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The Granny Smith gold deposit: the role of heterogeneous stress distribution at an irregular granitoid contact in a greenschist facies terrane

V.J. Ojala[1], **J.R. Ridley**[1], **D.I. Groves**[1], **and G.C. Hall**[2]

[1] Key Centre for Teaching and Research in Strategic Mineral Deposits, Geology Department, The University of Western Australia, Nedlands, WA 6009, Australia
[2] Placer Exploration, P.O. Box 764, Cloverdale, WA 6105, Australia

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Abstract. The Granny Smith gold deposits formed late in the structural history of the Yilgarn Block at a high crustal level in a largely brittle structural régime. Gold mineralisation is located along a N-S striking fault which wraps around the contact of a small granitoid intrusion. In different sections of the fault, mineralisation may be developed in the granitoid, in the adjacent sedimentary sequence and/or along the contact between them. In the granitoid, gold mineralisation is in conjugate networks of thin carbonate-quartz veins and their alteration halos. Small displacements along veins are common. In contrast, veins and faults in the sedimentary rocks are subparallel to bedding. Spatial variations in the conjugate vein orientations indicate that the local stress field was heterogeneous and controlled by the shape of the granitoid contact. The greatest variations in vein and implied stress orientations occur in zones where the contact is most irregular. These are also the areas of richest mineralisation. Fluid flow was thus focused in a regional-scale low mean-stress region created by the geometry of the granitoid intrusion. Its irregular contact caused deposit scale variations in fluid flow and resulted in heterogeneous gold grades along the contact zone.

Structure is the single most important factor controlling the distribution of Archaean gold deposits on the regional nd mine scale (Fyfe and Henley 1973; Kerrich and Allison 1978). Deposits are, in general, localised along discrete segments of individual structures and are generally related to late events in the regional deformation history (eg. Groves et al. 1988; Colvine et al. 1988). During these late events earlier formed structures are commonly reactivated and mineralised (eg. Fryer et al. 1979; Witt 1993). The mineralised parts of the structures are characterized by channelised fluid flow, and they represent sites where both the time-averaged normal stress across the structure (Vearncombe 1990) and the mean rock stress (Ridley 1993) is low.

To understand the localisation of mineralisation, it is important, therefore, to determine the variations in stress state in a rock sequence. Spatial variations in the state of stress result in curved stress trajectories which are reflected by variations in orientations of minor structures such as joints, faults and veins (Davis 1984). The Granny Smith gold deposits formed late in the structural history of the Yilgarn Block at a high crustal level in a dominantly brittle structural régime. The deposits are hosted in a granitoid stock and in adjacent sedimentary rocks, and have been largely unaffected by post-mineralisation deformation, thus preserving structures formed during gold mineralisation. These structures and the intensity of mineralisation show spatial variations throughout the deposit. This paper examines the variation in orientation of mineralised structures and uses this variation to constrain the stress distribution during mineralisation. It is demonstrated that the shape of the granitoid contact controlled stress distribution, and, hence, also the distribution of gold mineralisation.

Regional setting

The Granny Smith gold deposits are situated 250 km NE of Kalgoorlie and 20 km S of Laverton at lat. 28°48′ S, long. 122°25′ E in the Laverton-Leonora area of the North Eastern Goldfields Province of the Archaean Yilgarn Block, Western Australia (Fig. 1). Granny Smith is a relatively new discovery. Mine production commenced in 1990 after 10 years of exploration, and the development plan of the mine was based on proven and probable reserves of 21 Mt with an average grade of 1.7 g/t in three deposits (Placer Pacific Annual Report 1989; Hall and Holyland 1990).

The Laverton-Leonora area is, like most of the Yilgarn Block, poorly exposed, and the structure of the Laverton-Leonora area has not been studied in detail. Typically, Archaean greenstone belts are relatively narrow linear zones between large external granitoid intrusions, but in the Laverton-Leonora area the greenstone belt is about 100 km wide and it is largely characterized by broad folding and minimal penetrative deformation (Hallberg 1985).

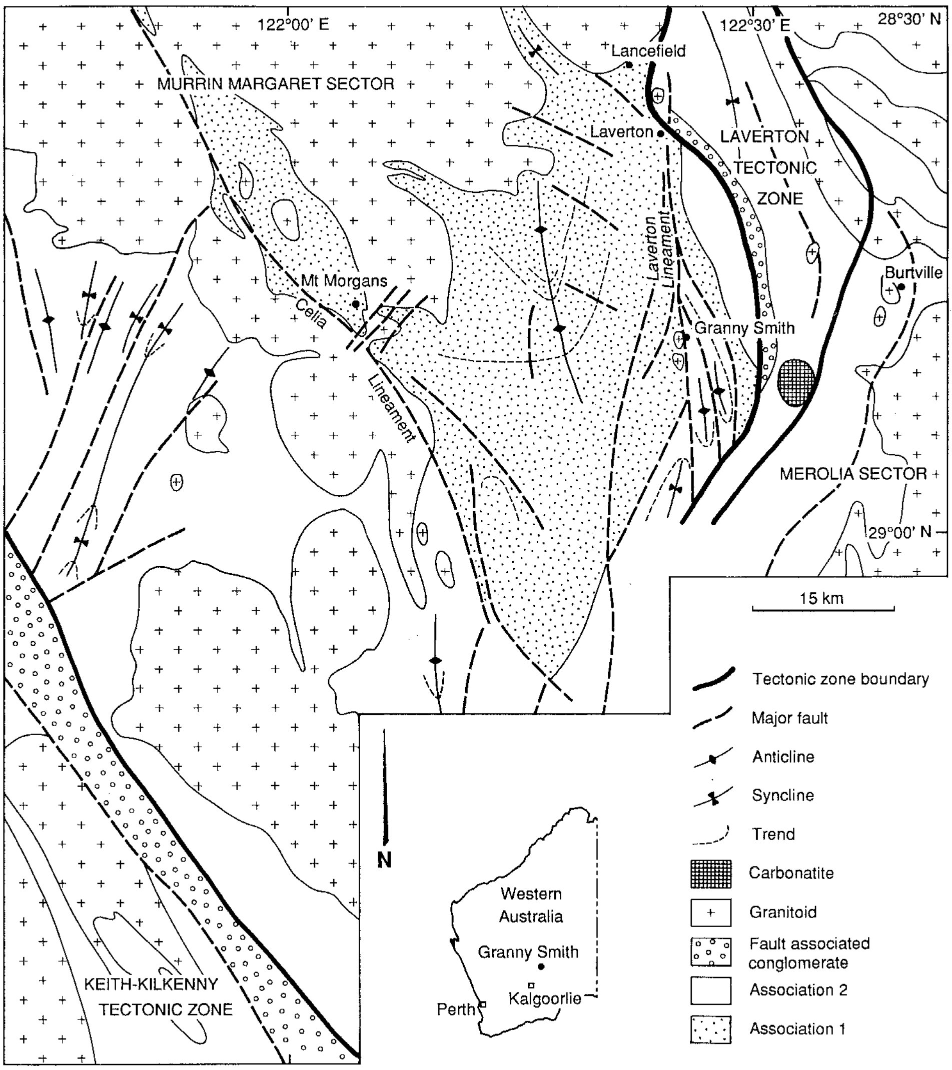

Fig. 1. Regional geological map of the Laverton region showing the location of Granny Smith, the distribution of stratigraphic associations and the major structures. Modified from Hallberg (1986)

