Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Precambrian Research 161 (2008) 77–88

Precambrian Research

www.elsevier.com/locate/precamres

Extension and gold mineralization in the Archean Kalgoorlie Terrane, Yilgarn Craton

Roberto F. Weinberg[a,b,*], Peter van der Borgh[b]

[a] *School of Geosciences, Monash University, Victoria 3800, Australia*
[b] *School of Earth and Geographical Sciences, University of Western Australia, WA 6009, Australia*

Received 11 May 2005; received in revised form 21 July 2006; accepted 7 April 2007

Abstract

This paper focuses on two extensional events affecting late Archean crust of the Kalgoorlie Terrane in the Eastern Goldfields, and which are associated with gold mineralization. These events bracket the duration of the crustal shortening event known as the Kalgoorlie Orogen. The early extension phase is preserved around the Raeside Batholith and gave rise to the earliest recognized structures, D_{1e}. This event is characterized by multi-directional horizontal extension, in contrast to unidirectional extension associated with core complexes. Extension uplifted the batholith in relation to the overlying greenstone sequence and produced recumbent folds. Gold, including the large deposits at Leonora, was deposited in normal shear zones around the batholith. We propose that extension triggered doming of gravitationally unstable granitic rocks buried under a greenschist sequence, and amplified the growth of extensional nappes.

The late phase of extension is evident in a number of gold deposits in the Kalgoorlie Terrane. This phase is characterized by (a) overprinting crustal shortening structures that suggests it is the latest structure in all localities; (b) gently dipping foliation, associated with recumbent folds, which are dragged into moderately dipping, normal shear zones; (c) maximum stretching axis, NW–SE or N–S, at high angles to the maximum shortening axis inferred from regional shortening phases of the Kalgoorlie Orogen and (d) hosting gold. This phase records relaxation of the Kalgoorlie Orogen and the findings suggest that gold mineralization was not restricted to a single deformation phase but started before the Kalgoorlie Orogen and waned at the end of the orogeny.

Keywords: Orogenic gold; Kalgoorlie Terrane; Extension tectonics; Archean; Tectonic evolution

1. Introduction

The concentration of structurally controlled, giant and world-class orogenic "lode" gold deposits in the Kalgoorlie Terrane has led to considerable efforts in understanding its structural evolution. The objectives of these studies were to understand the relative timing of mineralization (e.g., Weinberg et al., 2005; Williams and Currie, 1993; Witt, 2001), the role of active structures on controlling mineralization (e.g., Bucci et al., 2004; Micklethwaite and Cox, 2004; Ridley and Mengler, 2000; Weinberg et al., 2004) and the tectonic evolution of the terrane that ultimately led to mineralization (e.g., Archibald et al., 1978; Platt et al., 1978; Krapez et al., 2000; Swager et al., 1997, 1992; Weinberg et al., 2003; Witt and Swager, 1989).

The Kalgoorlie Terrane is the best studied of a number of terranes, which form the Eastern Goldfields, the eastern part of the Yilgarn Craton. In the most commonly presented regional structural history, extensional structures have typically been given less attention despite potential importance (Groves and Batt, 1984; Hallberg, 1986). The structural history of the terrane can be divided into two contractional orogenies. The first one encompasses the first crustal shortening event associated with deformation phase D_1, a N-directed thrust stacking (e.g., Witt and Swager, 1989). The second one encompasses subsequent deformation events D_2, D_3 and D_4 of previous workers, which collectively comprise the Kalgoorlie Orogen (Weinberg et al., 2003).

The timing and duration of gold mineralization and associated hydrothermal alteration in the Eastern Goldfields is currently being debated. Most schemes suggest a late gold mineralization, towards the end of the Kalgoorlie Orogen, following a protracted structural history (Davis et al., 2001; Groves et al.,

---

* Corresponding author. Tel.: +61 3 99054902; fax: +61 3 99054903.
E-mail address: Roberto.Weinberg@sci.monash.edu.au (R.F. Weinberg).

0301-9268/$ – see front matter. Crown Copyright © 2007 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.precamres.2007.06.013

