ELSEVIER

Journal of Structural Geology 26 (2004) 1087–1108

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Fault/fracture density and mineralization: a contouring method for targeting in gold exploration

Gerard I. Tripp[a,*], Julian R. Vearncombe[b]

[a]Placer Dome Asia Pacific, PO Box 862, Kalgoorlie WA 6430, Australia
[b]Vearncombe & Associates Pty Ltd, 38b Kintail Road, Applecross WA 6153, Australia

Received 27 November 2002; received in revised form 4 August 2003; accepted 25 September 2003

Abstract

A widely observed correlation between high fracture density and mineralization throughout terranes and geological time indicates a fundamental underlying ore-forming process. In Archaean greenstone-hosted deposits, high-density fracturing was accompanied by enhanced fluid flow during fault/fracture network development, producing regional-scale fluid pressure gradients that focussed hydrothermal fluids into preferentially fractured areas. Fracture density is both increased and decreased during faulting and fault healing, and fracture density accumulates over time, in zones of high palaeo-fluid flow. Localised zones where the density of fracturing is increased by deformation, become permeability nodes for migrating hydrothermal fluids leading to large zones of alteration and gold precipitation. The Ora Banda mining centre in Western Australia contains significant gold deposits that appear to demonstrate a close association between high-density fracturing and gold precipitation. Fracture density in the Ora Banda mines was enhanced by fault–fault intersections, fault–contact intersections and changes in fault geometry. The mine-scale relationships between fracture density and gold mineralization are repeated at smaller and larger scales, hence these relationships may be used in targeting for gold exploration. Contouring the density of fracturing in a region provides a semi-quantitative way to rank areas for exploration and uses data from mapping, drilling and high-quality geophysical data as a basis for analyses. Fracture density contouring is complementary to other prospectivity-analysis methods.

Keywords: Fault; Fracture density; Mineralization; Gold; Exploration

1. Introduction

The relationship between fracture density, fluid flow and ore deposition is well known and is extensively documented in the geological literature (Agricola, 1556; Lindgren, 1933; Bartley, 1948; Bateman, 1948; Lang, 1948; Meyer et al., 1968; Phillips, 1972; Sibson, 1987, 1996, 2002; Castaing, 1991; Caine et al., 1996; Oliver, 1996; Jamtveit and Yardley, 1997; Oliver et al., 1998; Cox, 1999; Lonergan et al., 1999; Gudmundsson et al., 2001; Robert and Poulsen, 2001; Madrid and Garwin, 2002; McLellan, 2002). Recent studies also document regional spatial links between gold mineralization and highly fractured zones in small-displacement faults in Archaean greenstone belts (Hodgson, 1989; Solomon and Groves, 1994; Witt et al., 1997; Vearncombe, 1998; Vearncombe and Vearncombe, 1999; Tripp, 2000a).

Archaean lode gold deposits in the north Kalgoorlie district, Western Australia, are mainly hosted by faults of small dimensions: up to several kilometres long, 0.5–20 m wide and with small displacements of tens of metres or less. The faults cross-cut stratigraphy and earlier regional-scale ductile shear zones forming a regionally developed interlinked network or mesh (Sibson, 1996; Vearncombe, 1998). Ore shoots in gold deposits of the Kalgoorlie district are generally controlled by fault/fracture interaction: high-grade ore shoots are developed at intersections with other faults/fractures or zones of anisotropy and at changes in orientation of a host fault. Such areas including dilational jogs, fault bends/terminations and fault–fault intersections, occur as components of interlinked fault/fracture networks. Fault/fracture networks are characterised by internal zones of high-density fracturing, controlled by fault/fracture geometry and intersection density. A simple positive correlation exists between the locations of perturbations in faults, the density of rock fracturing and fluid flow, as inferred from the distribution of rock alteration and

---

* Corresponding author.
E-mail addresses: gerard_tripp@placerdome.com (G.I. Tripp), julian@vearncombe.com (J.R. Vearncombe).

0191-8141/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.jsg.2003.11.002

mineralization. These zones may be further localised by anisotropy such as primary layering and intrusions (Tripp, 2000b).

A contouring method of quantifying the distribution of fault/fracture density is presented here to assist in the ranking of areas based on their potential as palaeo-conduits of enhanced fluid flow. The purpose of this paper is to present the fault/fracture relationships of gold mineralization at Ora Banda, Western Australia (Tripp, 2000a,b), and to communicate the exploration potential of fault/fracture density contouring as a complementary technique to the more common methods of prospectivity analysis (e.g. Knox-Robinson and Robinson, 1993).

2. Controls on fracture density during crustal faulting

Faults formed during fluid-pressure dominated deformation have resultant anastomosing to planar geometry. The faults may be manifest as a single plane of breakage, or may form zones of fracturing and brecciation of up to several metres thickness with low displacements on the order of tens of metres and rarely kilometres. The terms 'fault' and 'fracture' are used interchangeably in this paper. At a regional scale (1:100,000) the low displacements, which may be characteristic of the faults, are represented by negligible offset of stratigraphic markers with the faults appearing as simple fractures on regional plans. At a mine scale (1:10,000) the displacements are more pronounced and the same features are manifest as faults with offset. At hand specimen and microscopic scales, the faults may be manifest as zones of highly fractured rock with no indications of offset: the same structures are observable at different scales, with different characteristics dictated by the scale of observation.

The textural characteristics of fault rocks indicate that space creation during faulting is temporary with fault healing by hydrothermal vein precipitation. Pore volume and fluid flow rates increase with each failure episode, but then decrease as the fault is healed with the rock mass returning to an intact state. Faults that behave in this manner are analogous to valves that open and shut and control the flow of fluid during failure and healing (Sibson et al., 1988). The creation of space in rocks increases the existing permeability of the immediate rock mass and influences the permeability structure of the crust in regions of fault network development. In this paper we focus on the processes that increase fracturing in a rock mass over time, providing evidence for high volume fluid flow through spatially restricted zones.

2.1. Fracture density enhancement

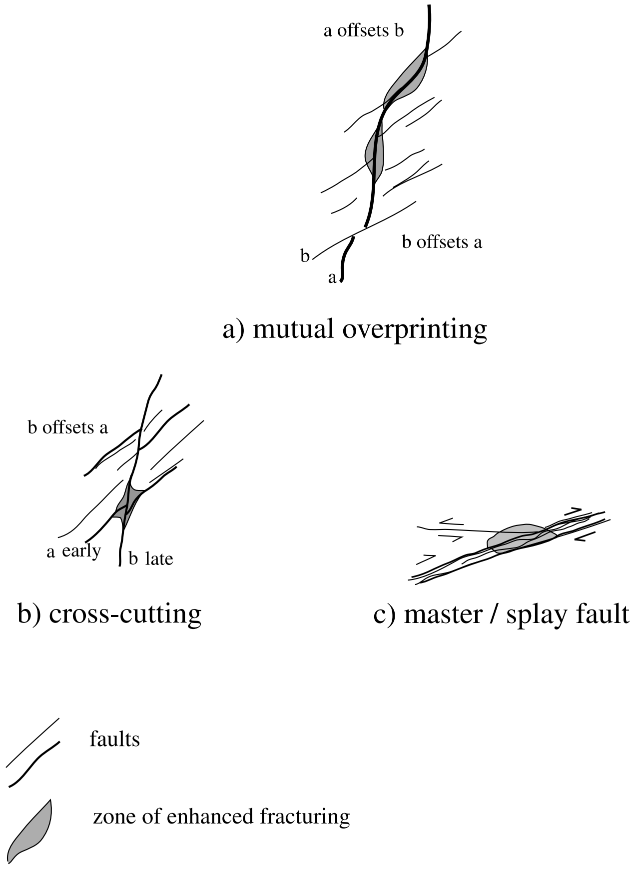


Fig. 1. Diagram of various fault–fault interactions: (a) mutual overprinting; (b) cross-cutting; (c) master/splay fault relationships. In (a) and (b) the interactions may result in either a simple offset or a zone of enhanced fracturing.

There are three primary ways that fracture density is enhanced within a fault; (1) changes of fault geometry; (2) fault–fault intersections (Fig. 1); and (3) intersections between faults and pre-existing anisotropy. Fault/fracture density may also be high from a concentration of subparallel faults in an area more amenable to faulting and fracturing. Vein emplacement is a common characteristic in faults, with variable relationships of emplacement timing including undeformed vein emplacement, intra-vein breccia, and shear vein development. The processes that enhance fracture density control the degree and type of vein emplacement in sites of low mean stress. Vein mineralogy and texture usually reflect the fluid composition and fluid pressure conditions, respectively, at the time of fracturing. Fluid flow can also be effective in faults and shear zones without a vein component (Craw et al., 1999).

2.1.1. Fault geometry

Changes of fault geometry localise zones of dilation leading to fluid influx and wallrock rupturing during fault movements (Sibson, 1987; McCaig, 1989) The orientational change and kinematics can control the dilational character of faults (e.g. right-hand bends in right-lateral faults; left-hand bends in left-lateral faults), and the concept is also applicable to normal and reverse faults where the faults either steepen or flatten in dip (Branquet et al., 1999; Jolley et al., 1999). Opposing fault bends can produce zones of enhanced fracturing in restrictional bends where the wall rocks are brecciated and abraded.

Fault bends may develop over time as a consequence of rupture arrest and dissipation of the fault displacement into horsetail splays, providing a process for linkage between adjacent faults. Fault bends are typically areas where dilational jogs develop, and may result from fault linkage between two parallel but separate structures with enhanced fracture-induced permeability and fluid migration pathways developed at the site of dilation (Connolly and Cosgrove, 1999).

2.1.2. Fault–fault intersection

Fault–fault intersections are commonly zones of enhanced fracturing, but the nature of the intersection can also be influenced by the kinematic characteristics of individual faults that are synchronously developed and mutually cross-cutting (Fig. 1a). If an earlier generation of faults is cross-cut by a later generation, the intersection may produce a linear body of more highly fractured rock or a simple offset. Where synchronous, the faults may be through going with a simple cross-cutting relationship (Fig. 1b), or have a master-and-splay fault relationship (Fig. 1c).

Interactions of conjugate faults are either volume neutral, net dilatant or net constrictional. A dilational zone may result if the kinematics of the two intersecting faults are different because of fault wedges in opposing quadrants of a fault couple moving away from the intersection point. Conversely where the kinematics of the two faults are the same, a net constriction may result if the fault blocks behave rigidly, have similar displacements and fault rotation is minimal. Torsion in the wall rocks of splay faults may also produce high density fracturing locally (e.g. Martel, 1999). Multiple intersections of synchronous faults in variable orientations can result in high-density fracturing at the intersection point regardless of individual fault kinematics.

2.1.3. Anisotropy

The presence of anisotropy is an important control on the partitioning of strain. Zones of anisotropy such as bedding contacts, igneous layering, rigid body rock contacts and zones of alteration hardening produce variations in rock properties (tensile rock strength, layer cohesion), which may lead to enhanced fracturing where the contacts are traversed by faults (e.g. Bateman, 1948).

The geometry and orientation of anisotropy and its type (rock layers, intrusion contacts, etc.) may also contribute to the development of high density fracturing at the point of intersection. Geometrical changes in granite contacts can provide sites of dilation where intersected by faults, whereas the orientation of bedding and igneous layering to the principal shortening direction in an orogenic belt may facilitate dilation (if parallel), shear (if at a low-moderate angle), or constriction (if normal).

2.2. Fluid flow considerations

Fault rocks commonly contain a significant vein component. Veins in rocks are characterised as planar zones of hydrothermal precipitation infilling rock fractures. Rock mass permeability and therefore fluid flow in a rock sequence is controlled by the amount of available pore space, and in regional metamorphic rocks may be principally controlled by grain boundary connectivity (Sanderson and Zhang, 1999). Fracturing developed as a result of imposed stresses increases the permeability of a rock mass and the rates of fluid flow by orders of magnitude (Bolton et al., 1999), and may link fluid sources and depositional sites at a percolation threshold, which is dependant on several variables including fracture connectivity (Cox, 1999). Fracture density therefore is an important control on permeability, and a time-control on fracture density accumulation needs to be considered when attempting to qualify the palaeo-permeability of a rock mass. Levels of permeability within the architecture of a fault zone can be distinguished (Caine et al., 1996), with the hydrologic properties of high-density fracture networks in the damage zone of a fault acting as the dominant control on fault permeability.

Palaeo-permeability nodes are localised zones of crust that accommodated large-volume fluid flow. Identifying these nodes requires a control for detecting the palaeo-flow of fluid. In mineralized terranes, large-scale alteration systems are characteristic of areas that were the focus of fluid flow. Regional metamorphic assemblages are locally replaced by new minerals, indicating the passage of a fluid through the rocks that was out of equilibrium with conditions in the local environment. These zones may be spatially restricted to the wallrocks of centimetre-thick veins, or may produce kilometre-scale wallrock alteration zones around major structures and intrusions (e.g. Eastern Goldfields Province, Western Australia). Recognition of these nodes in ancient terranes is indicative of regional fluid flow gradients when developed at kilometre scales: the flow of hydrothermal fluids was enhanced at the location of the node with decreasing flow rates and subsequently less alteration of the wallrocks away from the node.

Faulting and fracturing may enhance fluid flow, whereas high fluid pressure can also generate crustal faulting and fracture networks (e.g. Sibson and Scott, 1998). Hence a simple cause and effect relationship cannot be established between fault development and fluid flow. The most likely relationship is a feedback relationship controlled by a balance between deviatoric stress and fluid pressure. A coincidence of high density fracturing with recognised palaeo-permeability nodes indicates a close spatial relationship between fracture-density and fluid flow.