Subdivision of the Laverton-Leonora area

Hobson and Miles (1950) carried out the first regional study of the area. In their mapping they recorded folding of banded iron formations (BIF), which form conspicuous hills and ridges, but they did not recognise any major faulting. Subsequently, Gower (1976) mapped the area at 1:250 000 scale and recognised five structural sectors which have "a distinctive and coherent structure and are separated by lines of structural discontinuity". The most recent study was by Hallberg (1985, 1986), who remapped the area at 1:50 000 scale and based his subdivision largely on the subdivision of Gower (1976): this is now widely accepted (Fig. 1).

The division by Hallberg (1985) of the Laverton-Leonora area into two geological sectors (Murrin-Margaret and Merolia sectors) and two intervening tectonic zones (Keith-Kilkenny and Laverton tectonic zones) is based on differences in structural style, sedimentation and felsic igneous activity. The two geological sectors are characterized by broad folding, brittle fracturing, low-grade, low-strain metamorphism, and the absence of bimodal basalt-rhyolite sequences and granitoid-pebble conglomerates. The tectonic zones are zones of structural and stratigraphic discontinuity. They are not simple lineaments, but zones from a few kilometres to over 60 km in width, marked by intense folding, ductile deformation, peralkaline igneous plutonism and volcanism, and graben-associated sedimentary rocks.

Stratigraphy

Hallberg (1985, 1986) divided the Archaean volcano-sedimentary rocks of the Laverton region into two stratigraphic associations. The major differences are in felsic volcanic and sedimentary rock assemblages. Andesitic volcanic rocks are absent, and felsic rocks are uncommon in the older association 1 but are major components of the younger association 2. BIF is largely absent from association 2, which is locally overlain by granitoid-pebble conglomerates in basins along fault lines in the tectonic zones. These form the youngest Archaean sequence in the area. Regional metamorphic grade is largely greenschist facies in association 1 and prehnite-pumpellyite facies in association 2. Amphibolite facies assemblages in greenstone successions are restricted to areas adjacent to major granitoid plutons.

Regional structural history and tectonic setting

A number of contrasting structural histories have been proposed for the Laverton-Leonora area. Hallberg (1986) suggested that crustal extension was an important process in the development of the north-eastern Yilgarn Block. In his model early extension resulted in a basin which became infilled with mantle-derived volcanic rocks

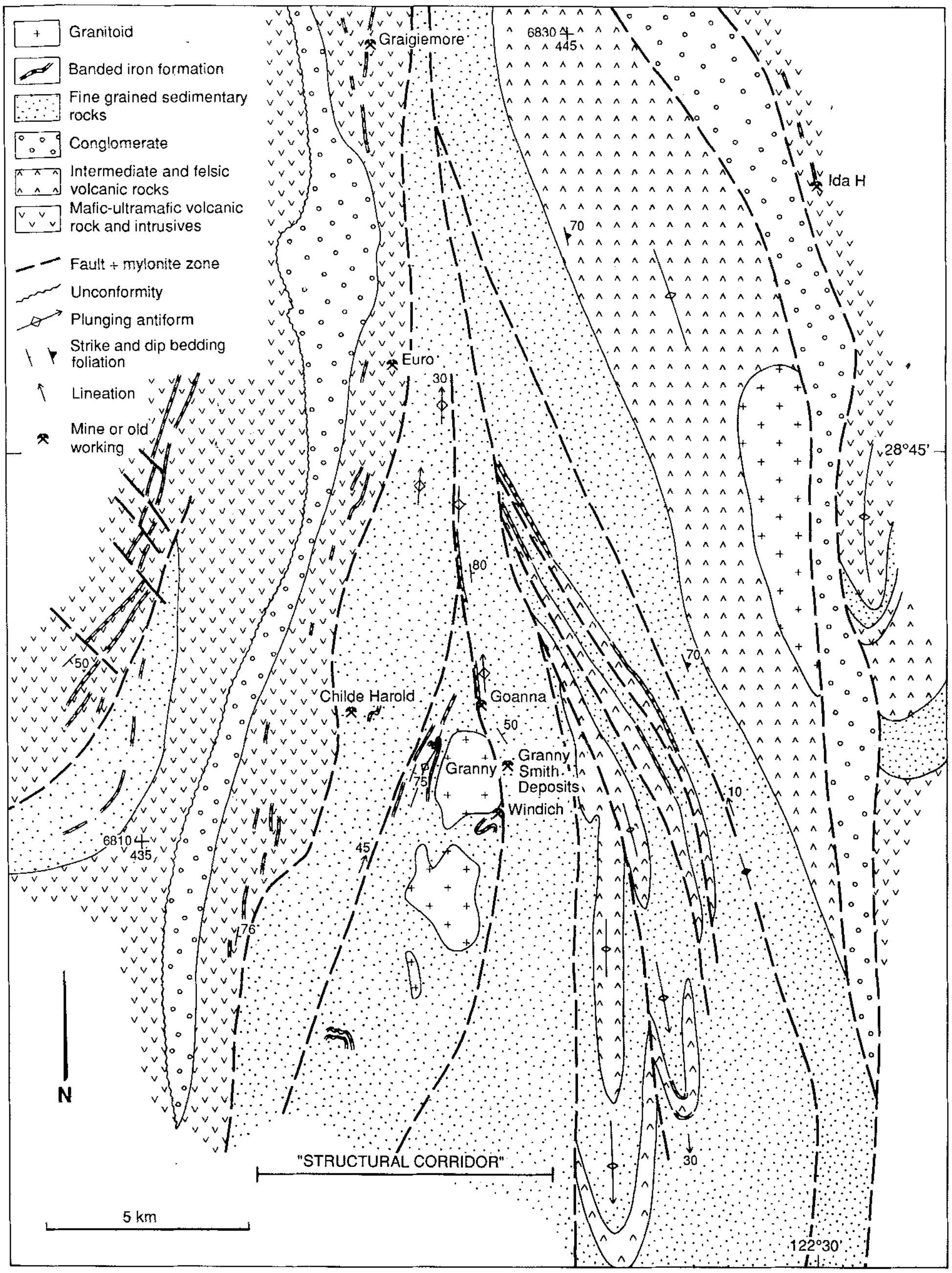

Fig. 2. Geological sketch map of the area surrounding the Granny Smith deposits showing the location of the Granny Smith Granodiorite in the structural corridor between areas of contrasting structural trend

and their sedimentary derivatives. The normal faulting related to this extension caused the repetition of the greenstone sequence that is observed in the geological sectors. Increased rates of crustal extension at the basin margins resulted in linear zones of tectonic disruption (tectonic zones) with penetrative deformation, growth faulting and graben formation. However, Keele (1991) suggested an oblique-slip transpressive régime for the Laverton area. He outlined a broad kinematic zonation in which sinistral displacements dominate the outer zones, dextral displacements dominate the inner zones, and both of these enclose a central core which has suffered only shortening.