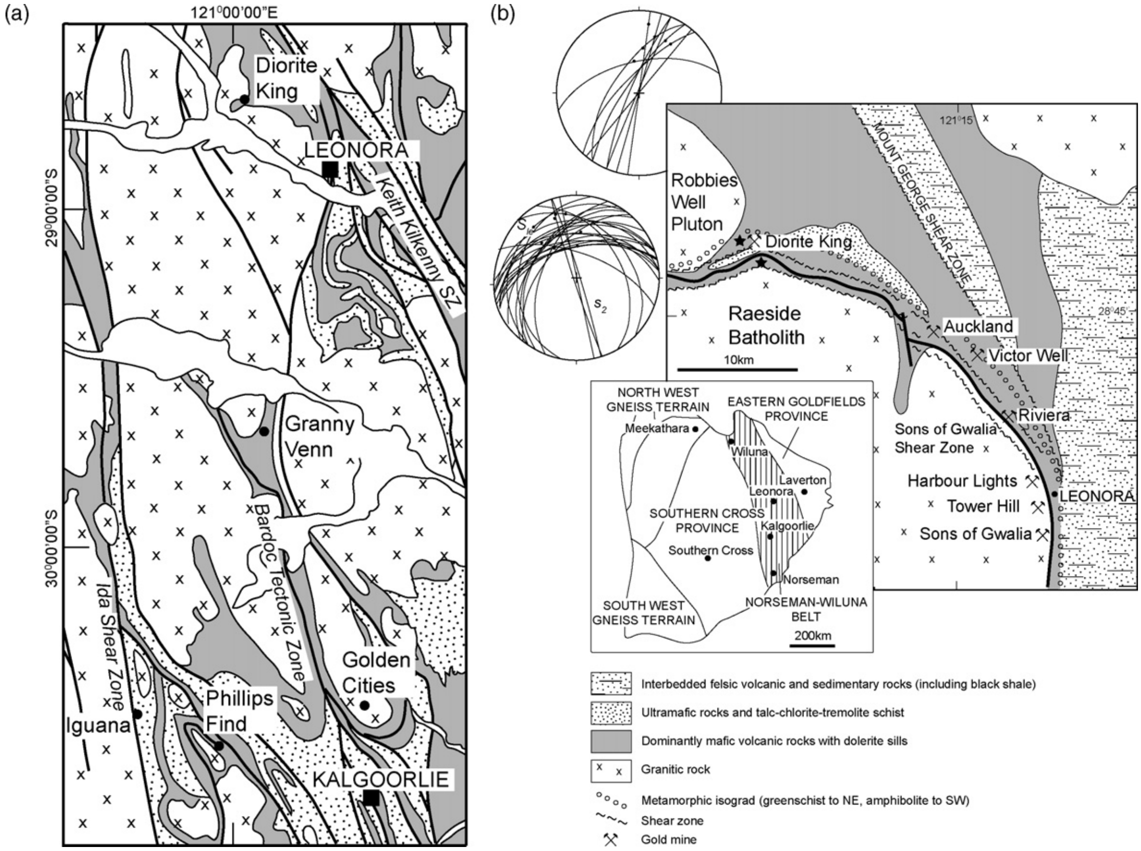

Fig. 1. (a) Simplified geological map of the Kalgoorlie Terrane indicating the four gold deposits (Iguana, Phillips Find, Golden Cities, and Granny Venn) with significant record of late extension and the major shear zones discussed in the text. Crosses indicate granitic rocks, grey tone indicates mafic–ultramafic rock sequences, white indicates dominantly sedimentary sequence, and dotted pattern indicates alluvium. (b) Geological map of the area surrounding the Raeside Batholith (after Williams and Currie, 1993). Map inset shows the Norseman–Wiluna Belt, which includes the Kalgoorlie Terrane. Stereonet insets summarize structures in the wedge of amphibolites between the Robbies Well Pluton and the Raeside Batholith, marked in the map by two black stars. The upper stereonet plots the attitudes of D_{1e} normal-dextral mylonitic shear planes and stretching and mineral lineations from a number of outcrops NW of Diorite King. The lower stereonet plots the attitude of foliations, including normal shear planes, and stretching and intersection lineations measured SE of Diorite King. In this stereonet there are also three NW-trending and steeply dipping planes indicative of the general attitude of S_2. The intersection lineations are nearly parallel to isoclinal fold axes and result from intersection between S_{1e} and NW- to N-trending, steeply dipping, S_2 foliations.

2000, 1995; Kent et al., 1996; Swager et al., 1992; Witt and Vanderhor, 1998). Others have argued for a more protracted mineralization (Bateman et al., 2001; Bucci et al., 2004; Davis and Maidens, 2003; Witt, 2001) that might have lasted the duration of the orogen.

This paper focuses on two extensional events that bracket all other major deformation phases in the Kalgoorlie Terrane. It starts by documenting well-preserved features of an extensional event that predates the Kalgoorlie Orogen around the Raeside Batholith in the Leonora area, north of Kalgoorlie (Fig. 1a). The extent to which this deformation has affected the Terrane remains undetermined. Lack of its description elsewhere may be due to strong overprint by subsequent shortening events. The paper then documents an extensional event that post-dates the Kalgoorlie Orogen, and is exposed in a number of spaced gold deposits closer to the town of Kalgoorlie (Fig. 1a). The implications of these two extensional phases to gold mineralization are discussed based on the assumption that shear zone-hosted gold mineralization was deposited either contemporaneously with the shear zone forming event, or later shear zone reactivation.

2. Deformation history: the current view

A generally accepted deformation scheme for the Kalgoorlie Terrane divides deformation into four main crustal shortening phases, D_1–D_4 (e.g., Swager et al., 1997). D_1 is sometimes described as an extensional phase of isoclinal recumbent folding and subhorizontal nappe-type translation (Archibald et al., 1978; Martyn, 1987; Passchier, 1994; Williams and Currie, 1993) and sometimes, mostly in the southern part of the Kalgoorlie Terrane, as a shortening phase associated with major thrusting to the north (Knight et al., 1993; Martyn, 1987; Swager and Griffin, 1990; Witt and Swager, 1989).

In the Leonora area, the earliest structures recognized correspond to an early phase of extension. Hammond and Nisbet (1992) argued for an early extensional phase, D_e, lasting throughout the deposition of the greenstone sequence and resulting in low-angle shear zones, which now occupy the contacts between greenstone and granite. In their view, reversal of the extensional structures and low-angle thrusting gave rise to D_1 thrust stacking. Williams and Whitaker (1993), using structures recorded around the Raeside Batholith close to Leonora, argued that their D_e resulted from an early phase of gneiss and granite doming, a conclusion challenged by Passchier (1994) who interpreted these early extensional structures to be a result of a regional N–S extensional phase, and postulated that extensional D_1 structures in the north could be contemporaneous with thrusting D_1 structures in the south.

Witt (1994) inferred the opposite sequence of events to the one proposed by Hammond and Nisbet (1992), with an extensional collapse stage following D_1 thrust stacking. This conclusion was based on a regional east–west, deep crustal seismic reflection profile north of Kalgoorlie, which indicated the presence of a prominent subhorizontal reflector interpreted as a detachment, underlying the greenstone sequence. The detachment was interpreted to result from east–west extension (Goleby et al., 1993), and it truncates layering of the greenstone sequence and thrusts. This extension would have preceded D_2 and would account for deposition of clastic sediments in late basins, which were folded during D_2 (e.g., Kurrawang and Merougil Sequences, Swager, 1997). Here, we refer to this early phase of extension as D_{1e}, to avoid ambiguities. The subscript *1* refers to the fact that it is the earliest recorded phase in an area, and the subscript *e* differentiates it from D_1, generally used in the literature to refer to the early thrusting event.

The Kalgoorlie Orogen started with D_2, the major fabric-forming event which produced the regional NNW–SSE trending thrusts, gently plunging folds, and a steep foliation that can be traced over long distances (Archibald et al., 1978; Platt et al., 1978; Swager and Griffin, 1990; Witt and Swager, 1989). It overprints D_1 shortening structures in the southern part, and D_{1e} structures in the northern part of the Kalgoorlie Terrane. Some authors suggest that an extensional phase took place during D_2 either contemporaneously with general crustal shortening, through granite doming (Swager and Nelson, 1997), or as a break in the general D_2 shortening (Blewett et al., 2004), caused by granitic intrusion and thermal crustal weakening (Davis and Maidens, 2003).

D_3 was a transpressive event which overprinted D_2 and is associated with NNW-trending sinistral shear zones, *en-echelon* folds (Swager and Griffin, 1990; Witt and Swager, 1989), and N–S or NNE-trending dextral shear zones (e.g., Hammond and Nisbet, 1992; Passchier, 1994; Platt et al., 1978). Initial foliation development occurred during D_2 folding and intensified during D_3. For the Kalgoorlie area, Swager et al. (1992) suggested gradual transition from D_2 to D_3 sinistral strike-slip producing a single fabric. Near Leonora, Passchier (1994) found that D_2 and D_3 are effectively inseparable and suggested that there could have been strain partitioning during the same event. The general evolution from D_2 to D_3 was interpreted to represent a natural progression of the Kalgoorlie Orogen from a phase of crustal thickening to a phase of lateral escape (Weinberg et al., 2003). D_4 was a phase of continued and possibly cooler crustal escape, where a conjugate brittle fault pair developed: a set of dextral NNE–SSW trending fault zones (Mueller et al., 1988; Ridley and Mengler, 2000; Vearncombe and Vearncombe, 1999) and a set of WNW–ESE sinistral lineaments well-defined in aeromagnetic images.