3. Fracture density and mineralization

Fault/fracture-controls on mineralization (faulting/shearing) are well documented throughout the economic literature and most authors recognise structure as a first order control on the siting of ore (e.g. Phillips, 1972; Hodgson, 1989; Vearncombe et al., 1989; Groves and Ho, 1990). This control may be: (1) in major shear zones or in higher order splay structures genetically related to movements on the main shear zone (Vearncombe et al., 1989; Phillips et al., 1998); (2) in zones of intersecting multiple faults of similar or markedly different orientation (Meyer et al., 1968); (3) in high strain zones localised by layer anisotropy such as bedding-parallel thrusts (Jolley et al., 1999); (4) in stockwork-type associations within highly-fractured rigid bodies (Ridley and Mengler, 2000); and (5) in folded structures such as saddle reefs in slate belt deposits (Cox et al., 1986; Forde and Bell, 1994). The intensity of structural development may be enhanced by other factors such as discussed in Section 2.1, and the processes of mineralization may be further enhanced by structures cutting rocks of favourable chemistry (e.g. Phillips, 1986; Groves and Phillips, 1987; Kerrich, 1989).

The concept addressed in this paper of the relationship between fault/fracture density and mineralization is extensively dealt with in the economic geology literature. From such wide recognition throughout terranes globally and in rocks of various geological ages, we consider the fault/-fracture density–mineralization relationship as a fundamental control on the development of ore in structurally controlled ore systems. References can be found as far back as Agricola (1556) and more recently Lindgren (1933), Bateman (1948), Lang (1948) and Meyer et al. (1968), dealing with the fracture-density and mineralization relationship in some detail especially in the control of high grade ore shoot location. Most of the references listed deal with the intersection of fractures, but some also deal with the time controls on cumulative fracturing (Meyer et al., 1968; Castaing, 1991), the controls of lithological diversity and planar anisotropy on the density of fracturing (Bateman, 1948), and geometrical changes of the hosting structure (Lindgren, 1933). Our approach is a logical outgrowth of this recognition, which attempts to use the relationship in exploration for high-grade shoots in known districts, and for the discovery of new mineralized districts.

The introduction of hydrothermal minerals into a rock mass via veins or foliation zones is an obvious result of the flow of mineralizing fluids. Pervasive fluid-flow is suggested as the most efficient regional process for extraction of ore fluid components from the crust under greenschist–amphibolite facies conditions (Oliver et al., 1998). This occurs via an interconnected grain-scale network across large regions driven by thermal or deformation induced regional fluid pressure gradients. The interconnected grain-scale network may be either a microcrack network produced during deformation, resulting in broad, evenly distributed low strains (Oliver, 1996), or an intergranular film localised along grain boundaries (e.g. Fyfe et al., 1978). Fluid-flow during metamorphism may be either pervasive or channelised (Oliver et al., 1998), and channelised flow is more likely to operate in the focussing and precipitation phase of fluid flow (Fyfe, 1991). Faults/fractures are conduits that localise gold fluids during deformation, whereas the grain–boundary network is a pervasive system that may not provide conditions favourable to ore formation.

Gold mineralisation occurs as a result of destabilisation of a fluid that transports gold. This destabilisation may occur by changing any combination of a number of variables that work to maintain the solubility of gold in a fluid. Variation in temperature, pressure, pH, oxygen fugacity (fO_2), sulphur fugacity (fS_2) and mole fraction of CO_2 (XCO_2) may result in precipitation of gold through fluid–wallrock interaction, mixing of two or more fluid species or phase separation in fluids associated with rapid loss of confining pressure during faulting. The particular control on ore precipitation may vary locally when rock chemistry or multiple fluid species are important controls (e.g. Groves and Phillips, 1987; Ridley et al., 1996). Destabilisation of equilibrium fluid conditions during fracturing is a common catalyst in all fault controlled ore systems (Mikucki and Groves, 1990). Space creation during fracturing dramatically changes the ambient pressure and temperature conditions and materially affects the permeability of a rock mass. Phase separation in general results in increasing pH and fO_2 with a decrease in reduced sulphur content, with competing effects on the gold-solubility of the remaining ore fluid (Mikucki and Groves, 1990).

4. Fault controls on Archaean gold deposits at Ora Banda, Western Australia

Examples of fault-controlled ore deposits are discussed in detail from the Ora Banda mining centre, 69 km northwest of Kalgoorlie in Western Australia (Fig. 2). Ora Banda mining centre is a gold production district of significance (85 tonnes Au) in the Ora Banda Domain of the Kalgoorlie Terrane (Swager et al., 1990), which forms part of the Archaean Norseman–Wiluna greenstone belt.

The geology of the Ora Banda mining centre is dominated by a moderately southwest-dipping sequence of igneous and sedimentary rocks, with extensive layer-parallel syn-volcanic mafic sills (Fig. 3). The sequence was intruded by late-tectonic granitoid stocks and porphyry dykes and sills. The Ora Banda mining centre is particularly suited to this analysis since the faults that control gold deposits have no major effect on the distribution of the greenstones, and hence do not suffer from equivocal movement and mineralization timing-relationships, as is characteristic of the larger greenstone controlling shear

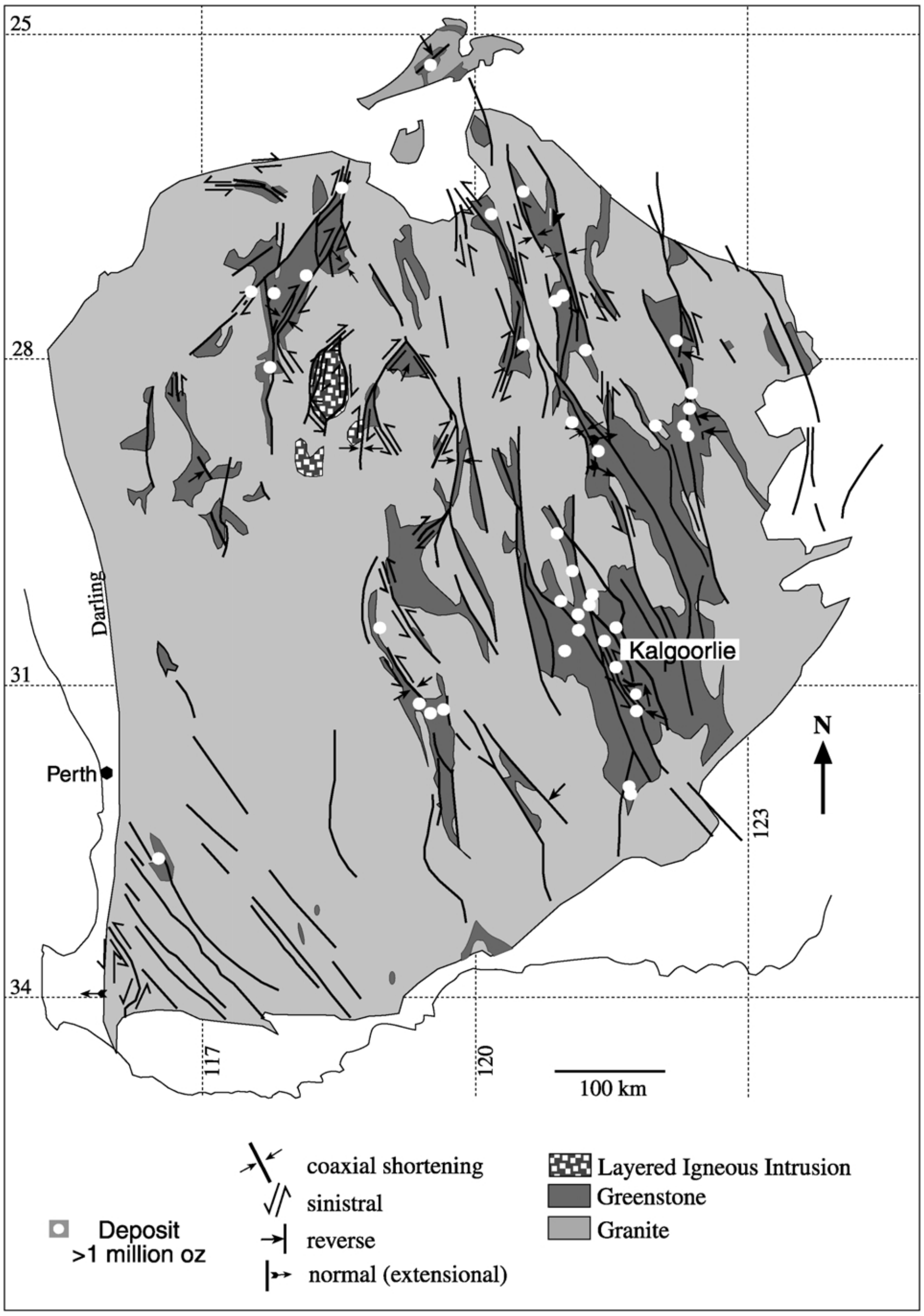


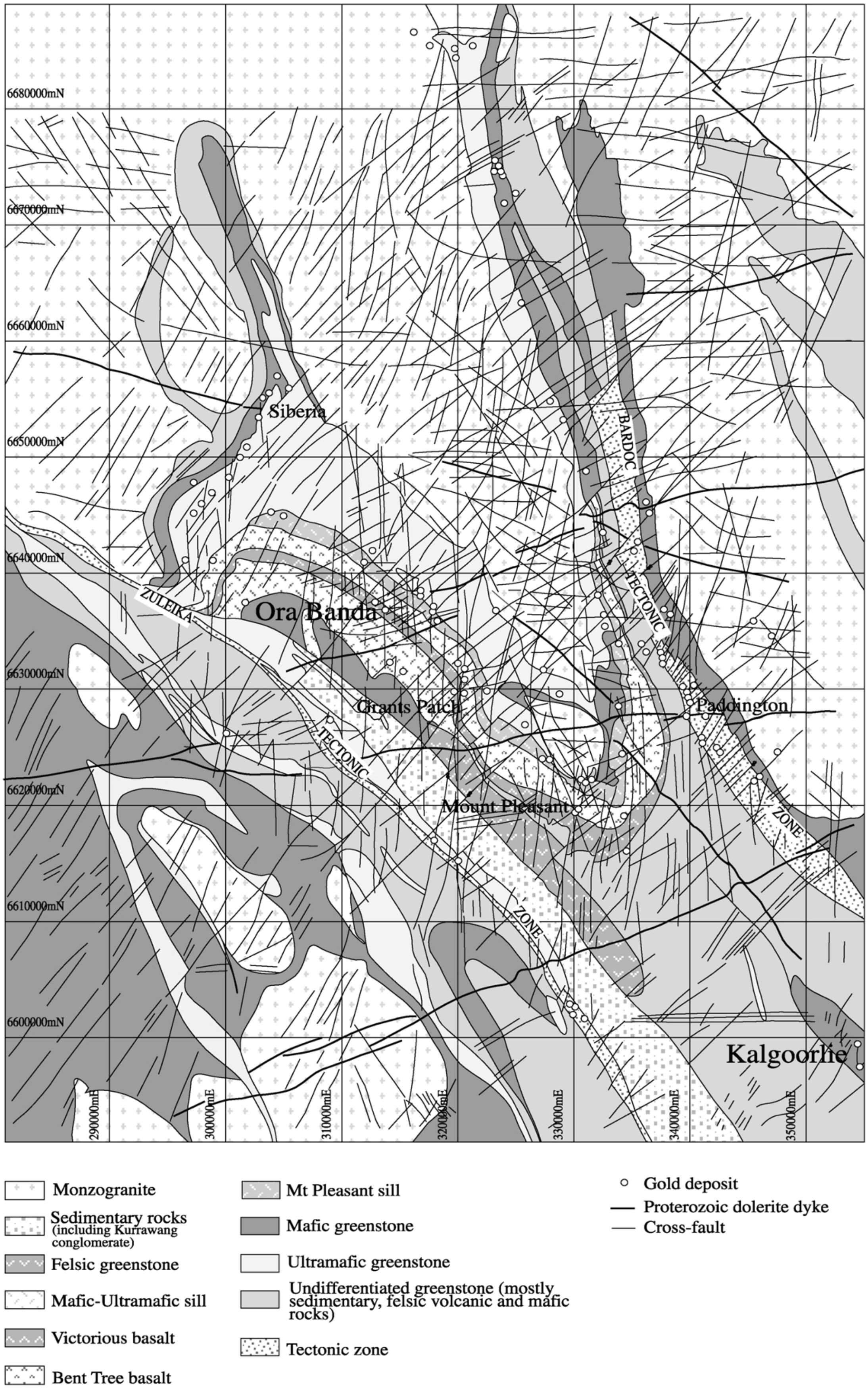
Fig. 2. Geology of the Yilgarn Craton, Western Australia showing the location of >1 million ounce gold deposits and the location of Kalgoorlie and Ora Banda, in the Eastern Goldfields Province.

zones. The faults are mostly small displacement structures (up to 1 km) with minor offsets and disruptions of a continuous stratigraphic sequence, and are readily identified on aeromagnetic images (cf. Figs. 3 and 4).

Two other gold mining centres at Grants Patch and Mount Pleasant are located within the same igneous succession as Ora Banda with similar fault controls on gold mineralization documented in each of these areas. The three major controls on fracture density (Section 2.1) are identified in the Slippery Gimlet, Gimlet South and Enterprise mines at Ora Banda (Fig. 5). The ore structures are stacked in a NW–SE direction with a similar geometry to ore shoots described by Peters (1993).

