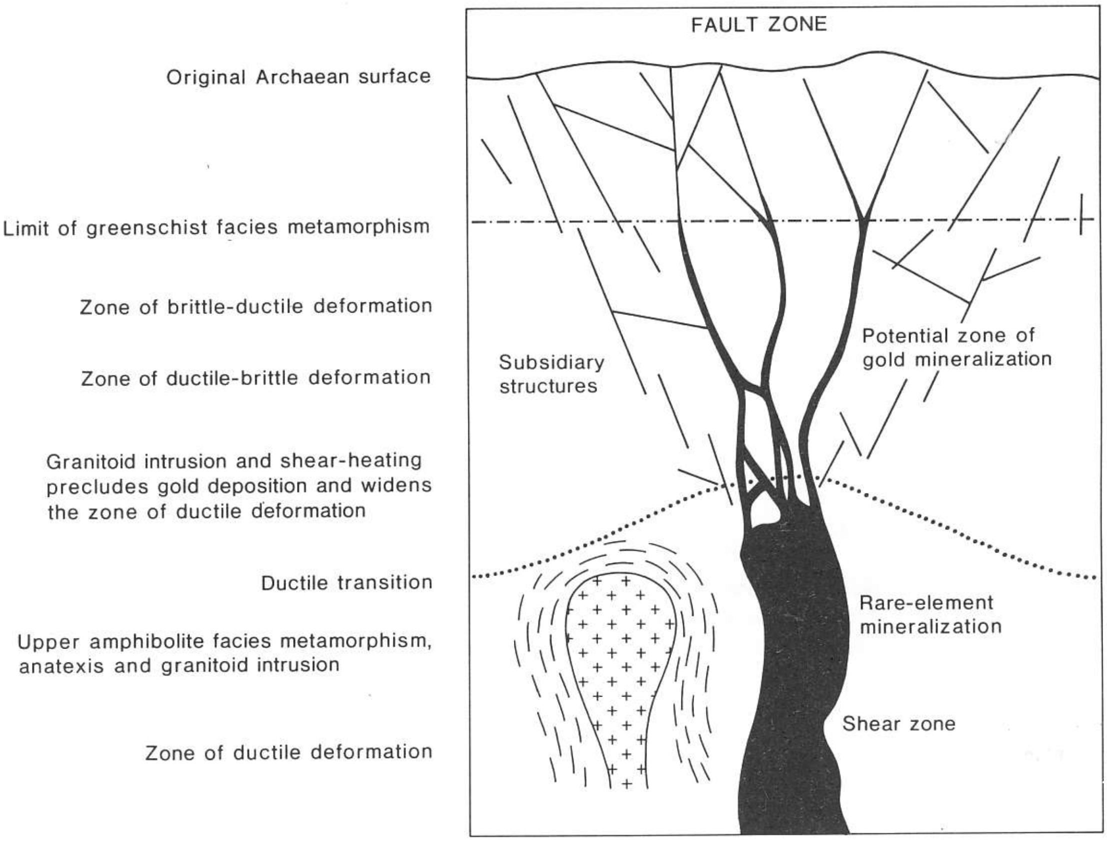


FIGURE 11 Crustal cross-section showing the potential zones of gold and rare-metal pegmatite mineralization with respect to metamorphic and structural regimes in an Archaean greenstone sequence

TABLE 3 Structural and metamorphic features indicative of ductile regimes

Metamorphic minerals	Structures
serpentine	layering
talc	feldspar augen
anthophyllite	recrystallization
tremolite	mica-fich
hornblende	pressure-shadows
quartz	C-structures
cummingtonite	S-structures
garnet	shear bands
Ca-plagioclase	flattened grains
biotite	quartz ribbons
calcite	stretching lineation
muscovite	pull-apart structures
K-feldspar	conjugate folds
staurolite	asymmetric folds
cordierite	sheath folds
andalusite	non-cylindrical folds
kyanite	helicitic structures
sillimanite	
gedrite	

CONCLUSIONS

Faults and shear zones were a dominant control of mineralization in Archaean terranes. These structures acted as channelways for both Au-bearing ore fluids and highly fractionated magmatic melts. However, these mineralization types rarely occur together because of the different temperature–pressure regimes under which they form. The types of structures and metamorphic conditions associated with each type of mineralization is distinctive. Gold deposits occur in brittle–ductile structures which were associated with low- to medium-grade metamorphism. In contrast, rare-metal magmas occur in parts of the crust in which ductile deformational processes dominated and which were associated with medium- to high-grade metamorphic conditions. Therefore, it should be possible to use the criteria outlined above, in conjunction with detailed structural and metamorphic mapping, to identify the most prospective parts of these fault or shear systems for gold or rare-metal mineralization.

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