The NNW-trending Ida Shear Zone marks the western boundary of the Kalgoorlie Terrane and separates it from the Southern Cross Terrane. A seismic section crossing it revealed a reflector interpreted to represent the Ida Shear Zone at depth, and recording normal movement on a plane dipping 30°E, displacing a mid-crustal boundary by 5 km, and warping the crustal-mantle boundary (Swager et al., 1997). These authors concluded that the fault developed at a very late stage in the tectonic history because it did not control deposition of the supracrustal rocks and because it defines a planar structure, not folded by the early phases.

3. Early extension: Leonora and the Raeside Batholith

3.1. Previous structural work

The structural geology of the Leonora area is strongly controlled by the Raeside Batholith (Fig. 1b). In this area the first deformation phase is extensional, and is followed by deformation phases that match those known from other areas in the Kalgoorlie Terrane (Williams, 1998). Passchier (1990) defined this early phase, which we term here D_{1e}, and found that its deformation is localized into shear zones surrounding undeformed lenses. The S_{1e} foliation is generally conformable to the Raeside Batholith and records consistently batholith-up normal sense of movement. On the northern side of the batholith, Passchier (1990, 1993) mapped L_{1e} lineations plunging N or NW on gently to moderately dipping normal shear zones. On the eastern side of the batholith, L_{1e} stretching lineations plunge E with consistent batholith-up movement sense, despite the 90° rotation in relation to northern exposures (Williams and Currie, 1993). Normal faulting has also been described from within the main gold deposits at Leonora (Skwarnecki, 1988, 1990; Vearncombe, 1992; Witt, 2001). Passchier (1990) described isoclinal F_{1e} folds in BIF with axes parallel to mineral lineation and defined a large-scale F_{1e} sheath fold. Early formed folds are also recorded as recumbent folds, with wavelengths of hundreds of metres, at Leonora (Williams et al., 1989; Williams and Currie, 1993).

Metamorphic isograds parallel the Raeside Batholiths and assemblages grade from amphibolite facies close to the batholith to greenschist facies further away. Williams and Currie (1993) described a juxtaposition of contrasting metamorphic conditions in a core drilled east of Sons of Gwalia mine, from the greenstone sequence in the east towards the batholith in the west. The upper part of the core, furthest away from the batholith contact, records greenschist facies and pressures between 2 and 3 kbar. These conditions change downwards across a narrow shear zone, to amphibolite facies assemblages with pressures 2–3 kbar higher. Witt (1994) also found a 3 km D_{1e} excision of stratigraphy south of Leonora suggesting that isograds and stratigraphic thinning could be related to doming and extension. This extension may have contributed to the formation of recumbent folds and low angle faults. Passchier (1994), in contrast, concluded that D_{1e} records a phase of regional extension that was not caused by granite doming since he noted that extensional features can be found away from granite margins.

The second deformation phase in the area, D_2, is characterized by upright folding and dextral shear zones resulting from a general ENE–WSW shortening (Passchier, 1993), related to D_2 elsewhere in the Kalgoorlie Terrane. Structures associated with D_2 in the Leonora area have a patchy distribution but tend to increase in intensity towards the east (Passchier, 1994) where D_2 produced large folds and the Keith–Kilkenny high strain zone (Passchier, 1993, 1994; Vanderhor and Witt, 1992). The north side of the Raeside Batholith is a strain shadow where D_2 is weakly developed (Passchier, 1993).

3.2. Results

This work broadly supports the findings of Passchier (1994), but extends them in three ways: (a) D_{1e} structures and accompanying amphibolite facies conditions close to the Raeside Batholith were overprinted and retrogressed to greenschist facies assemblages by D_2 structures; (b) D_{1e} was not simply a period of uniaxial N–S extension, but a period of vertical shortening and horizontal stretching along two roughly similar, horizontal stretching axes (generalized horizontal extension); (c) extension was most likely externally driven, but granite doming played a major role in the extensional process, with significant implications for the evolution of the Kalgoorlie Terrane.

Structures related to D_{1e} are well developed around Diorite King, in a kilometric wedge of amphibolites and minor talc–chlorite schists, BIF layers and slates (Passchier, 1993) between the Raeside Batholith and the Robbies Well Pluton (Fig. 1). In this area D_{1e} is characterized by isoclinal folds with axial plane parallel to the margin of the Batholith, and strain localization into normal or oblique normal-dextral shear zones (stereonet insets in Fig. 1b). This wedge of greenstones between the two granitic bodies can be divided into two zones separated by a NE-trending line running roughly through Diorite King (Fig. 1b). To the NW of this line, close to the Robbies Well Pluton, a steeply NW-dipping foliation is associated with a NNW-plunging lineation, and S–C fabrics recording dextral-normal oblique movement (stereonet in Fig. 1b). In this area, deformation is localized into shear zones in otherwise weakly deformed amphibolites, which are best exposed on a surface, by the northern side of the Old Agnew Road just past the diggings around Diorite King (Fig. 1b). Here, an array of metre-wide amphibolite facies D_{1e} dextral-normal shear zones, including isoclinal folds and mylonites, cut across an otherwise weakly deformed amphibolite. To the SE of the dividing line, close to the Raeside Batholith, foliation, S_{1e}, dips moderately between NE and NW, and strikes parallel to the margins of the batholith. This foliation is axial planar to isoclinal folds defined by bedding (Fig. 2), and the folds plunge moderately N or NW (Fig. 1b, inset). There are also shear zones parallel to S_{1e}, which have N to NW-plunging L_{1e}, roughly parallel to the fold axes of isoclinal folds. These shear zones are associated with normal movement (S–C fabric).

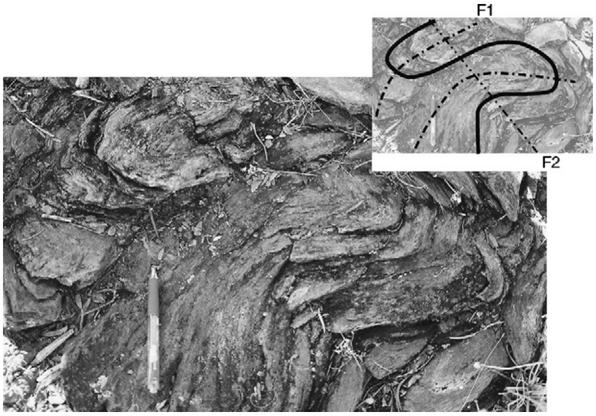

Fig. 2. Fold interference pattern close to Diorite King. Isoclinal F_{1e} refolded by F_2. The twofold phases are nearly co-axial.