4.1. D2 Shear zone/fault network

The structural geological history of the north Kalgoorlie district involved two main phases of shortening. Early D1 S–N thrusting produced localised stratigraphic repetition and folding of the greenstones. The D1 phase was followed by a major thick-skinned phase of shortening (D2) from an ENE–WSW direction resulting in upright folds (D2a) with


6680000mN
6670000mN
6660000mN
6650000mN
6640000mN
6630000mN
6620000mN
6610000mN
6600000mN
290000mE
300000mE
310000mE
320000mE
330000mE
340000mE
350000mE
Siberia
Ora Banda
Grants Patch
Mount Pleasant
Paddington
Kalgoorlie
ZULEIKA
TECTONIC
ZONE
BARDOC
TECTONIC
ZONE
Monzogranite
Sedimentary rocks (including Kurrawang conglomerate)
Felsic greenstone
Mafic-Ultramafic sill
Victorious basalt
Bent Tree basalt
Mt Pleasant sill
Mafic greenstone
Ultramafic greenstone
Undifferentiated greenstone (mostly sedimentary, felsic volcanic and mafic rocks)
Tectonic zone
Gold deposit
Proterozoic dolerite dyke
Cross-fault

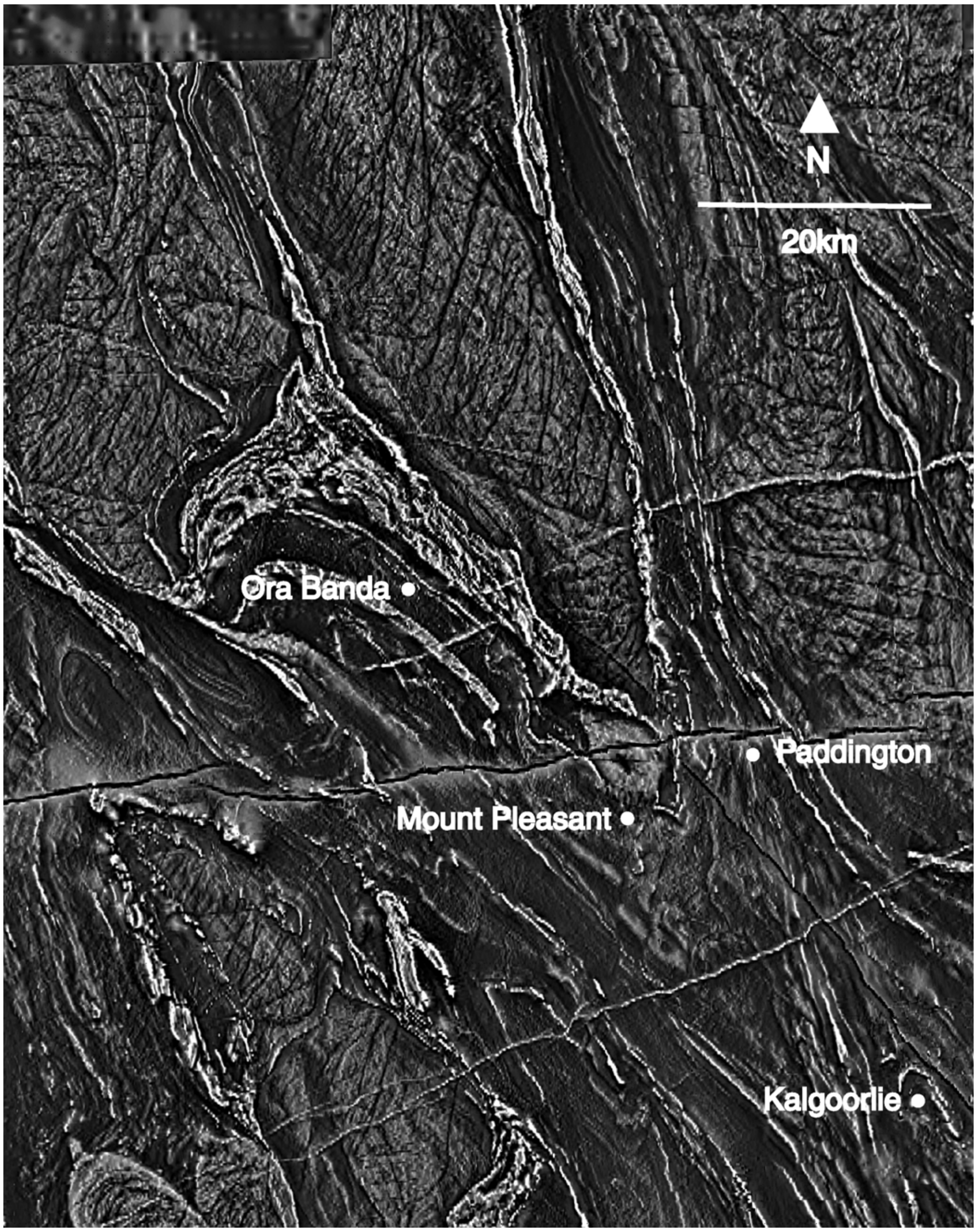
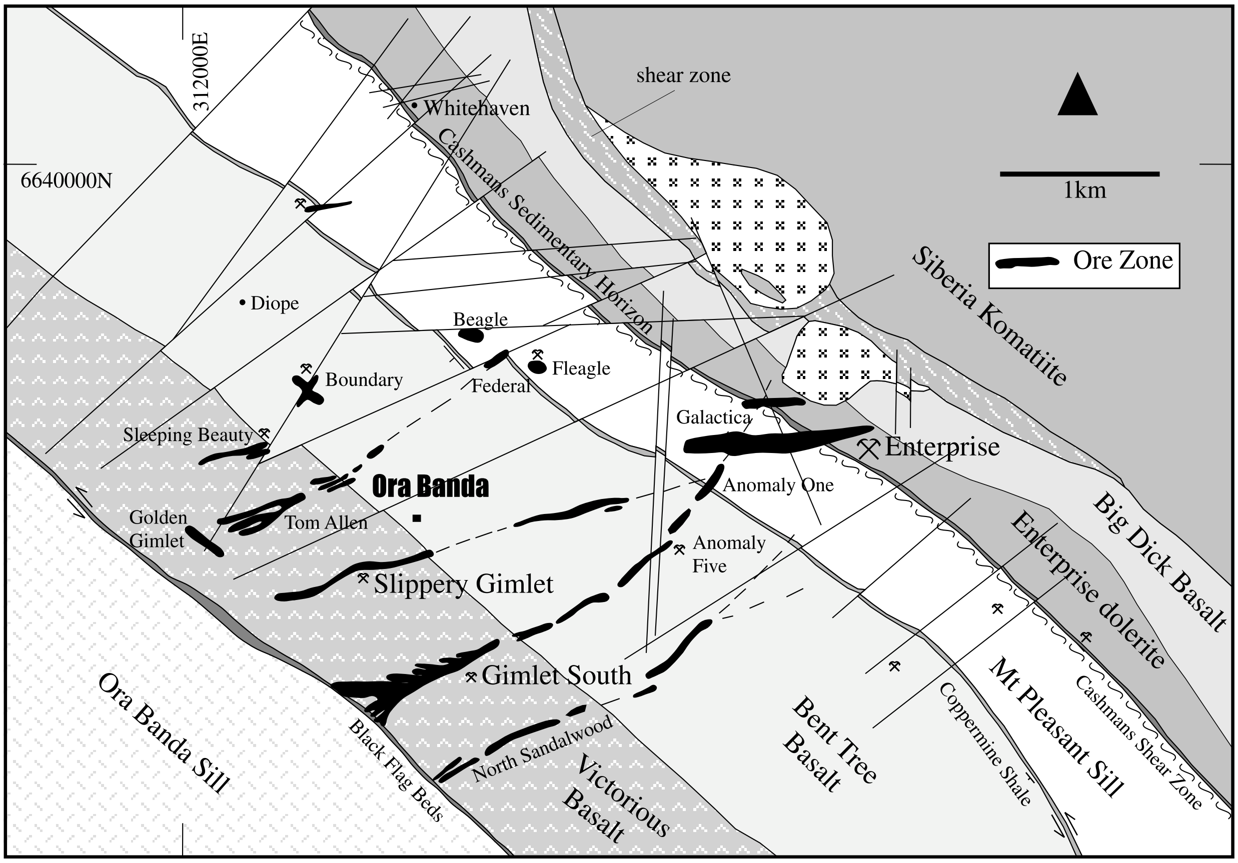


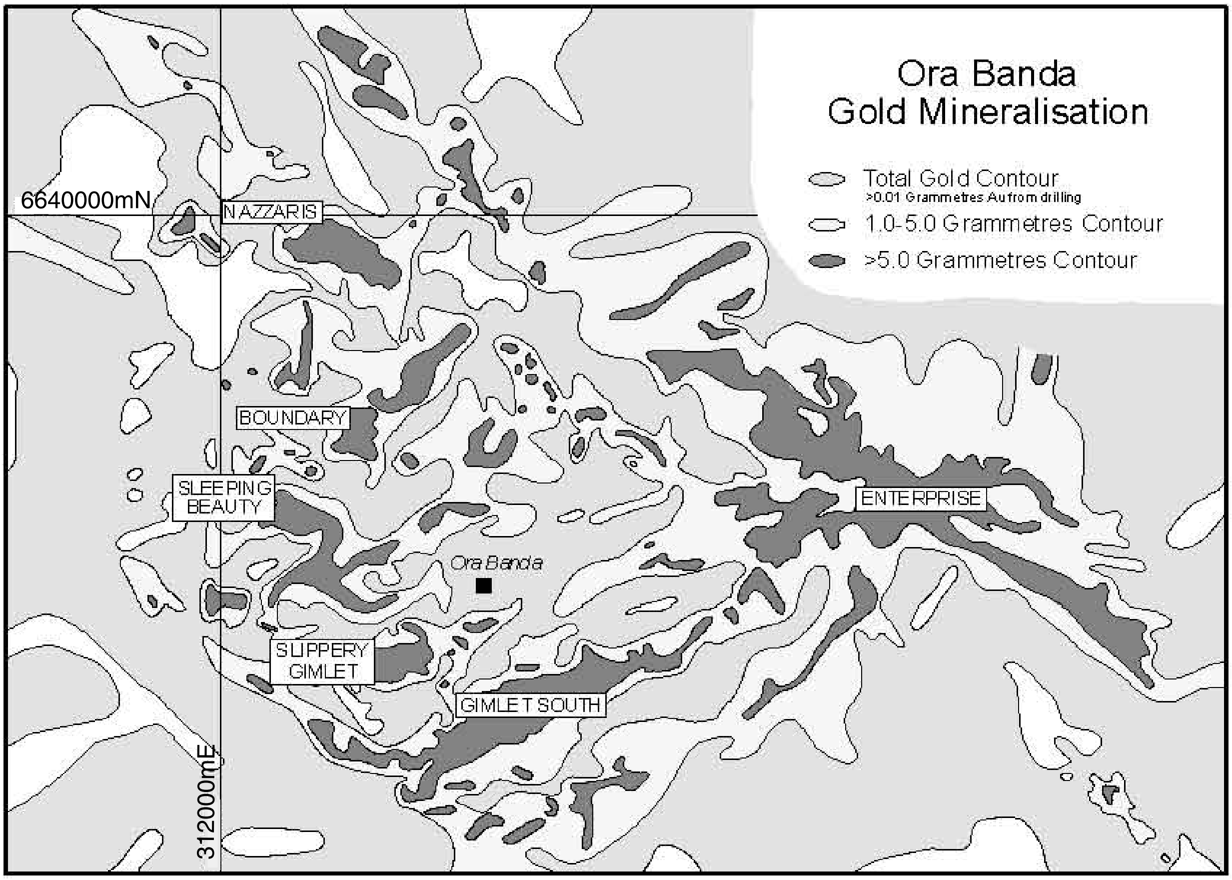
Fig. 4. Greyscale image of aeromagnetic data processed as a first vertical derivative of the raw data, reduced to pole, with auto gain control filtering applied. Light shades: high magnetic susceptibility; dark shades: low susceptibilities. Compare with the geological map in Fig. 3 for magnetic response of the various rock types.

subvertical axial plane cleavage. Folding was followed by partitioning of strain into NW- and NNW-trending shear zones; and reactivation of NW–SE-trending rock contacts as thrusts (D2b). As the crust was exhumed or strain rate increased with elevated fluid pressures, a regionally developed fault network cross-cut all earlier structures (D2c; Tripp, 2002). The faults are distributed as a network in the Ora Banda mining district with three principal fault orientations recognised as N–S, NE–SW and E–W. These three orientations are distinct in detailed aeromagnetic images as revealed from offsets of stratigraphic marker units, but the majority of mineralized structures have a NE–SW orientation (Fig. 5). Mine-scale observations confirm the three fault orientations, whereas analysis of the

---

Fig. 3. Geology of the north Kalgoorlie district (Australian Map Grid; AGD84). Elongate belts of greenstone are interspersed with batholithic monzogranite intrusions, and folded into upright, shallow plunging megascopic folds. The folds are truncated by narrow shear zones, and all structures are cross-cut by a regionally developed, interlinked fault network.