For the Leonora district, 120 km west of Laverton, Williams et al. (1989) proposed early regional nappe-style translations within the greenstone sequences, and a later event that caused regional wrench faulting. Swager (1989) suggested a similar structural evolution for the Kalgoorlie area, with recumbent folding (D_1) followed by upright folding (D_2) and sinistral wrench faulting (D_3). However, Hammond and Nisbet (1992) argue that sinistral wrench events were not so significant and that many structures regarded as major strike-slip zones are upturned D_1 thrusts, or have steep lineations and are likely to be D_2 structures.

Barley and Groves (1990) have interpreted the NE-Goldfields Province and Norseman-Wiluna Belt to represent volcanic arc and back-arc basin tectono-stratigraphic associations, respectively. In their tectonic model, emplacement of regional granitoids was broadly contemporaneous with deformation and metamorphism of the greenstone sequences, with broad zones of high-grade metamorphism adjacent to regional granitoid-greenstone contacts. Deformation included crustal shortening in response to oblique compression.

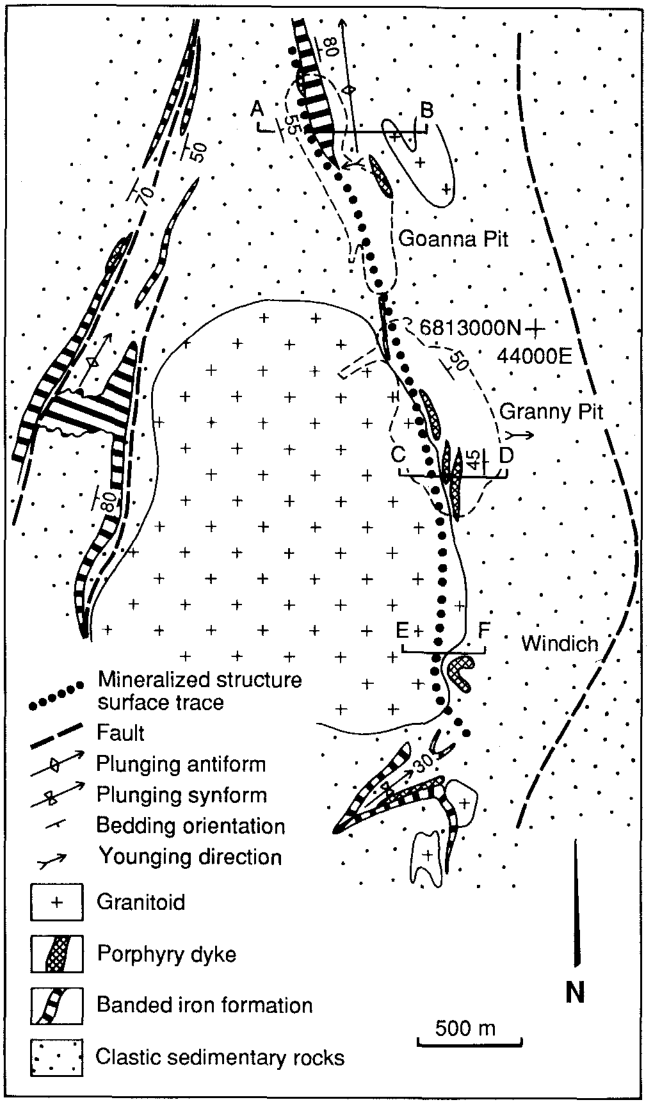

Fig. 3. Geological map of the Granny Smith gold deposits showing the position of the deposits relative to the granitoid, and the surface trace of the mineralised fault

Geology of the mine environs

Structural setting

The Granny Smith gold deposits are located within the Murrin-Margaret geological sector along the Laverton lineament (Gower 1976). The Laverton lineament is a discrete tectonic lineament cutting the sector a few kilometres west of the Laverton tectonic zone, and is a belt between areas of different structural orientations that Hall and Holyland (1990) termed "a structural corridor" (Figs 1, 2). Mafic rocks of association 1 dominate the western side of the structural corridor, and sedimentary rocks and felsic to intermediate volcanic rocks of association 2 dominate the eastern side, the corridor itself consists mainly of fine grained clastic sedimentary and felsic pyroclastic rocks. Hall and Holyland (1990) proposed that the corridor contains several parallel strike-slip faults. However, recent mapping suggests that the complexity of the corridor is due to small-scale thrust stacking, and that brittle faults, including the mineralised structures, are mainly reactivated reverse faults (Figs 2, 3 and 4a). Mylonite zones parallel to the structural corridor include pyrite porphyroclasts with pressure shadows which have symmetrical fibre development indicating mainly flattening with minor shear displacements (Fig. 2). No gold mineralised quartz veins have been found with these mylonites.

The Granny Smith Granodiorite

The Granny Smith Granodiorite is a small, elongate (about 2 km × 5 km in plan view), composite and zoned pluton which has porphyritic, more mafic margins. It intruded, together with marginal porphyry dykes, into the structural corridor after the main folding event. The transition from dioritic margin to granodioritic core of the pluton is generally gradational, but the last granodiorite phase cuts the earlier phases. Aplitic pegmatite dykes, which cut only the granitoid, represent the latest magmatic phase. The present erosion level is close to the roof of the pluton, and in places it has a thin cap of sedimentary rocks. As a consequence, the outcrop pattern of the granitoid is irregular. The pluton is surrounded by a 200–300 m wide contact metamorphic aureole that is zoned, progressively from the granitoid contact outwards through a several metres wide hornfelsed margin in which no sedimentary textures have been preserved, an andalusite-bearing slate, and a slate with mica spots. Euhedral biotite inclusions in igneous hornblende and clinopyroxene suggest that the intrusion crystallised from a hot, dry magma that would have been capable of intruding to a high crustal level (c.f. Wones 1981; Hyndman 1981). Intrusive breccias and especially miarolitic cavities indicate high level intrusion (about 1.5 kb), because at low pressures the volume increase of the H_2O-saturated magma is very large when H_2O is released (Burnham and Ohmoto 1980; Cerny 1990) so that overpressures will be large enough for the generation of gas cavities in the melt.