In the northern part of the Raeside Batholith, from Diorite King to Auckland, these early structures are overprinted by D_2 structures, which are also heterogeneously distributed. These are either open, upright, plunging folds, trending between 340° and 010°, nearly co-axial to F_{1e} folds or NNW to N striking, and steeply dextral shear zones. F_2 refolds F_{1e} isoclinal folds (Fig. 2) and amphibolite facies rocks are retrogressed to greenschist facies where intense D_2 structures develop. This is best exemplified at the shallow Victor Well pit (Fig. 1b), where a 1.5 m wide, dextral shear zone trending 010° to 020°, with gently north plunging lineation, cuts through amphibolites which are retrogressed in the shear zone to greenschists (Fig. 3). The amphibolites around the shear zone and an intrusive dyke, are also cut by normal, D_{1e} shear zones with a range of orientations, which suggest an extensional phase characterized by two main horizontal stretching axes of similar magnitude (Fig. 3b, inset). A similar pattern was found in the Riviera pit (Fig. 4), where listric normal faults are exposed.

3.3. Mineralization around the Raeside Batholith

Gold in the trenches at Diorite King (Fig. 1a) is hosted by shear zones, with strong N-plunging lineation, associated with normal movement (S–C fabric) defining a D_{1e} structure. These illustrate one of a number of small deposits around that area where D_{1e} shear zones are mineralized. The large deposit at Jasper Flat (Auckland in Fig. 1a; 2 t of produced gold; Williams, 1998) is also controlled by D_{1e} structures (Passchier, 1990) as also suggested by the WNW–ESE trend of the open pit, parallel to the dominant S_{1e}. Given the spatial coincidence between gold and D_{1e} shear zones, and the lack of later reactivation of these shear zones, we interpret that gold was deposited during extensional shearing. Other large gold deposits likely formed during D_{1e} but not investigated here are Harbour Lights (Skwarnecki, 1988), and Sons of Gwalia (Williams and Currie, 1993) on the east margin of the Raeside Batholith (Fig. 1b).

In the Victor Well deposit described above, the dextral greenschist facies D_2 shear zone is mineralized and cuts through un-mineralized normal shear zones in surrounding amphibolite facies rocks. A similar description is given to the Riviera deposit (Williams et al., 1989) and the Victoria Wells deposit (Passchier, 1990) suggesting that they too formed during D_2. Williams et al. (1989) concluded that mineralization around Leonora is virtually restricted to D_{1e} shear zones whereas Passchier (1990) raised

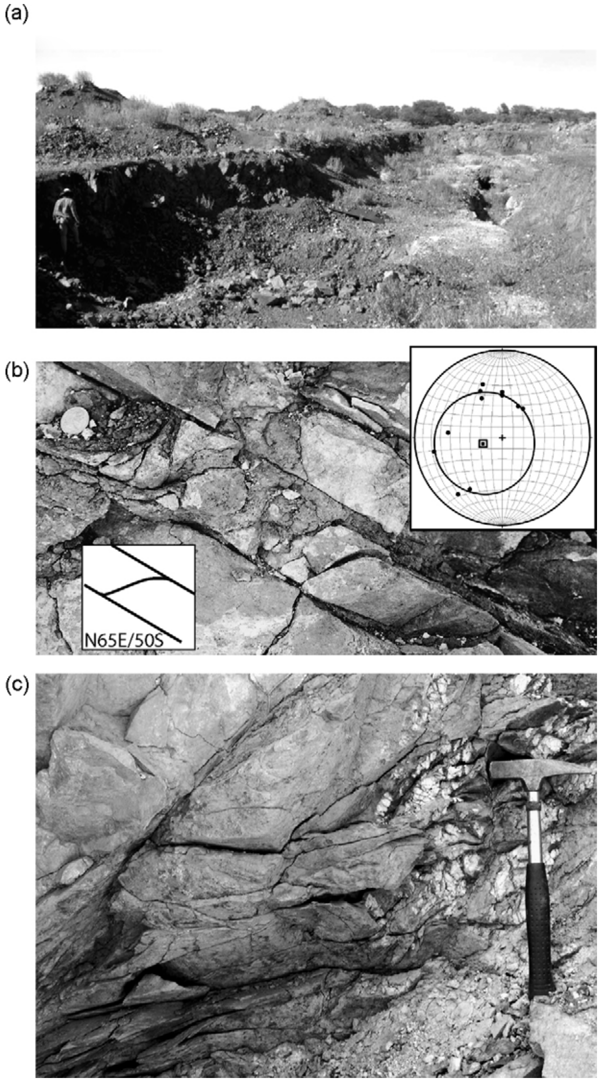

Fig. 3. Victor Well Pit (UTM 0331480 mE, 6811700 mN, WGS84). (a) View of the open pit looking south. The deepest part on the right-hand-side defines the 010–020°-trending retrogressed dextral shear zone, which cuts through amphibolites and a granite dyke. Away from the trench, these rocks are cut by normal shear zones as depicted in (b) (coin for scale on the upper left-hand-side). Inset in (b) is a lower hemisphere stereonet projection of the poles to normal shear zones, defining a cone, which implies a vertical maximum shortening strain axis and an undefined maximum horizontal stretching axis, suggesting general horizontal stretching. Cone centre (shortening axis) plunges 70° and cone half angle is close to 50°. (c) Normal shear zone trending 351°/68°E at a shallow open pit 800 m north of Victor Well (0331570 mE, 6812650 mN, WGS84).

the possibility that mineralization might be focused at D_{1e}–D_2 intersection. The evidence above supports the conclusion that mineralization developed during both events.

3.4. Nature of D_{1e}

Passchier (1994) emphasized the N-directed stretching nature of D_{1e}, characteristic of the area north of the Raeside Batholith. However, he also recognized that the stretching direction defined by lineations rotates 90°, changing with the trend of the margin of the Raeside Batholith. Passchier (1993, 1994) suggested that D_{1e} could have triggered and controlled the deposition of the bi-modal volcanism preserved in the Keith–Kilkenny Shear Zone, which would have required an E–W extension. These two dominant and roughly orthogonal directions of extension were recorded close to and far from the Raeside Batholith (see Fig. 12 in Passchier, 1994) suggesting that D_{1e} was a phase of vertical shortening and generalized horizontal extension. This conclusion is reinforced by the pattern of normal faults/shear zones recorded in the Victor Well open pit (Fig. 3b, inset) and Riviera pit (Fig. 4). The stereonet projection of fault poles in these pits defines a small circle (cone) with steep or vertical shortening axes (the cone axis), and extension close to the horizontal plane but without a preferential axis (generalized extension). More local and regional data is required to support this finding.