312000E
6640000N
shear zone
1km
Ore Zone
Whitehaven
Cashmans Sedimentary Horizon
Siberia Komatiite
Diope
Beagle
Fleagle
Boundary
Federal
Galactica
Enterprise
Sleeping Beauty
Ora Banda
Anomaly One
Golden Gimlet
Tom Allen
Anomaly Five
Slippery Gimlet
Gimlet South
Big Dick Basalt
Enterprise dolerite
Mt Pleasant Sill
Cashmans Shear Zone
Coppermine Shale
Bent Tree Basalt
Victorious Basalt
North Sandalwood
Black Flag Beds
Ora Banda Sill


Ora Banda Gold Mineralisation
Total Gold Contour
>0.01 Grammetres Au from drilling
1.0-5.0 Grammetres Contour
>5.0 Grammetres Contour
6640000mN
NAZZARIS
BOUNDARY
SLEEPING BEAUTY
ENTERPRISE
Ora Banda
SLIPPERY GIMLET
GIMLET SOUTH
312000mE

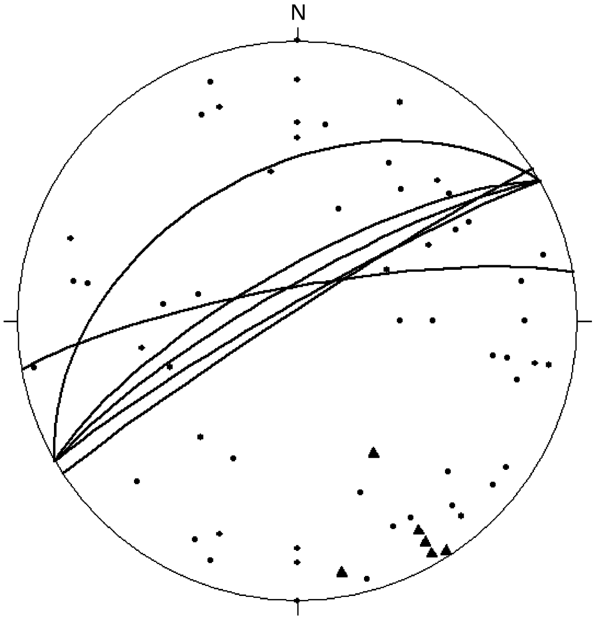


Fig. 6. Lower hemisphere, equal area stereogram showing the orientation of 66 gold deposits in the Ora Banda Domain. Great circles and triangular pole symbols are for deposits with >300,000 ounces endowment including the Gimlet South, Enterprise, and Quarters deposits: all >1 million ounces gold endowment.

distribution of gold compared with orientation shows that the majority of the endowment is contained in NE–SW- to E–W-trending faults (Fig. 6). The fault sets are mutually overprinting in all exposures with no consistent distinction in timing between the sets. Correlation of faults with mineralization indicates that the NE–SW faults are the best mineralized. However, there are no specific fault timings that preferentially relate to mineralization. Three examples of mines developed in these faults are discussed in detail as follows.

Gold mineralization is timed as beginning early in D2 and continuing throughout the various D2 shortening phases (Tripp, 2002). From this timing all thrusts, partitioned shear zones, network faults and their intersections are potential targets for mineralization. This deformation sequence treats only the contractional phases of deformation, which appear to be the main controls on mineralization. Earlier and intervening extensional deformation phases controlled the deposition of clastic basins, but, to date, are not demonstrated as controlling mineralization.

4.2. Slippery Gimlet mine

The Slippery Gimlet gold deposit is a small satellite deposit of the Ora Banda mining centre (Fig. 7), where historic production was primarily focussed on the Gimlet South deposit (Harrison et al., 1990). Slippery Gimlet was the initial discovery in a system of sub-parallel anastomosing faults with a dominant northeast structural trend, which cut across the strike of igneous layering at about 80°–90°.

The host sequence is the Victorious Basalt, a plagioclase-phyric series of lava flow rocks of the Grants Patch Group (Witt, 1990). Several continuous flow layers were distinguished petrographically and geochemically defining a ‘volcanic stratigraphy’ (Harrison et al., 1990). Individual flows are represented by zones of variable grainsize from fine-glassy pillow basalt to coarse-grained non-pillowed flow rocks. The coarse-grained varieties are integral parts of the sequence with preserved primary-gradational contact relationships that indicate an extrusive origin.

At the Slippery Gimlet mine, significant dilation occurred where a NE–SW-trending fault cross-cuts a rheologic boundary between fine-grained and coarse-grained pillow basalt units (Fig. 7). The Slippery Gimlet ore shoot is an example of a dilational jog at the mine-scale, where dilation and brecciation were enhanced by a change in fault orientations, or linkage of two sub-parallel faults along primary igneous contacts. In longitudinal section, the host structure exhibits lithologically controlled ore shoots plunging in the plane of the fault. The location of the dilational jog appears to be controlled by a significant change in grain-size of the basalt sequence, where it is intersected by the host fault. A mineral elongation lineation in the fault defined by aligned micas trending 20° → 245° indicates dominantly strike-slip movement sense, S–C fabric geometry indicates right-lateral displacement, and the mineral elongation lineation confirms normal oblique-slip movement on the fault. Very little displacement of the contacts is observed, which can be explained by the slip vector plunging at an angle close to the dip of bedding. The contact between fine-grained and coarse-grained basalt is a 0.6-m-wide layer-parallel shear zone with a strong mineral elongation lineation developed in the plane of foliation.

The two segments of the NE–SW-trending host fault are separated by a 35-m-wide jog zone that contains a series of planar parallel cataclasite zones and cross-cutting randomly distributed breccia lodes. Within the dilational jog, sub-parallel quartz veins are spaced at 2 m intervals, whereas breccia zones are irregularly developed. Individual veins average 10 mm wide, with calcite–muscovite–pyrite–pyrrhotite alteration halos up to several metres wide. The breccias and cataclasites display a wide range of textures from weakly deformed planar fracture zones with sub-parallel wallrock fragments, to complex mill breccia with rounding of clasts.

In summary, the presence of layer anisotropy at the

Fig. 5. Geology and mineralization of the Ora Banda mine corridor. Upper figure showing the NW-trending interlayered mafic volcanic sequence, cross-cut by high angle, low displacement faults; lower figure showing the distribution of gold mineralization over the same area contoured from exploration drilling, and the close association of fault–fault and fault–contact intersections on the distribution of high grade gold.

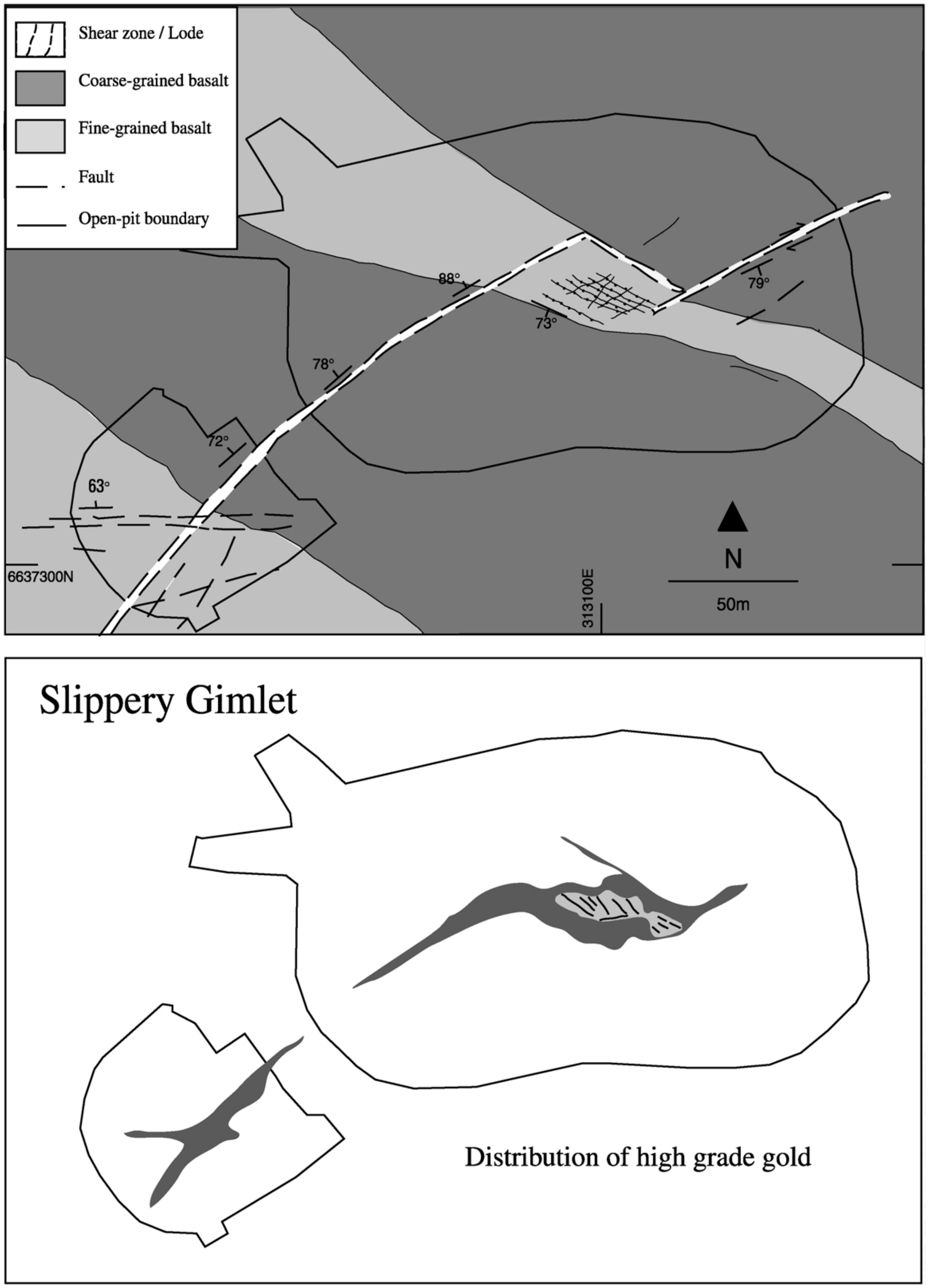


Fig. 7. Geology and mineralization of the Slippery Gimlet open pit mine. Upper figure showing the NW-trending grain-size variation in the layered basalt sequence cross-cut by the Slippery Gimlet fault; lower figure showing the distribution of gold mineralization over the same area, with the high grade zone located at the grain-size change (gold distribution map from C. Handley written communication, 1988).

Slippery Gimlet mine appears to be a major control on the location of the ore. The intersection of a NE–SW-trending fault pair with this planar anisotropy resulted in a zone of high density fracturing controlled by linkage of the two faults along primary igneous layer contacts. Fluid flow was enhanced through this zone with the introduction of hydrothermally precipitated minerals in veins and breccia lodes of markedly different mineralogy to the basaltic host rock.

4.3. Gimlet South mine

The Gimlet South gold deposit is located 800 m south of the Slippery Gimlet mine with a similar NE–SW-trending fault control within the Victorious Basalt and Bent Tree Basalt host rocks (Fig. 8a). The gold deposit here termed 'Gimlet South' includes the Victorious East lode, Wilson's Lode, Gimlet South lode, Far East lode, Farther East lode, Old Mate spur lode, Corsair spur lode, Avenger and Hornet lodes, which are all components of the same fault system. Full descriptions of the Gimlet South gold deposit are given in Petersen (1987) and Harrison et al. (1990).

At Gimlet South, the igneous formations are multi-layered sequences with a well-defined volcanic stratigraphy similar to those at the Slippery Gimlet mine. As host rocks to gold deposits, specific layers within the flows appear to be more favourable for gold mineralization. Each of the units consists of alternating pillowed, massive doleritic and coarse-grained layers; with the pillowed and massive units hosting gold ore-shoots (Fig. 8a). The intersection of NE–SW-trending faults with layering that dips SW, has produced southwest plunging ore shoots contained within the fault, along the line of intersection with the pillowed and massive units (Harrison et al., 1990) indicating strong fault–fault and fault–contact intersection controls on plunge (Fig. 8a).

The Gimlet South ore envelope is controlled by NE–SW-trending brittle–ductile faults with steep northwest dips. Secondary structural controls result from the intersection of E–W-trending splay faults (Wilson's Lode, Old Mate spur lode and Corsair spur lode) with the NE–SW-trending main structures. The intersection of these two structural orientations has produced zones of high fracture-density with coincident high-grade ore shoots located at the junctures (Fig. 8b). Fault–fault intersections at Gimlet South are of two types; cross-cutting and splay intersections (Laing, 1994). The gold lodes typically get wider at both types of fault–fault intersection and are coincident with well-developed zones of enhanced fracturing, which demonstrates the increased efficiency of fluid infiltration and fluid–wallrock interaction in the high fracture-density areas (Fig. 8b). This relationship also demonstrates a specific spatial relationship between mineralization and fault–fault intersections.