The granitoid and gold mineralisation are cut by carbonatite and lamprophyre dykes which are probably the same age as the large Proterozoic Mt Weld coarbonatite 15 km ESE from the Granny Smith mine (Fig. 1), which has been dated using K/Ar method (2064 ± 40 Ma) and Sr^{87}/Sr^{86} method (2020 ± 17 Ma) (Willett et al. 1986).

Geology of the individual deposits

Gold mineralisation is located along a N-S striking fault zone that partly follows the contact between granitoid and sedimentary rocks (Fig. 3). Economic gold grades occur in three deposits along the mineralised fault zone. The Goanna, Granny and Windich deposits are described below in order from north to south.

Goanna deposit

At the northernmost Goanna deposit, the smallest of the three deposits, gold mineralisation is hosted by sedimentary rocks. The mineralised zone is about 5 metres thick, and highest gold grades are where the main mineralised reverse fault intersects BIF in the hangingwall (Fig. 4a). The faulted contact of the hangingwall BIF is sharp with only minor reverse drag. In the footwall, the bedding and faulting are subparallel, although the average dip of the fault is shallower (about 35°E) than bedding (about 50°E). The location of the BIF horizon in the footwall is inferred from downhole geophysical data, and indicates a fault offset of about 900 metres. Striations on the fault surfaces indicate dip slip displacement. Near the granitoid, sedimentary rocks on both sides of the fault show a similar degree of contact metamorphism. As mineralisation postdates granitoid intrusion, most of the displacement along the fault probably occurred before mineralisation.

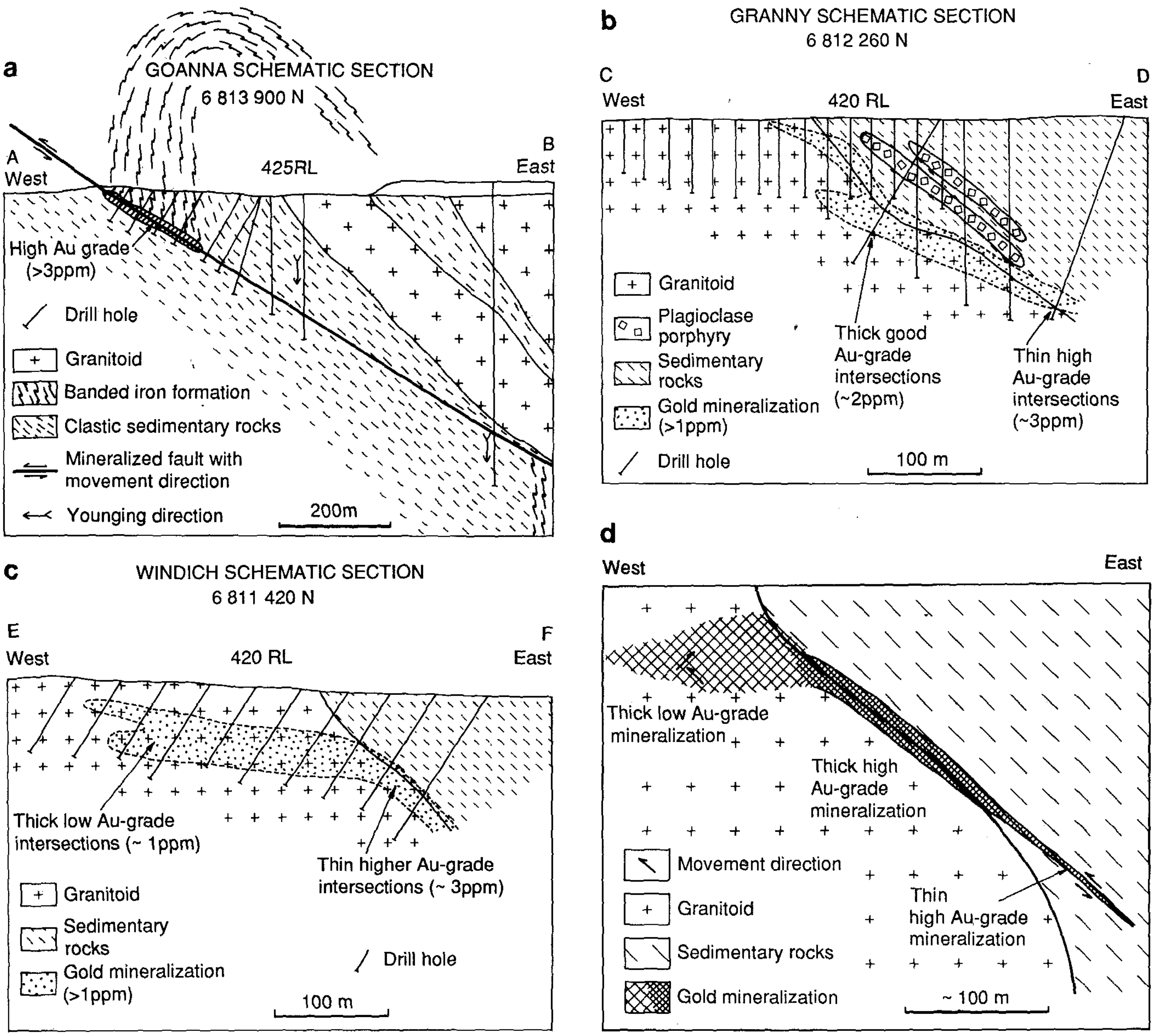

Fig. 4a–d. Schematic sections through the Granny Smith deposits. Section locations are shown on Fig. 3. **a** Schematic section of the Goanna deposit showing the reactivated reverse fault cutting the western limb of the overturned anticline. Location of the BIF in the lower part of the section is inferred from downhole geophysical measurements. **b** Schematic section through the Granny deposit showing the shape of the main mineralisation and the relation to the contact. **c** The Windich deposit. **d** Idealised section, based both on the Granny and Windich deposits, showing the relationship of the different types of mineralisation to the granitoid contact

Granny deposit

At the Granny deposit, the mineralisation largely follows the contact between the granitoid and sedimentary rocks. Some of the plagioclase porphyry dykes in the sedimentary sequence and their contacts are also mineralised. The cross-section (Fig. 4b), structure contour map of the contact (Fig. 5), and the gold-grade distribution (Fig. 6) show that mineralisation follows the contact where it dips at low angles (< 50°E). However, where the dip of the contact is greater, mineralisation occurs either in the granitoid or roughly follows bedding in the sedimentary rock. Where mineralisation is in the granitoid, it is confined to a subhorizontal zone in which ore is up to 40 m thick.