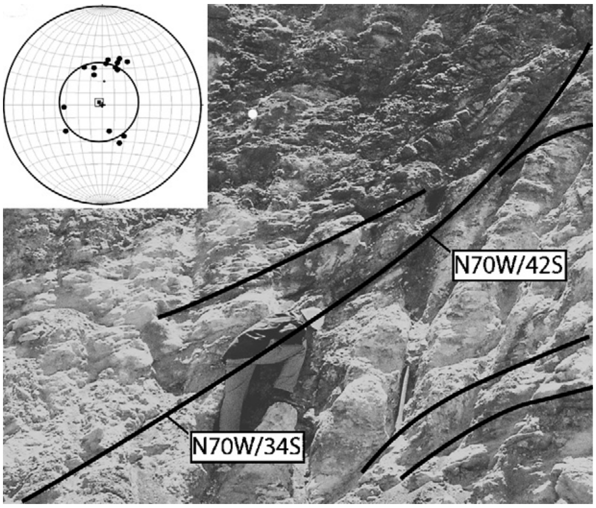

Fig. 4. Listric fault in weathered granite, Riviera open-pit (5 km north of Leonora UTM 0332830 mE, 6808700 mN, WGS84). Inset: lower hemisphere equal area projection of poles (filled circles) to all normal fault planes measured. They define a cone with a nearly vertical shortening axis and an undefined maximum horizontal stretching axis, suggesting general horizontal stretching. Cone centre (maximum shortening axis) is at 313°/87° (square), and cone half angle is 33°.

4. Late extension: Phillips Find, Golden Cities, Iguana, Granny Venn

Late-stage extensional structures in the Eastern Goldfields Province were described by Davis and Maidens (2003), who argued for a syn- or late-D_2 extensional event for the Laverton Terrane, east of Leonora. Vanderhor and Witt (1992) reported, though briefly, on a late NNW–SSE extensional deformation close to Leonora, on the Keith–Kilkenny Strain Zone. The extensional structures described here are from four widely spaced gold deposits in the Kalgoorlie Terrane and were the last deformation recorded in each area. We postulate that they record the last deformation phase, D_5, which corresponds to a stress relaxation phase at the end of the Kalgoorlie Orogen. We chose to describe these deposits because (a) they have well-developed late extensional features, whereas many other deposits or outcrops have either poorly defined or no evidence of late extension phases, and (b) their spread suggests that a late extensional event might have been a regional response, and not a local response to stress imbalances. We emphasize however, that neither the absolute timing nor the extent of distribution of these late features is yet fully established.

4.1. *Granny Venn and Auntie Nellie (UTM 0315200 mE, 6716800 mN, WGS84)*

These two open pits are located in the Menzies mining area (Witt, 1993), 110 km north of Kalgoorlie. They are in a narrow corridor of sandstone, mafic, ultramafic and felsic rocks, trending N10E between two large granitic bodies, close to Goodenough, an abandoned gold digging. Approximately 1.8 t of gold was produced from these pits and gold is hosted by heavily altered granitic bodies and the phlogopite alteration rim of the ultramafic country rock around the granites. These granitic rocks, now strongly altered, consist of tremolite–actinolite, plagioclase, K-feldspar and quartz, forming boudins within chlorite serpentinites, with varying amounts of tremolite and talc.

The two pits are aligned in a NNE direction and each pit is elongated along the same trend, reflecting the NNE trend of the mineralization. However, this trend contrasts with the E–W dominant structural pattern recorded within the pits. The serpentinites are intensely foliated and have a number of structures indicative of intense and penetrative normal movement to the south. Shear zones have varied anastomosing strike, mainly between 90° and 100° and varying dips between 30° and 60°S. Stretching or mineral lineations on these planes are not always present but, where documented, they plunge towards 180–200°, and S–C fabrics documented parallel to these lineations, and perpendicular to the foliation, indicate top-to-the-south movement. Shear zones are associated with drag folds of gently dipping foliation and develop into detachment planes associated with S-verging recumbent folds (Fig. 5a). One of these detachments cuts across isoclinal, recumbent folds in a quartz vein, indicating vertical shortening (Fig. 5b). Normal movement is also inferred from the south vergence of asymmetric folds, which overprint early formed isoclinal folds.

Irregular granitic intrusive sheets are folded producing recumbent folds and are boudinaged in a chocolate-tablet fashion in the horizontal plane. Both structures are also indicative of crustal extension (vertical shortening). Serpentinite at the margins of granitic rocks is altered to phlogopite schist, up to 1 m wide. One such margin, striking 250°/63°N was sheared in a normal sense, as defined by 20 cm-wide S–C fabric showing strain localization at the margin of the competent granitic body (Fig. 5c).

The timing of mineralization could not be ascertained, but mineralization is most likely late, associated with silicification and sulphide precipitation which post-dates granite intrusion and phlogopite alteration. The NNE-trend of the mineralization is not reflected in the S-directed normal event, which transposed any earlier structures.