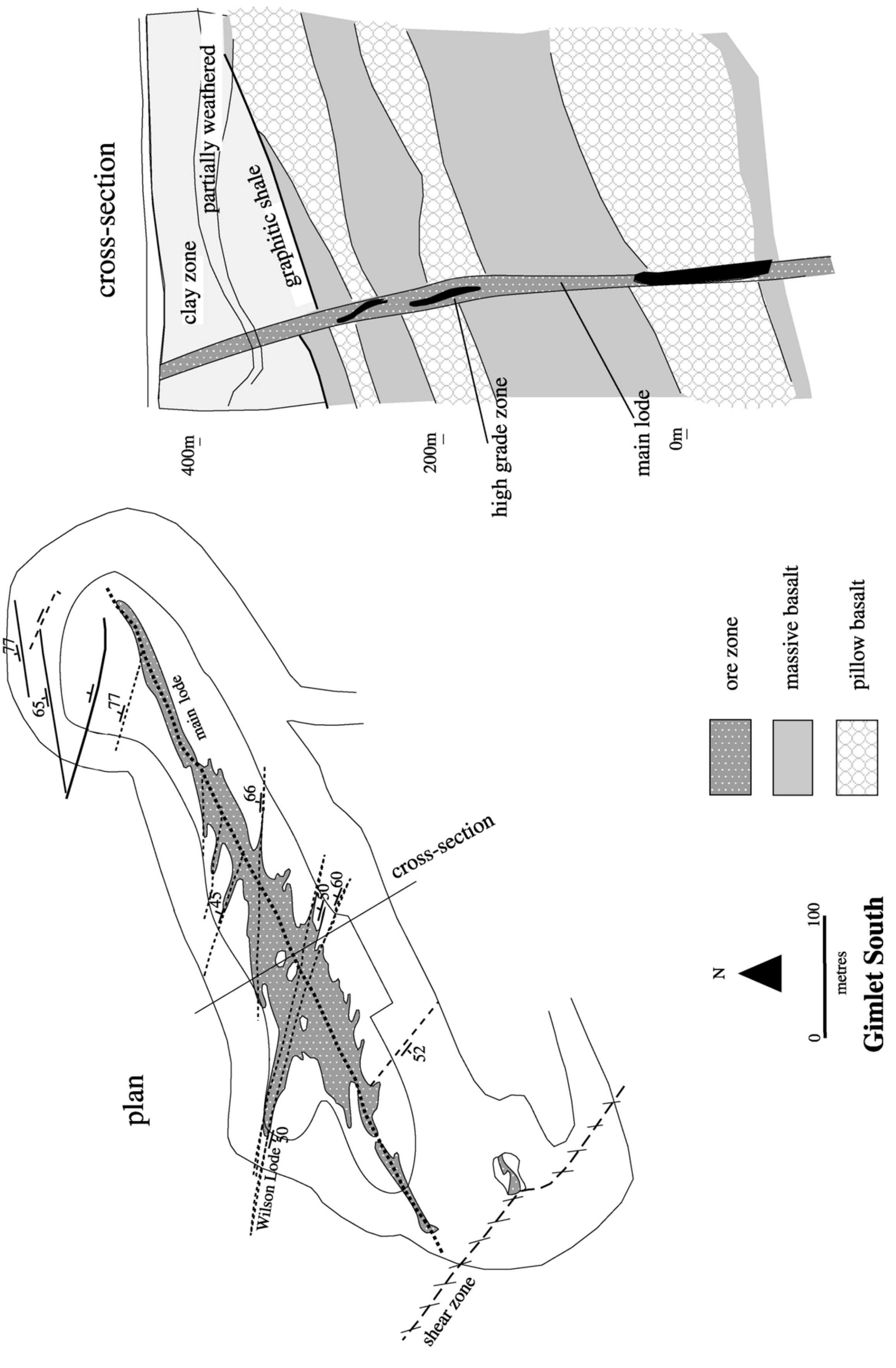
In summary, gold ore is coincident with high density fracturing at Gimlet South mine. The intersection of the host fault with a moderately dipping igneous layering produced broad SW-plunging moderate grade ore shoots. Within these ore shoots, very high-grade zones are controlled by structural fault–fault intersections between the main faults and E–W-trending splay faults. These structural intersections are mapped as intensely fractured zones.

4.4. Enterprise mine

The Enterprise gold deposit is located 2.5 km northeast of the Gimlet South mine at Ora Banda and is discussed in detail in Tripp (2000b). A large zone of intense fracturing and vein emplacement forms the Enterprise fault zone, which is a linking structure within the Ora Banda fault network (Figs. 5 and 9).

The host unit of the Enterprise deposit is a differentiated layered dolerite sill with tholeiitic bulk chemistry (Gregory, 1998), which intruded a 1–2-m-thick sulphidic interflow sedimentary unit (Cashmans Sedimentary Horizon). The Enterprise dolerite has an upper and lower chilled margin against its wallrocks with a crystallization sequence that resulted in the most differentiated part of the sill (Fe-enriched quartz dolerite) being located in the centre of the intrusion (unit 4). The sill is mostly concordant with surrounding country rocks and strikes 120° regionally, whereas its orientation changes to 150° in the vicinity of the Enterprise fault zone, and then to 110° further north. These changes in attitude may have been instrumental in localising the E–W-trending mineralized fault system.

The intersection of the Enterprise fault zone with igneous layering in the host rocks produced a series of plunging ore shoots at about 30° to 260°. The major structural controls in the area are the E–W-trending Enterprise fault zone, NW–SE-trending Cashmans Shear Zone and NE–SW-trending faults such as the Enterprise 030° fault. Ore shoot controls depend on the intersection of these faults with specific layers within the Enterprise dolerite sill, and on fault intersections with the Enterprise dolerite–Mount Pleasant Sill contact. A major change in grain size from the lower coarse-grained norite and hornblende peridotite layers of the Mount Peasant Sill across a contact into fine-grained, plagioclase-dominated Enterprise dolerite may produce a gradient in tensile rock strength. This relationship is suggested by intense meso- and micro-fracturing in the vicinity of the contact and development of a large sheeted quartz vein system, which is restricted to the Enterprise dolerite. This large system of sheeted veins is the most striking group of structures in the Enterprise mine, with strike persistent veins that are sub-parallel over hundreds of metres. Strong vein development in the Enterprise dolerite that does not extend into the overlying Mount Pleasant Sill indicates that the Enterprise dolerite was more amenable to fracturing than the surrounding rocks. High-grade ore shoots at Enterprise are localised in steeply plunging linear zones that coincide with the intersection of brittle–ductile faults and veins with enhanced gold-grade and fracturing at


cross-section
clay zone
partially weathered
graphitic shale
400m
200m
0m
high grade zone
main lode
plan
main lode
cross-section
Wilson Lode
shear zone
77
65
77
66
45
50
60
52
50
ore zone
massive basalt
pillow basalt
N
0
100
metres
Gimlet South

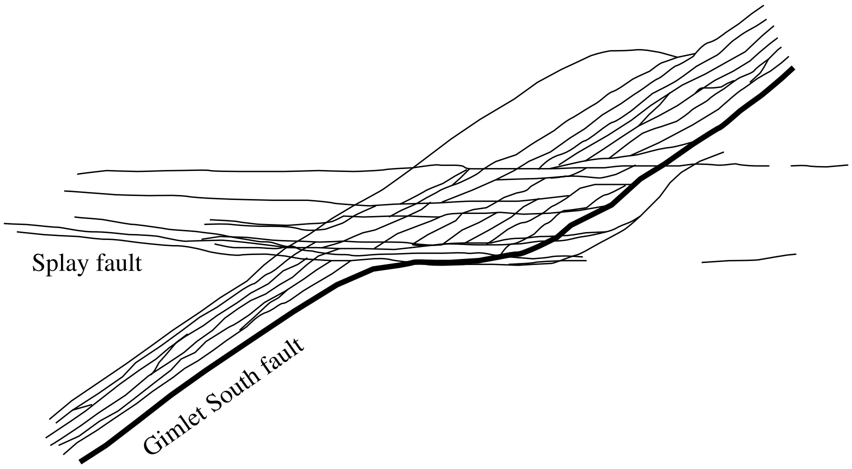


Fig. 8 (*continued*)

the intersections. Although planar faults are the primary control, the distribution of gold within any given brittle–ductile fault is variable along strike and at depth, and is controlled by fault–fault and fault–contact intersections.

In summary the Enterprise mine displays several controls on fracture density including changes in fault/contact orientation, fault–fault intersections and fault intersections with layer anisotropy. High-grade ore shoots are distributed tightly around these locations, and their geometry is predictable from analysing the structural controls.

4.5. Fracture density and mineralization at Ora Banda

The relationship between fault/fracture density and mineralization is amply demonstrated at a mine scale by the gold deposits of the Ora Banda mining centre (Fig. 5). A fractal relationship is demonstrated at a smaller scale on regional aeromagnetic imagery, with abundant kilometre-scale faults coinciding with mapped faults in the Ora Banda mining centre. Areas of localised high fracture-density within the mining centre are individual gold deposits. At the deposit scale, fault–fault intersections or fault–contact intersections produce high-grade ore shoots, and at a mesoscopic scale, high-fracture density zones are usually manifest as meso-fracture arrays at the intersection of two differently oriented structures or in the wallrocks of major brittle–ductile faults.

In the Ora Banda mine corridor, a series of sub-parallel faults characterises the structural framework. The Gimlet South gold deposit (31 tonnes Au) and Slippery Gimlet gold deposit (8 tonnes Au) are located within these faults with ore shoots located at the intersection of the faults with the southwest dipping basaltic host rocks. High-grade ore shoots are associated with grain-size changes, particularly in fine-grained pillow basalt over coarser-grained doleritic layers, and at the intersection of spur lodes (splay faults) with the Gimlet South main lode. Fine-grained flow layers appear to be more brittle and preferentially fractured over the coarser grained doleritic layers, which may be an effect of the overall rock rheology rather than the microstructural controls of grain size on the propagation and growth of cracks. The Enterprise gold deposit (40 tonnes Au) is controlled by a series of E–W-trending faults that intersect a contact between fine–medium-grained dolerite (Enterprise dolerite) and coarse-grained hornblende peridotite (Mount Pleasant Sill). The contact represents a sharp gradient in tensile rock strength evinced by the presence of extensive vein emplacement in the Enterprise dolerite. A zone of high-density fracturing is located adjacent to the contact within the Enterprise dolerite, and is also the location of the Enterprise gold ore shoot.

At Ora Banda, the Slippery Gimlet, Gimlet South and Enterprise mines are located where variations in grain-size of the dolerite/basalt host rocks influenced vein development, fluid focussing and ore precipitation. However, the localisation of high fracture density zones in fine-grained rocks is unexpected considering that coarse grain size promotes fracture propagation and growth over finer grain sizes in rocks of comparable composition (Eberhardt et al., 1999).

5. North Kalgoorlie district fault/fracture-density analysis

A regional-scale fault/fracture density analysis is applied to a typical Archaean granite–greenstone terrane in the

---

Fig. 8. (a) Plan of the Gimlet South mine showing lode size increase at the intersection of cross and splay faults with the main lode. Cross-sectional view showing the preferential development of high-grade ore shoots within the main lode, at the intersection with pillow basalt host rocks (modified from Harrison et al., 1990). (b) Schematic diagram showing the increase in fracture density at the intersection of splays with the Gimlet South fault. The high fracture density zone forms a plunging pipe of fractured rock and high-grade gold ore (modified from Laing, 1994).

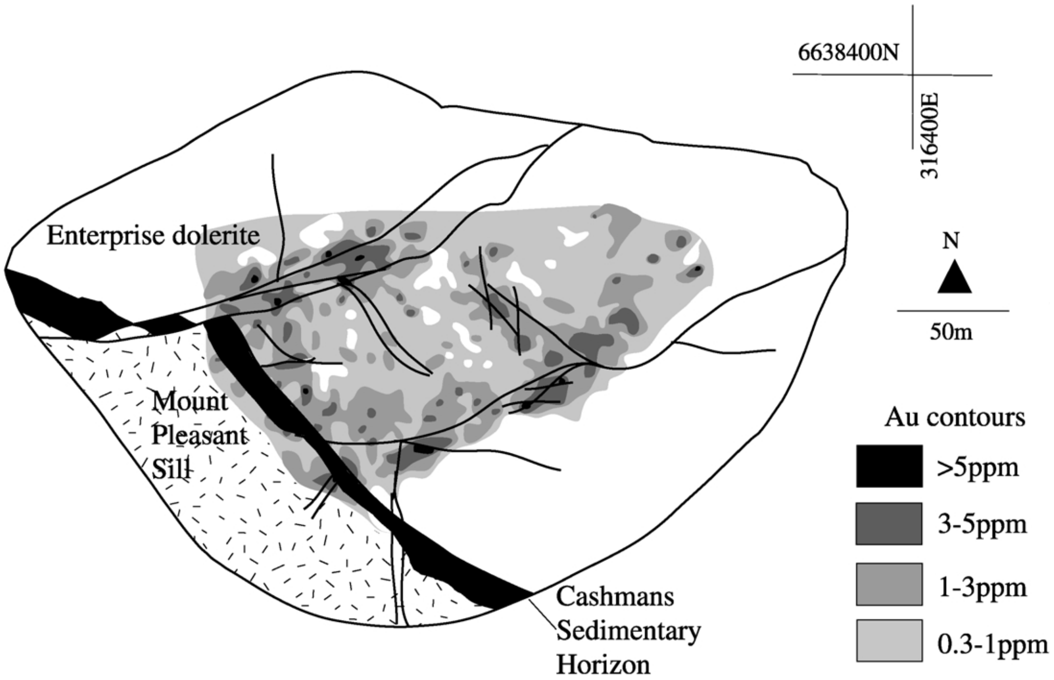


Fig. 9. Geology and mineralization of the Enterprise open pit mine. Figure showing the E–W-trending fault system cross-cutting a stratigraphic contact and the distribution of gold mineralization over the same area, with the high grade ore zones located at fault intersections and against the contact.

north Kalgoorlie district of Western Australia. The terrane is composed of elongate linear belts of greenstone interspersed with batholithic monzogranite intrusive complexes, and is cross-cut by a network of interlinked faults that are intimately associated with gold mineralization (Fig. 3). The area of the study is 7000 km^2, encompassing rocks of the Ora Banda Domain of Swager et al. (1990) and slightly overlapping adjacent fault bounded domains. The rationale of selecting this area for fault/fracture density analysis is the widespread observation of fault/fracture density control on gold mineralization at a mine scale within the Ora Banda Domain, as demonstrated by examples from the Ora Banda mining centre in Section 4. An essential pre-requisite to applying fracture-density contouring is the demonstration of fault–fault or fault–contact intersections as controls on gold deposit location regionally, and as controlling high-grade shoot development at the deposit scale. A lack of these structural controls may indicate the need to apply additional geological criteria or may affect the ranking of an area in targeting and area selection.

5.1. Method

A paucity of quality exposure in the Archaean Kalgoorlie Terrane necessitates alternative approaches to mapping the distribution of hydrothermal alteration in space. Rock outcrop accounts for $<10\%$ of the surface exposure in the north Kalgoorlie district, hence exploration grid-drilling augments classical geological mapping as a way to map the widescale distribution of gold alteration. The north Kalgoorlie district has blanket coverage of most areas by close-spaced (~300 m × 150 m) vertical exploration drilling, which provides bedrock sampling over a grid and allows the alteration mineralogy and geology to be mapped at a regional scale.