Deformation is brittle in the granitoid and brittle to brittle-ductile in the sedimentary rocks, within which mineralisation-related faulting and shearing is subparallel to the bedding (dip about 50°E). In the granitoid, offset along the individual vein-filled mineralised faults, measured from displaced pegmatitic aplite veins, is on a centimetre to decimetre scale.

Gold grade (Fig. 6) is controlled by the shape of the granitoid contact. The highest gold grades are in sedimentary rocks just above the granitoid contact where it is shallowly dipping and irregular. The dip of the mineralised zone shallows towards the centre of the granitoid pluton.

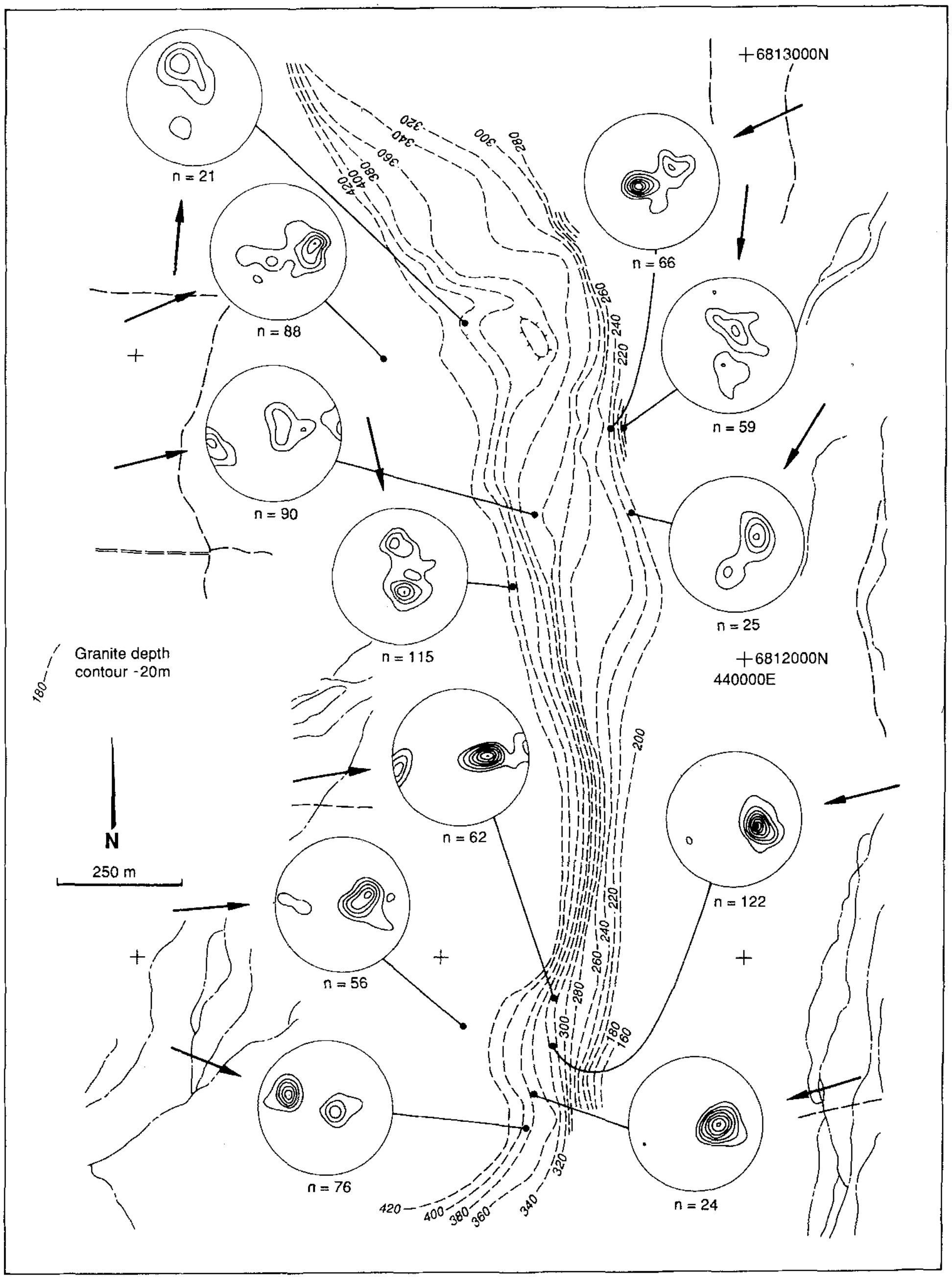

Fig. 5. Stereographic equal-area lower-hemisphere projections (2% contours, 1% area) of the mineralised vein orientations and inferred maximum stress direction with respect to the structure contour map of the east dipping contact between the granitoid and sedimentary rocks. The vein orientations discussed in this study have been measured from oriented drill cores and from the south and west walls of the Granny pit. Diamond drill cores have been oriented using downhole spear, and holes have been surveyed using Eastman single-shot camera to record dip and azimuth of the hole. Oriented drill cores intersect most of the eastern contact of the granitoid to a depth of about 150 metres

Windich deposits

At the Windich deposit, controls on mineralisation are similar to those in the Granny deposit. However, the dip of the contact is generally steeper and a wider zone of low grade mineralisation occurs in the granitoid.

Conclusion

In different sections of the Granny Smith deposits, mineralisation may be developed in the granitoid, in the sedimentary sequence, or along the contact between them. At the Goanna deposit in sedimentary rocks, high grade mineralisation is developed at the intersection of a reactivated reverse fault and a BIF horizon. At the Granny and Windich deposits, the mineralisation style and gold grades appear related to the shape of the granitoid contact. This relationship is examined further below.