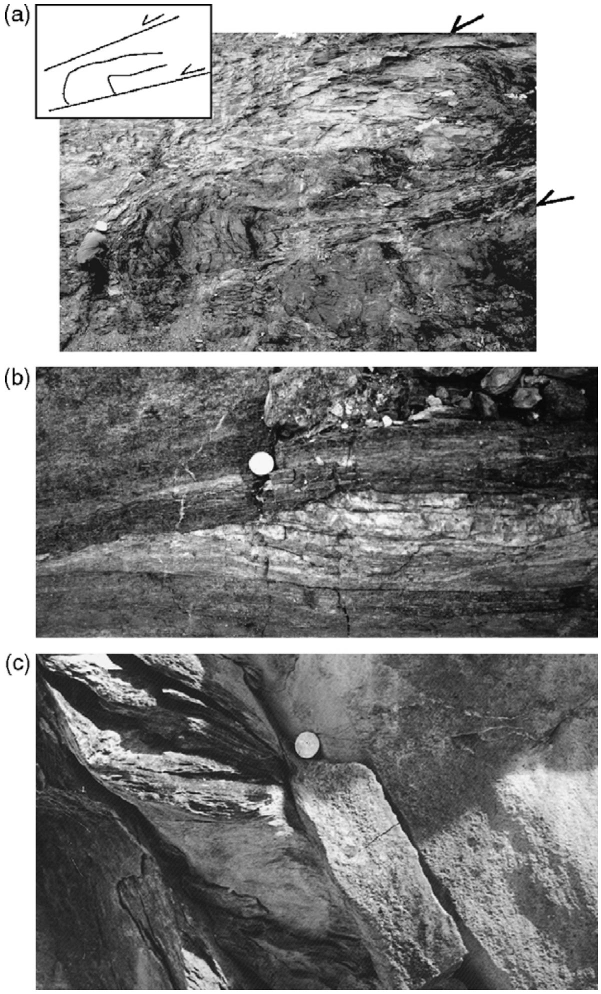

Fig. 5. (a) Detached nappes of ultramafic schist (Auntie Nellie pit), arrows indicate major normal faults. Inset: schematic line-drawing; (b) isoclinal, recumbent folds in quartz cut by a S-dipping detachment fault (Auntie Nellie pit); (c) normal shearing, in a 20 cm-wide zone of phlogopite alteration at contact with granitic boudin. South is towards the left-hand side in all photographs.

4.2. *Iguana (UTM 0275520 mE, 6623950 mN, WGS84)*

The Iguana deposit is of particular interest as it is only ∼15 km north of where a 1991 seismic traverse (EGF01) crossed the Ida Shear Zone (Goleby et al., 1993). The pit is located 1.5 km east of the main trend of the Ida Shear Zone, in a sequence of interleaved ultramafic, mafic, and sedimentary rocks. The mine stratigraphy is dominated by amphibolite, consisting of *Mg*–hornblende, *Ca*–plagioclase ($An_{>80}$) and titanite. The main shear fabric strikes 140° and dips 80°SW and is parallel to the regional S_2. A consistent down-dip mineral lineation is defined by acicular amphiboles. The amphibolites have pyroxene-rich boudin lenses, which plunge gently north and south, and provide further evidence for vertical extension. Rare asymmetries around competent porphyroclasts indicate a west-side-up shear sense.

The shear fabric is overprinted by a gently dipping foliation (Fig. 6a) of striking 300–350°, dipping 20–40°NE and associated with recumbent folds. Davis and Maidens (2003) demonstrated that the gently dipping foliations post-date peak metamorphism as they fold biotite grains formed during amphibolite facies metamorphism. Gold was won from quartz-K-feldspar veins, associated with biotite alteration of amphibole-bearing schist (Weinberg et al., 2002). The veins are

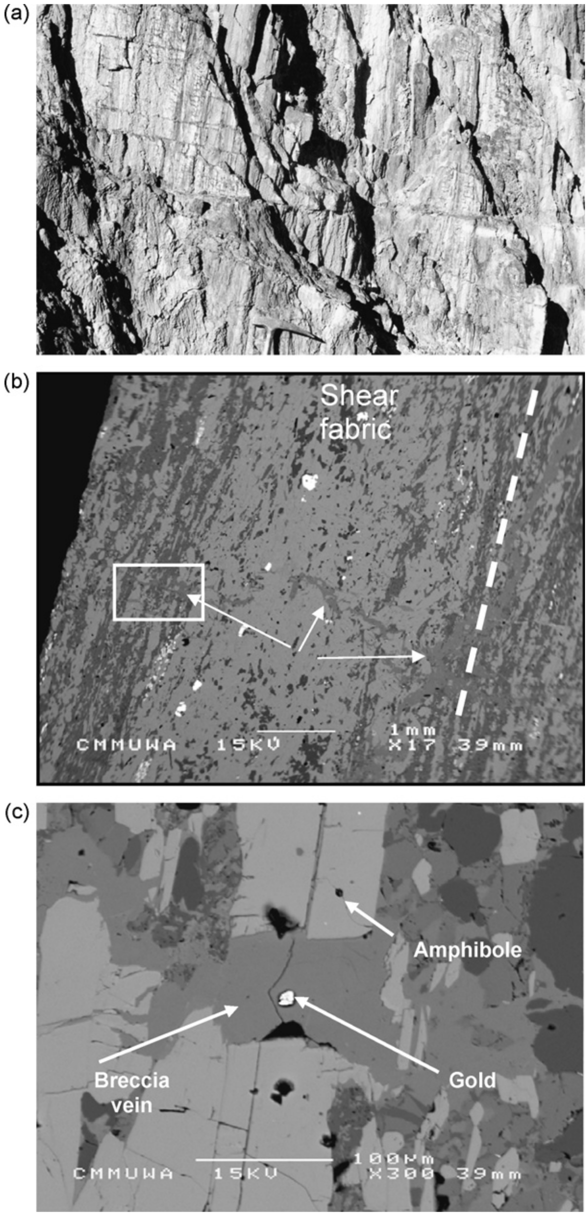

Fig. 6. (a) Steep down-dip lineation cut across by gently dipping (30–35°ENE) foliation planes in oxidized upper levels of Iguana open-cut. In deeper levels, the gently dipping foliation is penetrative. (b) Scanning electron microscope (SEM) images of the shear fabric (dashed line), highlighting the K-feldspar breccia veinlets that cross-cut the main shear fabric (arrows), and are themselves undeformed. Box represents area depicted in (c) where K-feldspar veinlet hosts a gold inclusion. The undeformed nature of the veinlet indicates that mineralization post-dated the main D_2 shearing event at Iguana.

sited within narrow zones where amphibolite has been boudinaged. Arsenopyrite is the main ore mineral (SEM imaging, Fig. 6b and c). Gold has also been imaged in one of several K-feldspar veinlets, which brecciate the main steep foliation (Fig. 6; Weinberg et al., 2002). The veinlets are not sheared or rotated, indicating that mineralization took place after the foliation developed (Fig. 6b) but we have not been able to confirm a possible relationship between mineralization and the late recumbent folds.

Recumbent folds and gently dipping foliation are indicative of an extensional phase, but no direction of maximum extension could be defined. Davis and Maidens (2003) suggested that this late phase of vertical shortening at Iguana could be related to their syn-D_2 extensional phase for the Laverton Terrane. However, the evidence implies that the late gentle foliation overprints S_2.