The mineral assemblages that provide indicators of gold mineralization are recorded as present or absent from each drillhole and the results are contoured on regional 1:50,000 and 1:100,000 scale plans. Pertinent assemblages include evidence of sulphidation (pyrite, pyrrhotite, arsenopyrite, chalcopyrite); carbonation (calcite, dolomite–ankerite); potassic alteration (biotite–white mica, muscovite); evidence of oxidised fluids (magnetite, fuchsite, hematite); and evidence of silica-rich fluids (vein quartz). These minerals are the most commonly observed in alteration zones around gold deposits in the North Kalgoorlie district. In the area covered by this study, significant alteration zones are located in the vicinity of the Ora Banda, Grants Patch, Mount Pleasant and Paddington mining districts and along some major shear zones. These alteration zones are interpreted as regional palaeo-permeability nodes, which reveal the areas of focussed fluid flow active at the time of mineralization in the Archaean.

5.1.1. Mapping

Meaningful interpretation of fault/fracture density contouring is largely dependent on the detail with which faults and geological contacts are mapped This mapping may include a combination of standard field mapping in areas of surface exposure and mines, interpretation from aeromagnetic data where faults are poorly exposed and extrapolation of known faults and contacts from exploration drilling

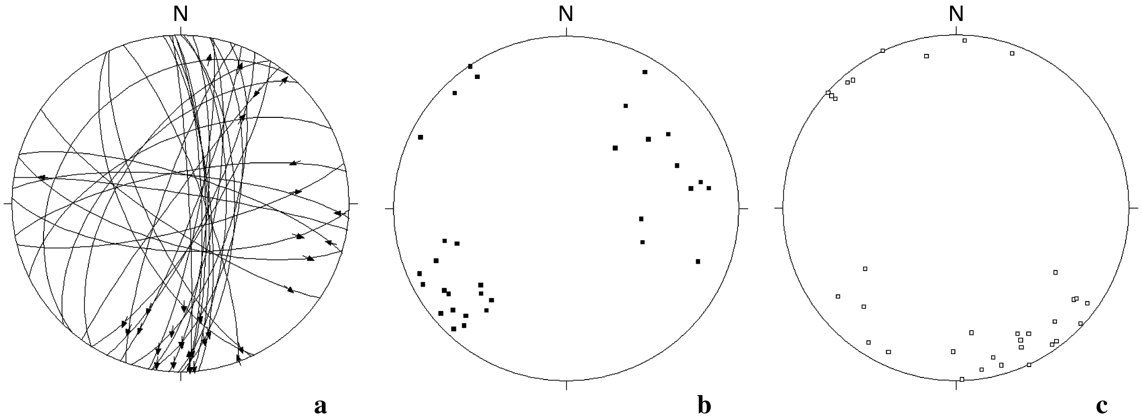


Fig. 10. (a)–(c) Stereograms showing kinematic analyses of fault slip data from the Enterprise mine by the method of Marrett and Allmendinger (1990). (a) Faults and slip lineations from 32 faults; (b) kinematic P-axes with a resolved axis of 055° or ENE–WSW; (c) kinematic T-axes.

(Fig. 4). In the example presented here, detailed mapping was conducted at all scales using each of the above approaches. The Archaean in the north Kalgoorlie district has extensive coverage with high-detail aeromagnetic data, mine exposure and exploration drilling. Field observations can be weighted relative to the type of exposure used to identify a given fault, and most of the faults presented here are identified on aeromagnetic imagery and then ground truthed by mapping, drilling, etc. The degree to which ground truthing can be used to weight observations is diminished by the variable character of faults/contacts along strike and with depth, as demonstrated in well-exposed areas (e.g. Tripp, 2002). Individual characteristics (width, kinematic character, texture, trace length) may change over a short distance, hence assigning a high or low quality to the observations of a given fault/fracture may have no basis in fact.

The analysis presented here is designed for exploration targeting at 1:100,000 scale. Examples from the Ora Banda mining camp are used to document the detailed structural controls at a larger scale, and to demonstrate a self-similar nature of the fracture-density concept across scales. A mining camp scale analysis has not been applied here, but would be a useful future exercise to predict the locations of new gold deposits or high-grade ore shoots within a mature mining camp.

5.1.2. Scale

Application of fracture-density contouring is dependent upon scale and the goals of the analysis: regional or local exploration targeting. In the example presented here gold deposits are distributed in clusters at a regional scale (1:100,000), and fault/fracture density contouring is applied at this scale to attempt the prediction of areas of high fracture-density, for targeting as new mining camps.

Known historic mining camps in the north Kalgoorlie district are located at Siberia, Ora Banda, Grants Patch, Mount Pleasant and Paddington (Fig. 3). Individually, each of the mining camps listed is best represented on a map at 1:10,000 scale. A given deposit may be represented on a map at 1:1000 scale, where high-grade ore shoots can be recognised at fault–fault and fault–contact intersections. At this 'deposit scale' the faults are usually internal splay faults of a larger fault zone, whereas the lithological contacts are both bounding and internal lithological contacts within sedimentary and igneous successions (flow layering in basalt, differentiated layering in sills).

5.1.3. Plotting technique

Fault–fault and fault–contact intersections are plotted as points from the regional aeromagnetic interpretation on an overlay At a regional scale (1:100,000), fault–fault and fault–contact intersections and gold deposits are best represented as points since the true surface area of each of these features is much less than this at 1:100,000 scale (Fig. 3). Points for the intersections are counted using a grid of squares with each square equal to 1% of the area of the map. The results are then re-calculated to give a percentage of fault intersections per 1% area of the map. Percentages of fault intersections are contoured using contours of 1, 2, 3, 4, 5 and 6% per 1% area, or a suitable range of percentages depending on the density of intersections.

5.1.4. Fault/fracture network kinematics

Kinematic data have a valuable use in the analysis presented here to identify fault–fault intersections that are predisposed to dilation A large data set of structural observations and kinematic analyses is used to determine the kinematic character of the fault sets that comprise the regional fault network in the north Kalgoorlie district. These data show similar kinematics for each of the fault sets.

Inferences are made about the kinematic character of faults that are interpreted from aeromagnetic imagery, supported by detailed observations in well-exposed areas. From these studies, consistent kinematics are demonstrable for each of the principal fault orientations of N–S dextral, NE–SW dextral and E–W sinistral. Variation from these summary relationships is due to strain field perturbation,

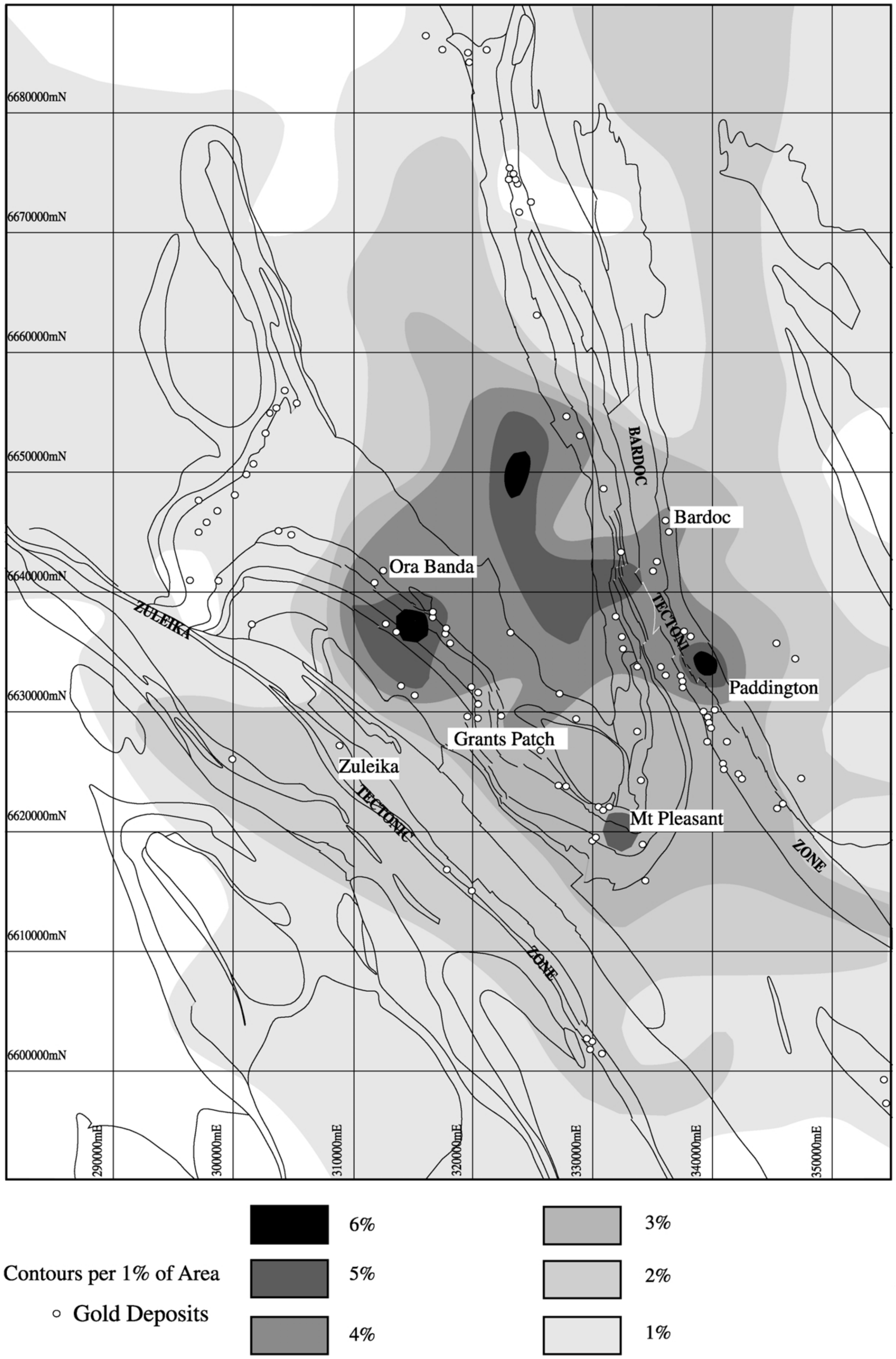


Fig. 11. Contour plot of fault–fault intersections in the north Kalgoorlie district, generated from the fault map in Fig. 3. Contacts from the geological interpretation form a background for reference.

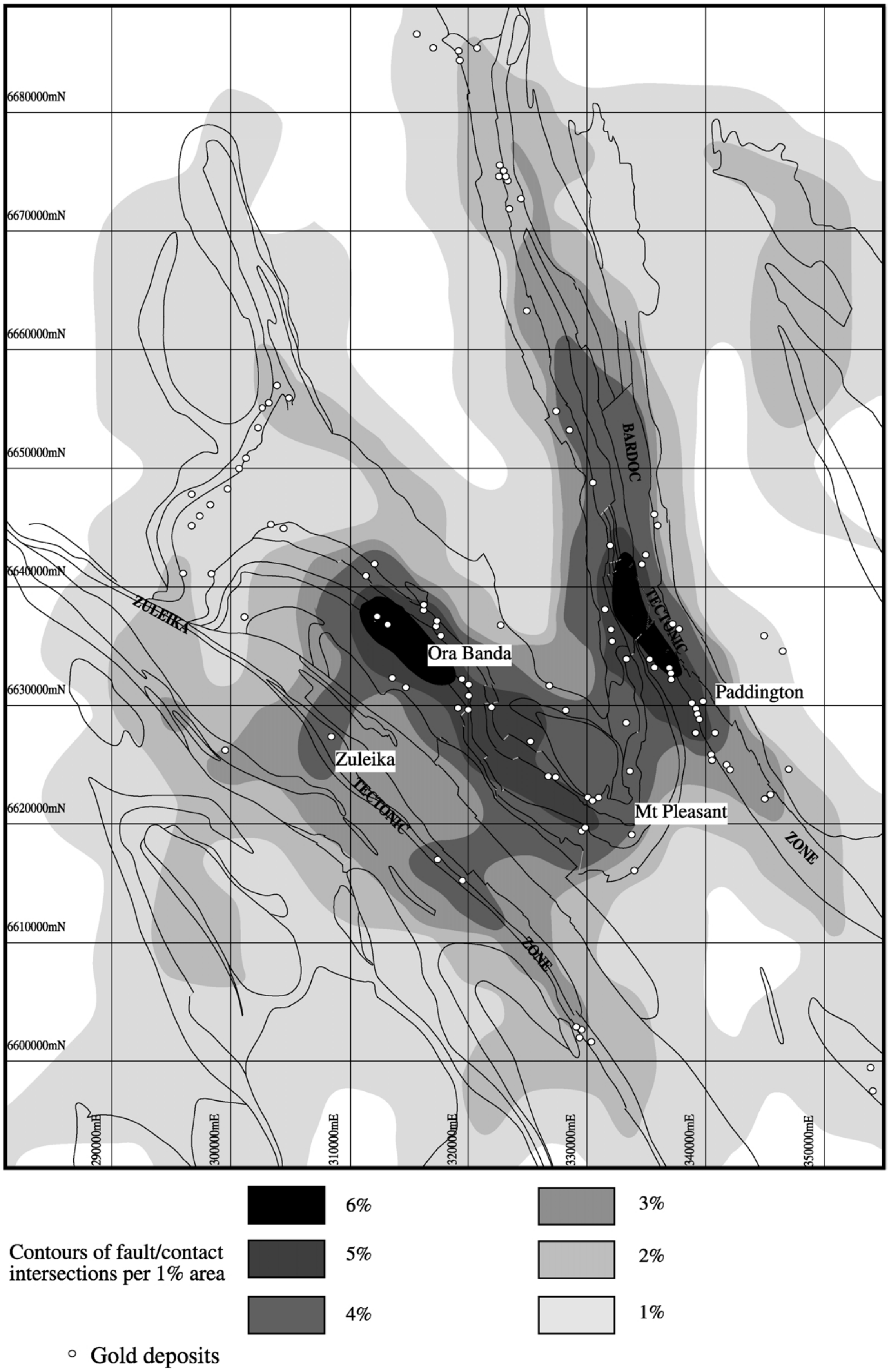


Fig. 12. Contour plot of fault–contact intersections in the north Kalgoorlie district, generated from the fault map in Fig. 3. Contacts from the geological interpretation form a background for reference.