Nature of mineralisation and alteration at Granny and Windich

Two stages of alteration associated with gold mineralisation are recognised in the Granny and Windich deposits: earlier hematite alteration and overprinting sericite-carbonate alteration. Hematitie alteration occurs only in the granitoid, in which it is widespread and pervasive. The sericite-carbonate alteration, which represents the main mineralisation stage, is more fracture controlled, and

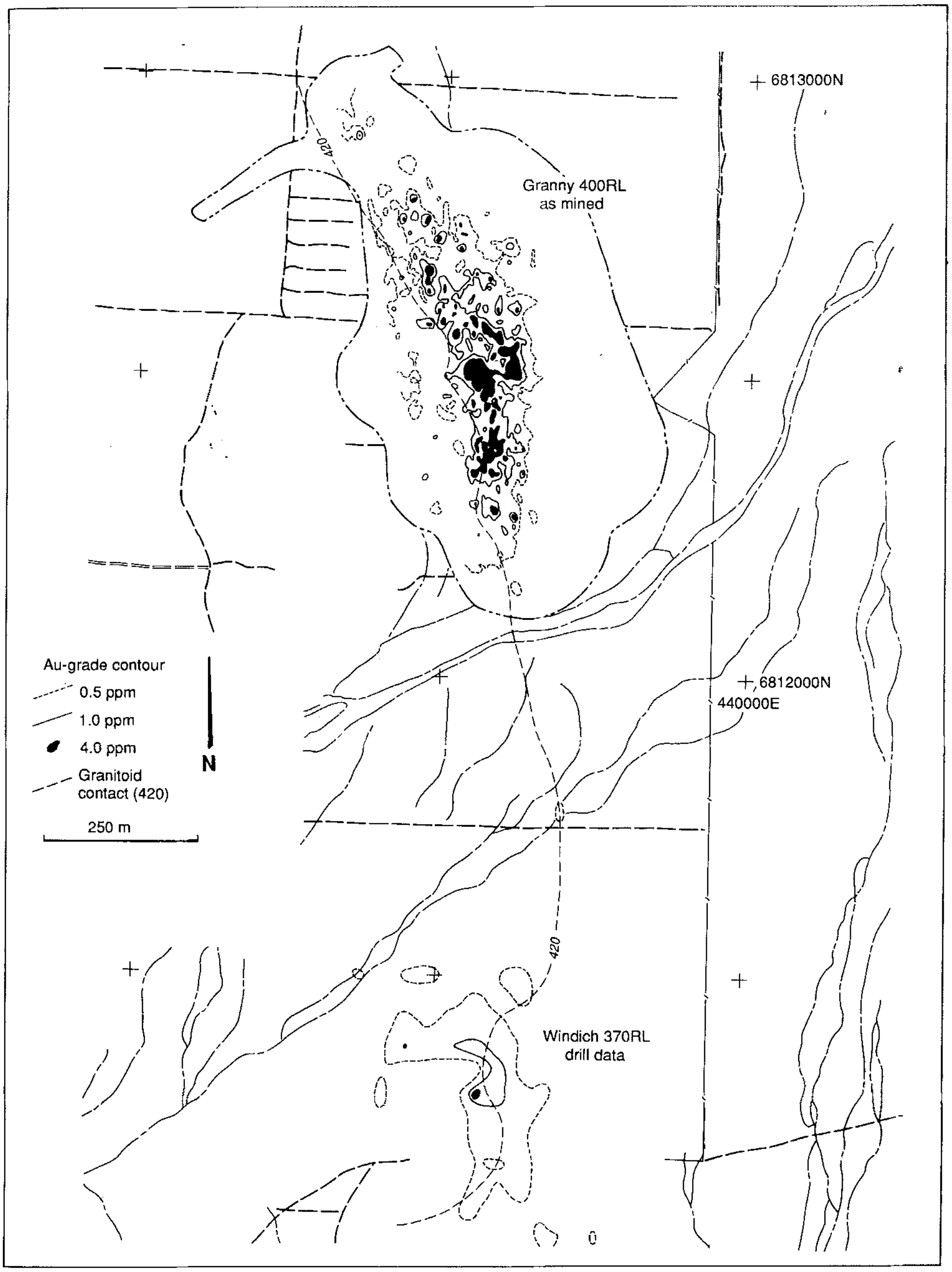

Fig. 6. Gold grade contours of the Granny and Windich deposits

occurs in the alteration envelopes of a network of thin millimetre-scale ankerite-quartz breccia veins.

The wall rock alteration around individual veins is typical of that of lode gold deposits in Archaean greenschist facies domains (eg. Colvine et al. 1988; Groves et al. 1989). Distal alteration is a few centimetres wide and typified by breakdown of clinopyroxene and hornblende and development of retrograde sericite-carbonate (calcite ± ankerite) ± biotite ± chlorite alteration. The proximal zone is several millimetres to two of centimetres wide, comprising sericite-ankerite-pyrite-silica ± rutile alteration (visible "bleaching"). In the proximal zone, plagioclase has been altered to albite and K-feldspar is locally present. Gold occurs in both veins and in alteration haloes. Gold grade is strongly correlated with the intensity of associated pyrite alteration, and the typical high-grade ore is a thoroughly brecciated and bleached, ankerite-pyrite-silica ± sericite altered rock. Pyrite is the main sulphide phase, pyrrhotite, chalcopyrite, galena, sphalerite and arsenopyrite are common but minor sulphides. Gold-, Ag-, and Pb-tellurides occur mainly in rare late-stage quartz-ankerite veins.

Mineralised vein orientations

In the granitoid and in much of the hornfelsed sedimentary rocks, gold mineralisation is associated

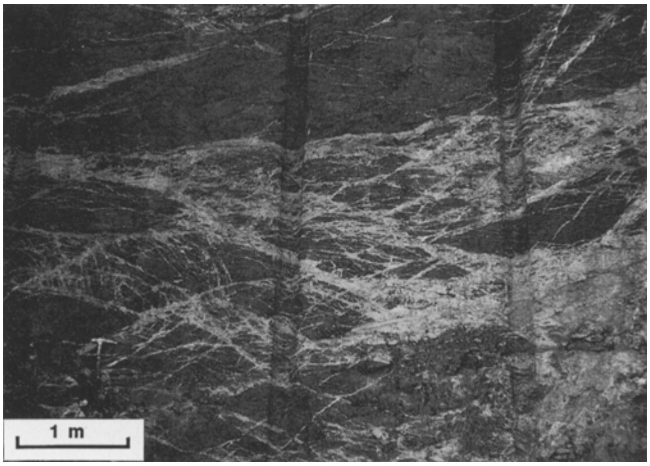

Fig. 7. Photograph of typical conjugate vein sets in the low gold-grade ore on the south wall of the Granny deposit

with a network of thin millimetre-scale ankerite-quartz breccia veins. In contrast, mineralised veins and faults in sedimentary rocks away from the contact are parallel to bedding. These are not considered further here.

In the granitoid, mineralised veins typically form conjugate sets, on scales from a few millimetres to tens of metres (Fig. 7). The conjugate pattern of veining and alteration is most obvious in low grade ore in which individual veins are clearly distinguishable, but even vein orientations measured from apparently chaotically veined and more thoroughly altered granitoid show commonly a bimodal distribution, although one of the sets is normally better developed (Fig. 5). All offsets, for instance, of pegmatitic aplite dykes along mineralised faults, fractures and veins indicate a reverse sense of movement. The conjugate vein sets have opposing senses of movement, and neither set consistently offsets the other.