4.3. *Golden Cities (UTM 0346060 mE, 6635100 mN, WGS84)*

Golden Cities (Fig. 1b) consists of two open pits, Havana and Suva, hosted by the Golden Cities granodiorite. They are part of the Woodcutters group of gold deposits which include the Federal deposit, inside the Scotia–Kanowna Dome, with a reported total resource of 43 t of gold out of which 1.3 t were produced (Zhou et al., 2003). We focus on Suva (Fig. 7). This deposit is hosted by a muscovite–biotite granodiorite where the main ore minerals are pyrite, chalcopyrite, gold with trace galena, tellurides and bismuth minerals (Davis, 2002) accompanied by silica, carbonate, sericite, epidote and chlorite alteration.

Mineralization is found in <20 cm wide shear/fault zones striking between 035° and 080° and dipping between 45° and 60°NW. These zones are spaced between 1 and 4 m apart, in the main mineralised area preserved on the SW wall of the pit (Fig. 7a). Lineation in the shear zones is characterized by slickenline quartz fibres or scratches, and is close to, or slightly north of, down dip. Normal sense of shear was established based on drag folds (Fig. 7b and c), S–C fabric in ductile shear zones, and by tension gashes linking overlapping brittle faults overprinting ductile zones. Under the microscope, the ductile shear zones have intense recrystallization of quartz, bending of plagioclase twin lamellae, folding of the coarse-grained bands of sulphides, and crenulation of the fine-grained sericitized matrix (Fig. 8). Brittle faulting overprints ductile shear zones and forms cataclasites (Fig. 8a).

Away from shear zones, and particularly evident in weathered regions, the granodiorite preserves a gently dipping foliation, striking between 020° and 030°, and dipping between 15° and 30°SE. No lineation was found associated with this foliation, but S–C relationships suggest a possible oblique dextral and normal movement sense. This gentle foliation is dragged into the steeper NW-dipping normal shear zones described above, and the sense of shear derived from the drag folds is also normal (Fig. 7b and c).

Aeromagnetic images show NW-trending lineaments offset by lineaments striking 100°. Suva and Havana lie along one of these NW-trending lineaments, whereas the Federal deposit, another nearby pit in the Woodcutters group, lies on another NW-trending lineament (Zhou et al., 2003). There is, however, no evidence in the Suva pit of a NW-trending shear zone. This contrasts with the Federal deposit where mineralization follows a NW-trending shear zone or fault, and high-grade ore-shoots occur at intersections with structures striking 020° and dipping steeply NW (Zhou et al., 2003). No kinematic indicators

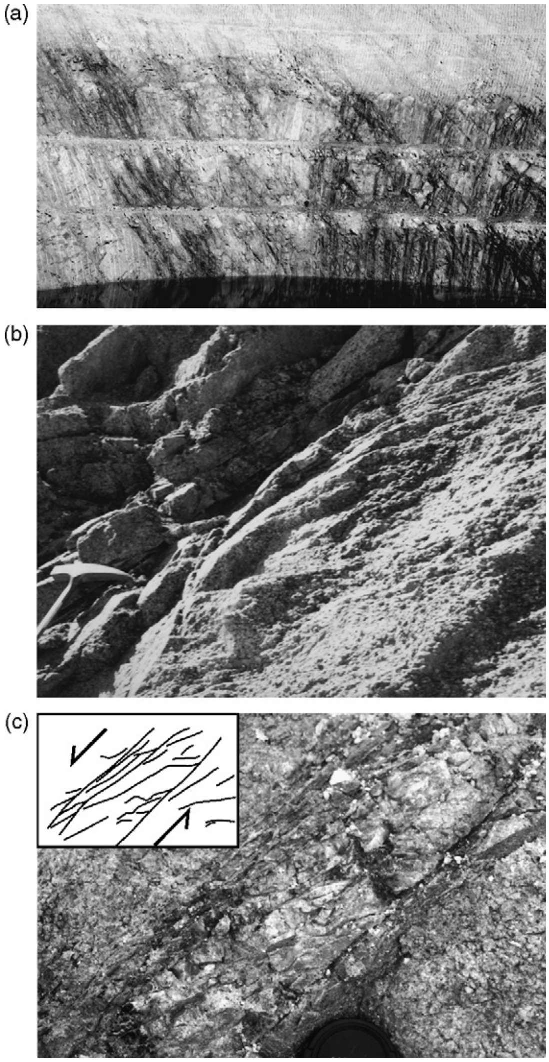

Fig. 7. (a) SW wall of the Golden Cities-Suva open pit showing the mineralized NW-dipping shear/fault zones. (b) SE-dipping gentle foliation dragged into a NW-dipping normal shear zone in the oxidized part of the pit. (c) Detail of silicified mineralized shear zone on the walls of the open pit, showing drag fold and S–C fabric indicative of normal movement. Inset shows line drawing of major planes.

have been reported for these NW-trending shear zones, and so cannot be interpreted in the context of the Suva deposit. In summary, mineralization at Suva was contemporaneous with normal shearing and faulting, but no evidence was found to establish the relative timing between the extensional structures and other regional structures.

4.4. Phillips Find (UTM 0305000 mE, 6612500 mN, WGS84)

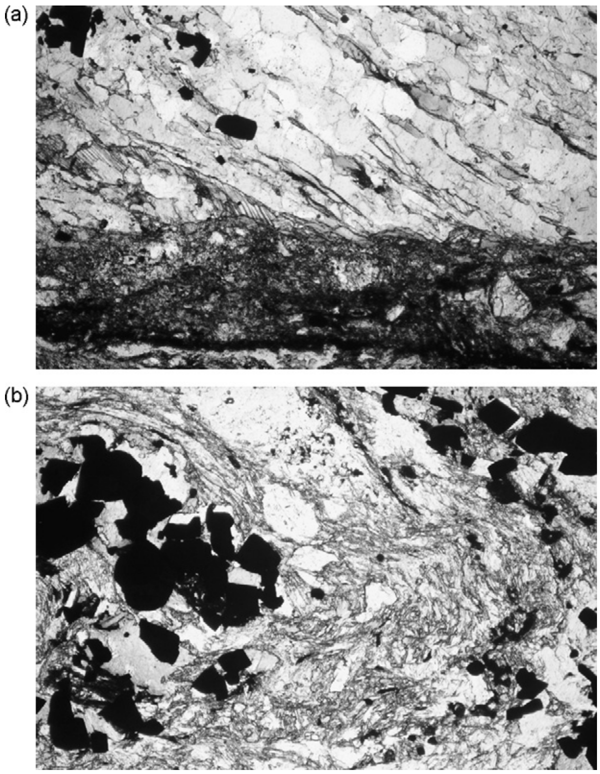

Fig. 8. Photomicrograph of shear/fault zone in the Suva open pit: (a) quartz, calcite, chlorite and opaques alteration sheared and recrystallized (upper half), cut by later cataclastic faulting (lower half). Field of view 1.5 mm; (b) folded ore stringer and crenulated matrix. Field of view 2 mm.