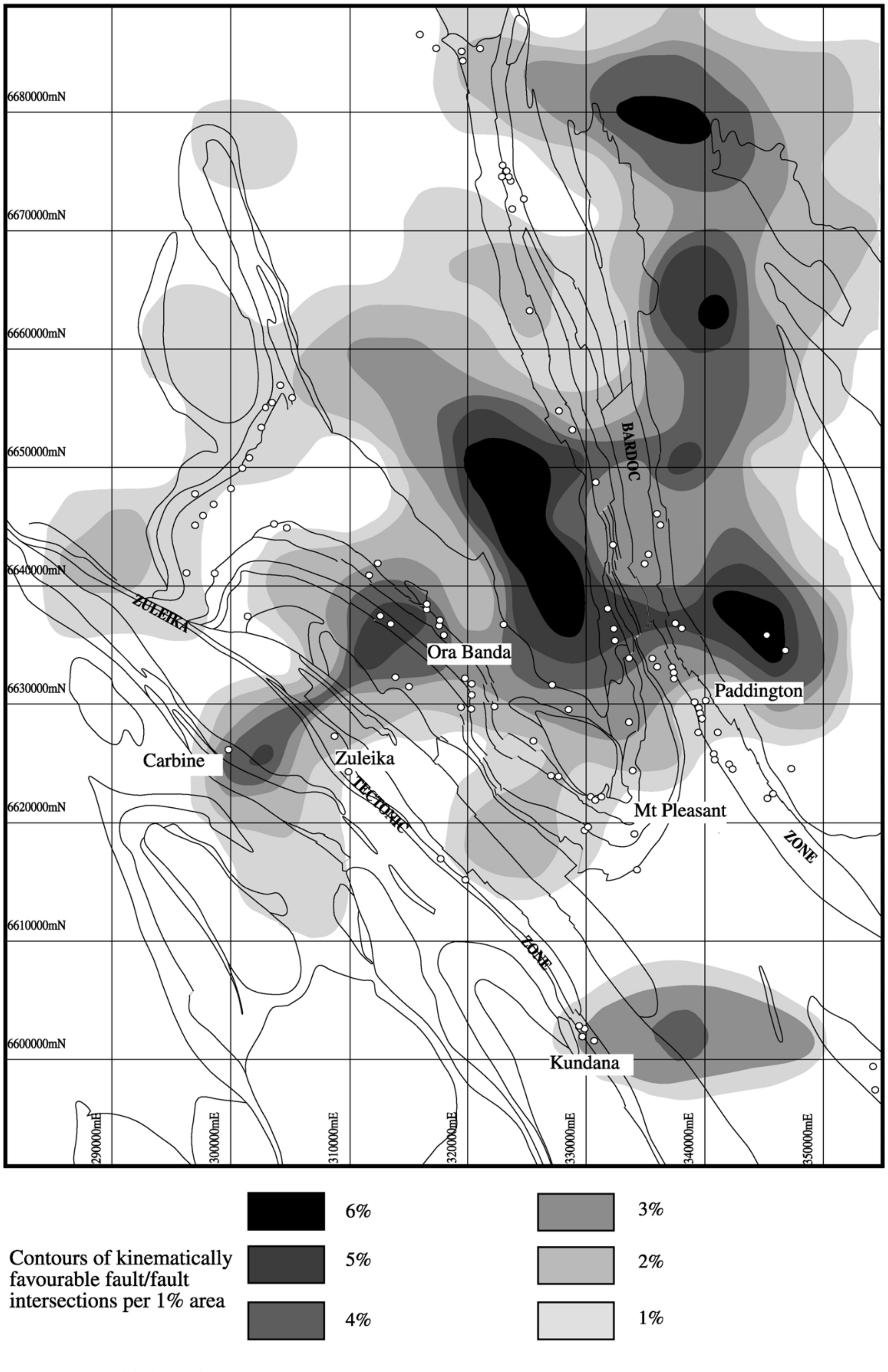


Fig. 13. Contour plot of kinematically favourable fault–fault intersections in the north Kalgoorlie district, generated from the fault map in Fig. 3. Contacts from the geological interpretation form a background for reference.

induced by the orientation of layer anisotropy or the presence of granitoid intrusions, which may alter local kinematic histories (e.g. Tripp, 2002). However, the extent of this variation is generally minor and confined to specific localities. As discussed in Section 2.1, intersections between faults of different kinematics may produce zones of high fracture density at the juncture. Hence intersections of N–S faults with E–W faults, and NE–SW faults with E–W faults are rated preferentially over N–S/NE–SW fault–fault intersections.

In well-exposed areas the fault network components are mutually overprinting with consistent kinematics and hence are interpreted as synchronously developed during the D2c contractional deformation phase. A small data set from the Enterprise mine demonstrates an ENE–WSW directed axis of principal shortening for faults produced in the D2c faulting event using the method of Marrett and Allmendinger (1990) (Fig. 10). The faults at Enterprise and in many other exposures (e.g. Tripp, 2000b) are dominantly strike-slip faults with shallow to moderately plunging slip vectors.

5.2. Results of the analysis and prospectivity interpretation

5.2.1. Fault–fault intersection analysis

The results of fault/fault fracture density analysis for the north Kalgoorlie district reveal high fracture density zones located in the vicinity of the Ora Banda, Paddington and Mount Pleasant mining centres, which broadly match with the known distribution of high gold endowment areas (Fig. 11) Some highly fractured areas are highlighted to the west of Bardoc, whereas low fracture densities at Grants Patch are also resolved by the analysis.

Three fracture density peaks are located at the positions of high gold endowment at Ora Banda and Paddington (6% intersections per 1% area) and Mount Pleasant (5% intersections per 1% area). The high fracture density zones are tightly distributed in the mining districts within broader zones of moderate density fracturing: the gold deposits appear to flank the highest density areas but are contained within the contour of moderate to high fracture density. Contours at 3% intersections per 1% area delineate the periphery of high density fracturing, and form a broad anomaly along the Zuleika Shear Zone (Fig. 11).

An elongate zone of high fracture-density to the west of the Bardoc township is highlighted as an interesting target zone for which there are no known economic gold occurrences. The area is well defined on the aeromagnetic image as contained within granitic rocks and intersected by multiple faults in various orientations (Fig. 11). This anomaly has similar fracture densities (6% intersections per 1% of area) as recorded at all the major mining centres with the exception of Mount Pleasant (5%). The zone also appears to be the result of several major structures that trend about N–S, intersecting with a swarm of E–W and NE–SW faults. An elongate distribution of the anomaly is projected south from the peak along the same N–S-trending faults. Economic occurrences of fault-controlled gold deposits in Archaean granitic rocks elsewhere make this an interesting exploration target (Kehal et al., 1999; Phillips and Zhou, 1999).

A low fracture density at the Grants Patch area is observed in an area of small to moderate gold occurrences. The Grants Patch area has similar fracture density and gold endowment to the Zuleika area, hence the results are not unexpected. The prospectivity of this area would be either downgraded based on the results of the study, or alternate controls on mineralization assessed, since the corridor is not devoid of gold occurrences. Several major N–S faults are mapped in this area, whereas the number of intersections is low due to few faults in the other principal orientations (Fig. 3).

5.2.2. Fault–contact intersection analysis

The contoured fault–contact intersections show a markedly different distribution of fracture density to the fault–fault intersection analysis. Two elongate areas of high fracture density are delineated, oriented parallel to the gross trend of the greenstone layering (Fig. 12). One of these areas lies on the Ora Banda–Mount Pleasant mafic sequence and the other on the Bardoc Tectonic Zone sequence. On the Ora Banda–Mount Pleasant trend, a peak of 6% intersections per 1% area of the map is located at the Ora Banda mining centre on the western limb of the regional anticline. A S-trending tail of high density fracturing of 4% intersections per 1% area, extends over the Grants Patch district and into the northern reaches of the Mount Pleasant district. On the Bardoc Tectonic Zone trend, a peak of 5% intersections per 1% area is located to the north of the Paddington mining centre, with north and south tails of $>4\%$ intersections per 1% area, of limited strike extent.

The two major zones of high fracture density delineated in the fault/contact analysis are broadly distributed along the limbs of the major regional anticline and coincide with areas that have an elongate trend, at a high angle to the swarm of interpreted NE–SW striking cross faults. This distribution reflects an underlying bias for lithological units that are favourably oriented geometrically, with respect to the regional fault network. Reactivation of moderately SW-dipping lithological contacts as thrust faults in the Ora Banda sequence may favour this area for dilation over the steeply-dipping Bardoc Tectonic Zone sequence: the latter accommodated the regional shortening deformation by constriction of bedding contacts.

5.2.3. Analysis of kinematically favourable fault–fault intersections

Intersecting faults with different kinematic modes (dextral vs sinistral) may induce dilation and high density fracturing, given certain conditions (Section 2.1.2). The kinematic modes of some of the fault groups in the north Kalgoorlie district produce such interactions: (intersection of E–W sinistral faults with N–S and NE–SW dextral faults), whereas others may produce interactions with a predicted net-constriction (e.g. intersection of N–S dextral and NE–SW dextral faults). The former is considered kinematically favourable for high fracture density development (Fig. 13).

The distribution of high density fracturing produced by kinematically favourable fault intersections shows results that are somewhat unexpected. Three mineralized districts are highlighted by the analysis: (1) Federal/Golden Cities in granitic rocks west of Paddington, (2) Ora Banda, in a NE–SW-trending zone of high density fracturing that extends southwest from Ora Banda into the Carbine area, and (3) Kundana, with a bulls-eye anomaly in the southeastern corner of the map (Fig. 13). Several large areas of $>6\%$ intersections per 1% area are highlighted in areas composed mostly of granitic rocks (cf. Fig. 3), which may include some bias from the greater visibility of faults and shear zones in these rocks, on aeromagnetic imagery (Fig. 4).

Other major mineralized districts at Paddington and Mount Pleasant are represented by low order fracture-density anomalies, at the periphery of the granitic intrusions. The highlighted areas in granitic rocks are potential areas of interest regardless of the visibility bias, since the linears recognised on aeromagnetic imagery are confirmed as shear zones and faults at the Federal mine (Phillips and Zhou, 1999), with similar high fracture density.

6. Discussion

A comparison of the fracture density analyses and the locations of the known major gold districts demonstrates a close association between fracture density and mineralization in the north Kalgoorlie district. Fault–fault intersection analysis shows a better correlation with known gold deposits than fault–contact intersection and fault-kinematic analyses, and highlights new areas of potential high density fracturing unrelated to the trend of stratigraphic successions. At the scale of the analysis, fault–fault intersection contours show a correlation between high fracture densities ($>5\%$ intersections per 1% area of the map) and the areas of high gold endowment. However the highest fracture densities ($>6\%$ intersections per 1% area) are flanked by the gold deposits within the highlighted districts. This result is an effect of scale that shows the highest density of fracturing at the mine corridor location, but due to the coarseness of the fault interpretation and analysis at 1:100,000 scale, individual mine locations are not highlighted. The apparent mismatch demonstrates the need for mine-scale fault/fracture density analyses if mine-scale targeting is the goal of the analysis.

The regional distribution of gold deposits in camps with coincident clustering of high density fracturing appears to be a good match. Locations of individual gold deposits may be affected locally by factors such as host rock chemistry and alternate fluid sources. Significant gold deposits are located in all rock types present in the Kalgoorlie Terrane; hence, the combined distribution of lithotype and structure promotes a widespread spatial distribution of gold deposits with no spatial restrictions controlled by specific host units or major shear zones. The regional fault network in the north Kalgoorlie district contains zones of high density fracturing that coincide with broad zones of alteration. Greater intensity of alteration leads to an interpretation of the zones as palaeo-permeability nodes where fluid flow and mineralization were enhanced. Identifying zones of high density fracturing is a method of revealing potential ore targets prior to extensive exploration drilling.

The contouring technique presented here is designed for identification of fracture-density anisotropy in two dimensions (i.e. on a geological map), but the two-dimensional nature of the analysis does not address the high likelihood for variations of fracture density in the depth dimension. Orientational change of individual faults is more useful generally at a mine scale to determine the geometry and location of high-grade ore shoots along a one-dimensional line. Fault–fault intersections and fault–layer intersections define the fracture connectivity at a regional scale, whereas orientational change of individual faults influences connectivity at a local scale only. Contouring fault/fracture density is a direct way of assessing the fracture connectivity of a region.

Our method of dealing with the fault/fracture density–mineralization relationship is to attempt to quantify the fracture density of a region, by contouring some of the factors that enhance the density of fracturing in faults (fault–fault intersections, fault/host rock contact intersections and kinematically favourable intersections). A close relationship between fault/fracture density and mineralization is an empirical observation of ore body character in the Archaean Ora Banda Domain. This relationship appears to continue across scales, and mapping of this relationship to identify high-grade shoot locations (a routine task in operating mines) can be applied also at a regional scale as a potential targeting tool.

7. Conclusions

Structure is arguably one of the principal controls on Archaean gold ores, and the formation of high fracture-density zones within faults and shear zones may provide pathways of enhanced permeability and fluid-flow during metamorphism. In the north Kalgoorlie district, a spatial relationship exists between the density of fracturing and the distribution of gold mineralization. Fracture density contouring is a method of quantifying the density of fracturing of a region and can be applied to terranes where ore deposits have a demonstrated relationship between high-density fracture and ore-shoot development.

Using low level aeromagnetic images, geological mapping and exploration drilling to map the distribution of faults, targets can be generated in a semi-quantitative way to provide locations for drill sampling and prospect ranking. Recognising the feedback relationship between fracture-density enhancement and fluid flow is an important consideration that has been overlooked in many types of prospectivity analyses to date. We emphasise the role of fracture-density mapping as a useful additional parameter in area selection and prospectivity mapping.