Stereographic projections of the mineralised vein orientations (Fig. 5) show that the vein distribution is not random. The pit wall observations of conjugate veining are confirmed by bimodal vein distributions at all stations, although distributions are not perfectly symmetrical. The dominant pattern is a ENE-WSW dipping conjugate pair, but large variations occur both between and within individual deposits. Variations in the vein orientations are greatest within the Granny deposit in the area where the granitoid contact is most irregular and best mineralised (Fig. 6); and differences of up to 90° occur in the orientations of the conjugate vein sets. At the Windich deposit, the granitoid contact is less complex and vein orientations vary less. The acute angles between the conjugate vein sets are close to 60°, and the bisectors are subhorizontal in most cases. However, there are larger angles between conjugate vein sets at the Windich deposit, and, in one case, the bisector of the acute angle is subvertical.

Discussion

Stress orientations

One of the simplest structures by which palaeo-stress fields can be constrained are conjugate sets of fractures or faults formed through plane strain in a homogenous rock mass in the brittle régime. Experimental studies have shown that, in frictional materials, shear fractures develop at angles less than 45°, with angles of about 30° being particularly common, to the maximum principal stress axes (σ_1) (eg. Hobbs et al. 1976). In cases of plane strain, two sets of faults are sufficient to accommodate the deformation, whereas three or four sets of faults in orthorhombic symmetry are required for three dimensional strain (Reches 1978, 1983). For a single set of conjugate faults, therefore, the bisector of the acute angle is the direction of maximum compressive principal stress and the line of intersection of faults is the axis of the intermediate stress (Anderson 1951; Hobbs et al. 1976; Ramsay and Huber 1987). The variations in vein orientations shown in Fig. 5 can thus be analysed to obtain the stress distribution across the Granny Smith deposit during mineralisation. Although one conjugate vein set is normally dominant, the development in all stations of a few veins of the weaker set allows the stress orientation to be determined.

Initially, it needs to be confirmed that the conjugate fractures were formed as a result of imposed tectonic stresses on a homogeneous rock mass. For instance, a pluton may develop late-state primary fractures, which are similar to fracturing formed in an imposed external stress field, as a natural response to the dynamics of intrusion (Davis 1984). However, such fractures are not considered important at Granny Smith because shear failure conditions within plutons are always followed by tension failure conditions, ie. normal faults (Knapp and Norton 1981). At the Granny pit, all observed displacements and movement directions along the mineralised structures are reverse, and the mineralised fault zone continues into the sedimentary rocks. Hence, there is no evidence for cooling fractures, and it is considered that fracturing associated with cooling of the pluton alone is not a significant component of the observed mineralised faults and veins. However, if the orientation of the stress field during the cooling of the pluton was the same as during gold mineralisation, such a distinction would not be possible. Reactivation of pre-existing anisotropies, which were not ideally oriented to the imposed stress field, would produce a more complex fault and vein pattern than conjugate sets (Wallace 1951; Angelier 1979; Aleksandrowski 1985; Marrett and Allmendinger 1990). Hence it is assumed that reactivated earlier faults and fractures have not had a significant effect on the fracture patterns in the granitoid.

The conjugate nature of the veins supports the assumptions of plane strain and a homogenous rock mass on the scale of the vein measurements. Although one of the conjugate sets is normally dominant, the approximately equal dip of the major and minor sets indicates that the minimum principal stress direction was vertical and maximum and intermediate stresses were horizontal. The dominant orientation of the mineralised conjugate vein sets in the Granny Smith granodiorite

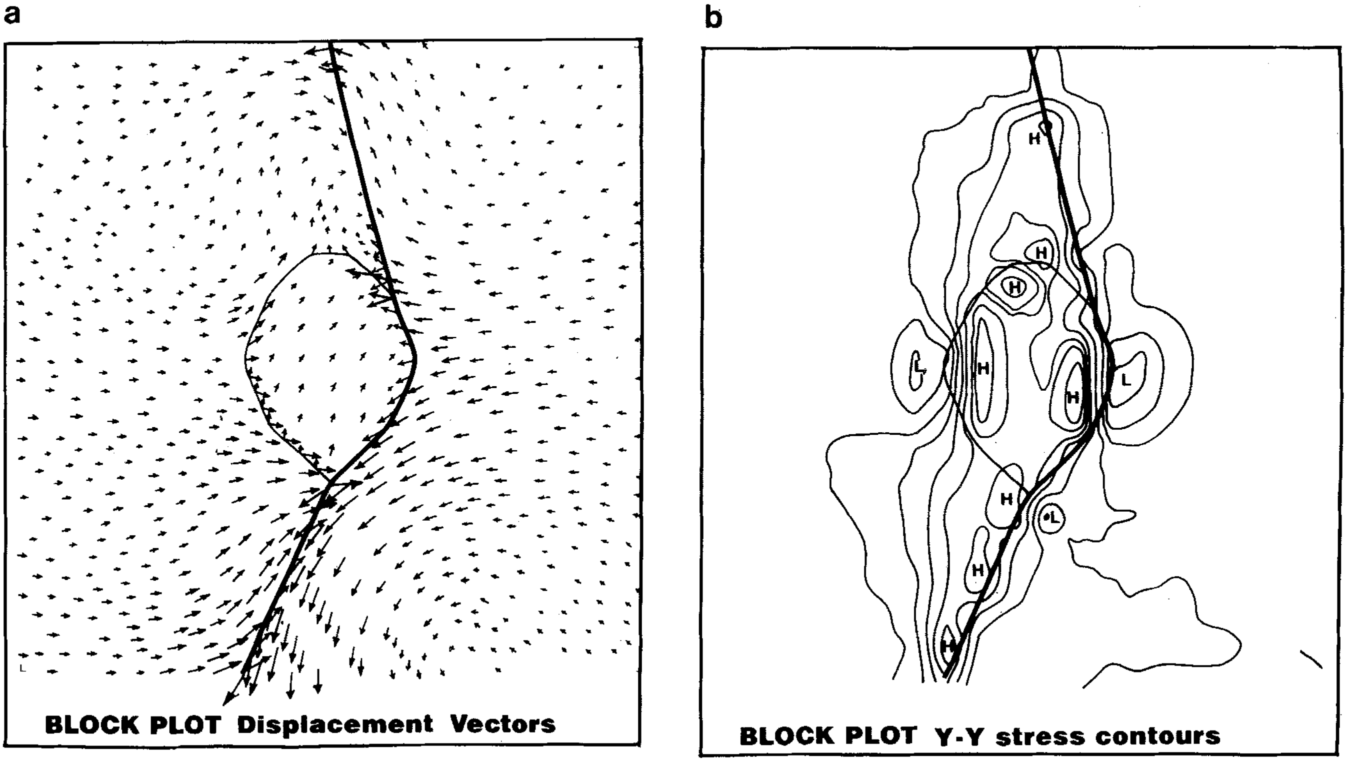

Fig. 8. **a** Rigid body in an inhomogeneous matrix which includes a weak zone wrapping one side of the body. The weak horizon allows divergent slip along the obliquely oriented parts of the zone. The *arrows* show the amount and direction of displacement. Far field stress orientation is E-W. **b** Stress contour map showing high (*H*, compression) and low (*L*, dilation) stress areas. Low stress develops in the areas of divergent flow. Plots are computer generated using the UDEC program (Holyland 1990a)