Acknowledgements

The authors thank Placer Dome Asia Pacific for permission to publish these results. We are grateful to Tom Blenkinsop, Jon Standing and two anonymous reviewers whose comments improved the manuscript. The data used are from a M.Sc. study by GT at Curtin University of Technology Perth, and unpublished consulting studies by Vearncombe and Associates Pty Ltd.

References

Agricola, G., 1556. De Re Metallica. Translated from the first edition of 1556 by H.C. Hoover and L.H. Hoover. Dover Publications Inc., New York, 1950.

Bartley, M.W., 1948. Steep Rock iron ore mine. In: Structural Geology of Canadian Ore Deposits. Canadian Institute of Mining and Metallurgy, Vol. 1.

Bateman, A.M., 1948. Economic Mineral Deposits. Wiley and Sons.

Bolton, A.J., Clennell, M.B., Maltman, A.J., 1999. Nonlinear stress dependence of permeability: a mechanism for episodic fluid flow in accretionary wedges. Geology 27, 239–242.

Branquet, Y., Cheilletz, A., Giuliani, G., Laumonier, B., Blanco, O., 1999. Fluidized hydrothermal breccia in dilatant faults during thrusting: the Colombian emerald deposits. In: McCaffrey, K., Lonergan, L., Wilkinson, J. (Eds.), Fractures, Fluid Flow and Mineralisation. Geological Society of London, Special Publications 155, pp. 183–195.

Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. Geology 24, 1025–1028.

Castaing, C., 1991. Incremental emplacement of mineralization under mechanical controls at various scales of space and time. In: Pagel, M., Leroy, J.L. (Eds.), Source Transport and Deposition of Metals. Proceedings of the 25 years SGA Anniversary Meeting Nancy, 30 Aug–3 Sept 1991, pp. 435–438.

Connolly, P., Cosgrove, J., 1999. Prediction of static and dynamic fluid pathways within and around dilational jogs. In: McCaffrey, K., Lonergan, L., Wilkinson, J. (Eds.), Fractures, Fluid Flow and Mineralisation. Geological Society of London, Special Publications 155, pp. 105–121.

Cox, S.F., 1999. Deformational controls on the dynamics of fluid flow in mesothermal gold systems. In: McCaffrey, K., Lonergan, L., Wilkinson, J. (Eds.), Fractures, Fluid Flow and Mineralisation. Geological Society of London, Special Publications 155, pp. 123–139.

Cox, S.F., Etheridge, M.A., Wall, V.J., 1986. The role of fluids in syntectonic mass transport and the localisation of metamorphic vein-type ore deposit. Ore Geology Reviews 2, 65–86.

Craw, D., Windle, S.J., Angus, P.V., 1999. Gold mineralisation without quartz veins in a ductile–brittle shear zone, Macraes mine, Otago Schist, New Zealand. Mineralium Deposita 34, 382–394.

Eberhardt, E., Stimpson, B., Stead, D., 1999. Effects of grain size on the initiation and propagation thresholds of stress-induced brittle fractures. Rock Mechanics and Rock Engineering 32 (2), 81–99.

Forde, A., Bell, T.H., 1994. Late structural control of mesothermal vein-hosted gold deposits in central Victoria, Australia: mineralization mechanisms and exploration potential. Ore Geology Reviews 9, 33–59.

Fyfe, W.S., 1991. Gold transport and deposition: rules of the game. In: Ladeira, E.A., (Ed.), Brazil Gold '91, pp. 7–9.

Fyfe, W.S., Price, N.J., Thompson, A.B., 1978. Fluids in the Earth's Crust, Developments in Geochemistry 1, Elsevier, Amsterdam.

Gregory, M.J., 1998. The geochemistry and petrology of the Enterprise dolerite, Ora Banda, Western Australia. B.Sc. Thesis, University of Melbourne (Australia).

Groves, D.I., Ho, S.E., 1990. A short review of gold in the Yilgarn Block. In: Hughes, F.E. (Ed.), Geology and Mineral Deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, pp. 539–553.

Groves, D.I., Phillips, G.N., 1987. The genesis and tectonic control on Archaean gold deposits of the Western Australian shield—a metamorphic replacement model. Ore Geology Reviews 2, 287–322.

Gudmundsson, A., Berg, S.S., Lyslo, K.B., Skurtveit, E., 2001. Fracture networks and fluid transport in active fault zones. Journal of Structural Geology 23, 343–353.

Harrison, N., Bailey, A., Shaw, J.D., Petersen, G.N., Allen, C.A. 1990. Ora Banda gold deposits. In: Hughes, F.E. (Ed.), Geology and Mineral Deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, pp. 389–394.

Hodgson, C.J., 1989. The structure of shear-related, vein-type gold deposits: a review. Ore Geology Reviews 4, 231–273.

Jamtveit, B., Yardley, B., 1997. Fluid Flow and Transport in Rocks. Chapman and Hall.

Jolley, S.J., Henderson, I.H.C., Barnicoat, A.C., Fox, N.P.C., 1999. Thrust fracture network and hydrothermal gold mineralisation: Witswatersrand Basin, South Africa. In: McCaffrey, K., Lonergan, L., Wilkinson, J. (Ed.), Fractures, Fluid Flow and Mineralisation. Geological Society of London, Special Publications 155, pp. 153–165.

Kehal, H., Stephens, J., Anderson, A., Shrimpton, K., Harris, S., Osborn, M., 1999. Golden Cities—the discovery of gold deposits in Archaean Granite. In: New Generation Gold Mines '99, Australian Mineral Foundation.

Kerrich, R., 1989. Geochemical evidence on the sources of fluids and solutes for shear zone-hosted mesothermal gold deposits. Geochemical Association of Canada. Short Course Notes 6, 129–197.

Knox-Robinson, C.M., Robinson, D.C., 1993. Application of geographic information systems (GIS) to regional-scale gold prospectivity mapping. In: Williams, P.R., Haldane, J.A. (Eds.), An International Conference on Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields. Australian Geological Survey Organisation Record 1993/54, pp. 211–215.

Laing, W.P., 1994. Ore systems at New Celebration and Ora Banda and a comparison with the Kalgoorlie system. Newcrest Mining Western Australia Ltd. Unpublished consultancy report.

Lang, A.H., 1948. The Cordilleran region of Western Canada. In: Structural Geology of Canadian Ore Deposits. Canadian Institute of Mining and Metallurgy, Vol. 1, p. 17.

Lindgren, W., 1933. Mineral Deposits, McGraw Hill, pp. 155–163.

Lonergan, L., Wilkinson, J.J., McCaffrey, K.J.W., 1999. Fractures, fluid flow and mineralization: an introduction. In: McCaffrey, K., Lonergan, L., Wilkinson, J. (Eds.), Fractures Fluid Flow and Mineralisation. Geological Society of London, Special Publications 155, pp. 1–6.

Madrid, R.J., Garwin, S.L., 2002. Structural methods for targeting gold deposits, northern Carlin Trend, Nevada. In: Swager, C.P., Stone, B., Reddy, S. (Eds.), Applied Structural Geology for Mineral Exploration and Mining, Kalgoorlie 2002, Australian Institute of Geoscientists, Extended Abstracts, pp. 118–121.

Marrett, R., Allmendinger, R.W., 1990. Kinematic analysis of fault slip data. Journal of Structural Geology 12, 973–986.

Martel, S.J., 1999. Mechanical controls on fault geometry. Journal of Structural Geology 21, 585–596.

McCaig, A.M., 1989. Fluid flow through fault zones. Nature 340, 600.

McLellan, J.G., 2002. Numerical modelling of fluid flow in extensional environments. In: McLellan, J.G., Brown, M.C. (Eds.), Deformation, Fluid Flow and Mineralisation (Rick Sibson Symposium) Extended Abstracts. James Cook University EGRU Contribution 60, pp. 71–79.

Meyer, C., Shea, E.P., Goddard, C., Staff, J.R., 1968. Ore deposits at Butte Montana. In: Ridge, J.D., (Ed.), Ore Deposits of the United States, 1933–1967, Vol. 2, p. 1395.

Mikucki, E.J., Groves, D.I., 1990. Gold transport and depositional models. In: Ho, S.E., Groves, D.I., Bennett, J.M. (Eds.), Gold Deposits of the Archaean Yilgarn Block, Western Australia: Nature, Genesis and Exploration Guides. University of Western Australia, Department of Geology and University Extension Service, Publications 20, pp. 278–284.

Oliver, N.H.S., 1996. Review and classification of structural controls on fluid flow during metamorphism. Journal of Metamorphic Geology 14, 477–492.

Oliver, N.H.S., Rubenach, M.R.J., Valenta, R.K., 1998. Precambrian metamorphism, fluid-flow and metallogeny of Australia. AGSO Journal of Australian Geology and Geophysics 17, 31–53.

Peters, S.G., 1993. Nomenclature, concepts and classification of oreshoots in vein deposits. Ore Geology Reviews 8, 3–22.

Petersen, G., 1987. Gold mineralisation at Gimlet South, Ora Banda, WA. In: Witt, W.K., Swager, C.P. (Eds.), The Second Eastern Goldfields Geological Field Conference, Abstracts and Excursion Guide 1987, Geological Society of Australia (Western Australian Division), pp. 78–85.

Phillips, G.N., 1986. Geology and alteration in the Golden Mile. Economic Geology 81, 779–808.

Phillips, G.N., Vearncombe, J.R., Eshuys, E., 1998. Yandal greenstone belt, Western Australia: 12 million ounces of gold in the 1990's. Mineralium Deposita 33, 310–316.

Phillips, G.N., Zhou, T., 1999. Gold-only deposits and Archaean granite. SEG Newsletter Society of Economic Geologists 37, 8–13.

Phillips, W.J., 1972. Hydraulic fracturing and mineralisation. Journal of the Geological Society of London 128, 337–359.

Ridley, J.R., Mengler, F., 2000. Lithological and structural controls on the form and setting of vein stockwork orebodies at the Mount Charlotte gold deposit, Kalgoorlie. Economic Geology 95, 85–98.

Ridley, J.R., Mikucki, E.J., Groves, D.I., 1996. Archaean lode-gold deposits: fluid flow and chemical evolution in vertically extensive hydrothermal systems. Ore Geology Reviews 10, 279–293.

Robert, F., Poulsen, K.H., 2001. Vein formation and deformation in greenstone gold deposits. Society of Economic Geologists, Reviews 14, 111–155.

Sanderson, D.J., Zhang, X., 1999. Critical stress localization of flow associated with deformation of well-fractured rock masses, with implications for mineral deposits. In: McCaffrey, K., Lonergan, L., Wilkinson, J. (Eds.), Fractures, Fluid Flow and Mineralisation. Geological Society of London, Special Publications 155, pp. 69–81.

Sibson, R.H., 1987. Earthquake rupturing as a mineralizing agent in hydrothermal systems. Geology 15, 701–704.

Sibson, R.H., 1996. Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology 18, 1031–1042.

Sibson, R.H., 2002. Stress and fluid pressure controls on mineralisation. In: Swager, C.P., Stone, B., Reddy, S. (Eds.), Applied Structural Geology for Mineral Exploration and Mining, Kalgoorlie 2002, Australian Institute of Geoscientists, Extended Abstracts, pp. 189–191.

Sibson, R.H., Scott, J., 1998. Stress/fault controls on the containment and release of overpressured fluids: examples from gold-quartz vein systems in Juneau, Alaska, Victoria, Australia and Otago, New Zealand. Ore Geology Reviews 13, 293–306.

Sibson, R.H., Robert, F., Poulsen, K.H., 1988. High-angle reverse faults, fluid-pressure cycling and mesothermal gold-quartz deposits. Geology 16, 551–555.

Solomon, M., Groves, D.I., 1994. Geology and Origin of Australian Mineral Deposits. Clarendon Press, Oxford, p. 76.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, R.W.M., McGoldrick, P.J., 1990. Geology of the Archaean Kalgoorlie Terrane—an explanatory note. Western Australia Geological Survey, Report 48.

Tripp, G.I., 2000a. Fault control on Archaean gold deposits, Ora Banda, Western Australia. Australian Institute of Geoscientists, Newsletter 62, 1–6.

Tripp, G.I., 2000b. Structural geology and gold mineralisation of the Ora Banda and Zuleika districts, Eastern Goldfields, Western Australia. MSc thesis, Curtin University of Technology.

Tripp, G.I., 2002. Nature of the Archaean Zuleika Shear Zone, Kalgoorlie, Western Australia. In: Swager, C.P., Stone, B., Reddy, S. (Eds.), Applied Structural Geology for Mineral Exploration and Mining, Kalgoorlie 2002, Australian Institute of Geoscientists, Extended Abstracts, pp. 212–215.

Vearncombe, J.R., 1998. Shear zones, fault networks and Archean gold. Geology 26, 855–858.

Vearncombe, J.R., Vearncombe, S., 1999. The spatial distribution of mineralization: applications of Fry analysis. Economic Geology 94, 475–486.

Vearncombe, J.R., Barley, M.E., Eisenlohr, B.N., Groves, D.I., Houstoun, S.M., Skwarnecki, M.S., Grigson, M.W., Partington, G.A., 1989. Structural controls on mesothermal gold mineralisation: examples from the Archaean terranes of southern Africa and Western Australia. Economic Geology, Monograph 6, 124–134.

Witt, W.K., 1990. Geology of the Bardoc 1:100,000 sheet. Western Australia Geological Survey, Record 1990/14.

Witt, W.K., Knight, J.T., Mikucki, E.J., 1997. A synmetamorphic lateral fluid-flow model for gold mineralisation in the Archaean southern Kalgoorlie and Norseman terranes, Western Australia. Economic Geology 92, 407–437.