indicates ENE-WSW compression (Fig. 5). In the Yilgarn Block the orientation of regional foliation, fold axes and early Proterozoic dykes suggests E-W to ENE-WSW compression during the late Archaean and early Proterozoic (eg. Swager et al. 1990; Holyland 1990b; Libby et al. 1991), and dominant vein orientations at Granny Smith are consistent with this.

The greatest variations in stress orientations, as determined by the local orientations of conjugate vein sets at Granny Smith, are in the areas of the most irregular granitoid contact, where up to 90° variations in stress orientation occur both about horizontal and vertical axes. This area of the contact is also the most concave with respect to the E-W maximum far-field stress direction, and this concave zone is surrounded by NE and ESE-plunging troughs (Figs 5, 6). Thick high-grade ore in this area suggests high fluid flux.

Variations in mineralisation style

The Granny Smith deposit is characterized by significant spatial variations in mineralisation style (Fig. 4d). This variation can be understood by considering the rheological effect of variations in the dip of the granitoid contact. The contact between the granitoid and the sedimentary sequence is mineralised where the dip of the contact is less than about 50°which is close to the empirically best orientation (45°–30°) for shear fracture assuming a horizontal maximum principal stress (Hobbs et al. 1976). In this orientation, slip is expected to occur selectively along the contact. At greater contact dips, the shear strength of the contact would exceed the shear strength of the granitoid, and the energy should be released in deforming and fracturing of the granitoid. As there are no significant pre-existing rheological heterogeneities in the granitoid, the resultant fault zone is wide and marked by conjugate fractures.

In the sedimentary rocks, bedding planes dipping about 50°E are existing heterogeneities which are also close to the favourable orientation for slip. Within the sedimentary rocks, faulting and veining normally follow bedding planes. It appears therefore, that the deformation in the sedimentary rocks was by slip along bedding planes. Obviously, there was strong focussing of fluid flow along bedding planes, with poor permeability across the bedding planes in the fine grained sedimentary rocks, hence restricting fluid flow along discrete bedding-parallel fault planes, which formed conduits of enhanced hydraulic conductivity. As a result, high-grade but narrow ore shoots developed.

Regional scale fluid focussing

On a more regional scale, focussing of the mineralised fluids into the Granny Smith area appears to have been the result of mean stress variations created by the gross granitoid-greenstone geometry. A sub-circular rigid body in a ductile matrix creates an area of low mean stress at boundaries perpendicular to the maximum principal stress if the rigid body is wrapped by a weak horizon which allows divergent flow of the ductile matrix around the body (Fig. 8a); this is scale independent (Holyland 1990a; Ridley 1993). As the entire Granny Smith granodiorite behaved as a rigid body in a ductile matrix, a regional low mean stress area was created during E-W compression. The largest concentration of gold is in the Granny deposit, which is sited where the contact is concave against ENE-WSW compression, hence where the predicted stress gradient is largest (Fig. 8b). Smaller scale heterogeneities, for instance irregular contacts between contrasting competencies, behaved in a similar manner and created mean stress variations within the deposit. The mean stress differences resulted in a heterogenous stress field, variable fracture and vein orientations, heterogeneous fluid flow, and consequent irregular gold-grade distribution.

Conclusions

The Granny Smith gold mineralisation formed at upper greenschist facies conditions in a largely brittle structural régime. The brittle structural style of mineralisation is similar to that of other high crustal-level deposits, such as Wiluna (Hagemann et al., 1992) and Racetrack (Gebre-Mariam et al., this volume). However, at Granny Smith major faults have reverse rather than strike-slip movement.

At Granny Smith, there are variations in the siting of veins associated with gold mineralisation between domains where the host rocks are sedimentary rocks and where they are granitoids. Furthermore, conjugate vein sets have different orientations in different sections of the granitoid, dependent on their position with respect to the variably oriented granitoid contact.

Orientation data for the vein sets are interpreted to indicate that stress along the granitoid-sedimentary rock contact was heterogeneous and was controlled by the geometry of the contact. In areas where the contact is in a favourable orientation for slip, deformation was localised along the contact, and flatter-dipping areas along it created pressure shadows and dilational jogs. Fluid flow was focussed into these low pressure areas and they became sites of high-grade mineralisation (c.f. Sibson 1987). The pressure shadows were areas of low mean stress and, as a result of changes in the stress field, the stress trajectories become curved both laterally and vertically. The observed variable vein orientations are a reflection of this heterogenous stress field. This inference of heterogeneous stress broadly supports the concepts behind the stress mapping technique (Holyland 1990a). It shows that large variations in the stress field may occur even on a small scale, and that they are probably the main control on fluid focussing and resultant gold-grade variations in some deposits. However, variations in the magnitude of the mean stress cannot be estimated from vein measurements.

Other studies that have pointed to heterogenous stress fields as a possible control on fluid flow and the siting of Archaean lode-gold deposits include the studies of Dubé et al. (1989) at the Norbeau Gold Mine in Quebec, Canada, and Oliver et al. (1990) at Mary Kathleen, Australia, an area of polymetallic uranium-rich mineralisation. The study of Dubé et al. (1989) shows how the axis of extension, and hence the complex array of shear zones, was guided by the layering of the Bourdeau sill. They conclude that the anisotropy of a stiff layer and its orientation have induced an internal strain different from regional strain. Therefore, the veins are strongly controlled by the orientation of the body, as the sill behaved as a competent sheet in a matrix of more ductile sedimentary rocks. There are thus strong similarities with the situation at Granny Smith. Oliver et al. (1990) studied metamorphic fluid flow during regional amphibolite-facies metamorphism and deformation at Mary Kathleen. Intense fluid flow was localised within strong, relatively brittle intrusive bodies and in veined, brecciated and altered zones around their margins. The conclusions of their study and modelling were that a strong body in a weaker matrix caused stress variations during deformation, that stress and strain heterogeneities influenced the development of metamorphic fluid pathways, and that fluid flow was focused in the low mean-stress regions. Again, there are obvious analogies between their results and the controls on gold mineralisation at Granny Smith argued in this paper.

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