Phillips Find is a gold deposit in the greenstone sequence east of the Doyle/Dunnsville Granite, 2 km southeast of a NE–SW trending magnetic lineament (Fig. 1b), which crosses the granite and separates it into two lithologically distinct parts (Witt and Davy, 1997). There are two open pits. We focus on the one to the SE where dolerite crops out SE of a contact with shales. Both rocks are intruded by a tremolite–actinolite-bearing granodiorite with rounded mafic enclaves and angular xenoliths. All rocks are sheared and irregular granitic dykes are folded with the shales exposed in the northern wall of the pit. The dolerite is cut by a 2 m-wide shear zone with numerous, intensely folded and disrupted quartz veins (Fig. 9a and b) associated with a similarly deformed alteration marked by biotite, carbonate, chlorite, sulphides and minor epidote. The shear zone trends 235°, parallel to the regional magnetic lineament, and dips 50–60°NW. Normal sense of shear is inferred from the down-dip plunge of the stretching and mineral lineation in the shear zone schist (azimuth between 270° and 310°), and slickenlines on the surface of quartz veins, combined with S–C fabric, and down-dip vergence of folds in the quartz veins. Crenulation of the shear zone schist defines a crenulation lineation at a relatively high angle to the stretching lineation. On its footwall, in the deepest part of the pit, dolerite is brecciated by quartz and sulphides.

Outside the shear zone, the dolerite records an early deformation phase characterized by tight folds, with axial planar foliation striking 300°, dipping subvertically and accompanied by an old phase of quartz veins. This steep foliation is overprinted by a gently dipping (20–30°NW) anastomosing high strain zone, which wraps around lensoidal, metric lithons preserving the steep foliation. In the absence of a stretching or mineral lineation, an oblique dextral-normal sense of movement was inferred for these high strain zones by combining S–C fab-

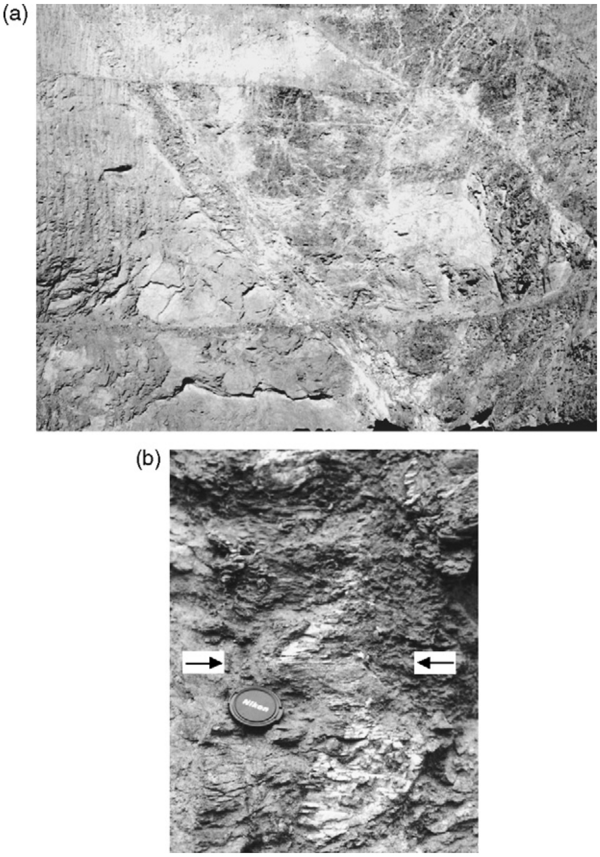

Fig. 9. Phillips Find open pit. (a) Main shear zone (diagonal zone from upper left to lower right) and a secondary shear zone (right). Looking SW at an estimated 50 m vertical wall. (b) Steep wall showing a steeply dipping quartz vein, and steep foliation (not visible), overprinted by a gently dipping foliation (arrows) related to open, recumbent folds.

ric in vertical and horizontal exposures. This gentle foliation is also associated with open, recumbent folding of steep foliation and quartz veins (Fig. 9b). Significantly, gentle foliations are dragged in a normal sense by steeper shear zones with a similar attitude to the main normal shear zone in the pit, striking NE–SW strike with a moderate NW dip. Their normal sense is further confirmed by S–C fabric.

The following deformation history for this pit is inferred: (a) a first phase of folding affected all lithologies exposed, including the granitic intrusion and gave rise to NW-trending steep foliation; (b) anastomosing, gently NW-dipping, dextral-normal shear zones and recumbent folds mark the beginning of an extensional deformation phase; (c) extension gave rise to moderately NW-dipping, normal shear zone that hosts gold mineralization, associated with silica, biotite and sulphide alteration within the shear zone; (d) continued shearing deformed early alteration products and fluid pressure oscillation led to changes between shearing and brecciation of the footwall.

The earliest, steep foliation and folds correspond regionally to D_2 and extensional deformation post-dates that. Parallelism between the normal shear zones at Phillips Find and the major NE-trending magnetic lineament (Swager, 1994) suggests contemporaneity. The lineament cuts across the greenstone belt and displaces D_3 shear zones (the Kunanalling Shear Zone in Swager, 1994, Fig. 2 and p. 13) suggesting that the extensional event post-dates D_3.

4.5. *Nature and timing of late extension*

The main features of this late event are (1) a gently dipping foliation dragged into moderately dipping normal faults (Phillips Find, Golden Cities and Granny Venn); (2) structurally the latest event (Phillips Find, Iguana and Granny Venn); (3) association with gold mineralization (Phillips Find, Golden Cities, possibly at Iguana). The inferred maximum stretching axis varies between NW–SE (Phillips Find and Golden Cities), ~N–S at Granny Venn and indeterminate at Iguana.

In all areas described here, extensional structures overprint D_2 structures and therefore could not be contemporaneous with this phase (Davis and Maidens, 2003). The relationships at Phillips Find suggest that extension there post-dates D_3. Although the constraints are incomplete, we postulate that late extension in different areas represents the same event and records the last phase of deformation of the Kalgoorlie Terrane, D_5. We postulate further that this phase corresponds to the waning stages of the Kalgoorlie Orogen, following a history which started with crustal thickening D_2, progressed into lateral escape dominated by strike-slip motion during D_3 and D_4, and finally relaxed during D_5.

5. Discussion

5.1. *Granite Doming*

Williams and Whitaker (1993) ascribed the typical pattern of granite-gneiss domes surrounded by conformable rock packages and conformable isograds with sharp gradients, as resulting from doming, such as in metamorphic core complexes, post-dating the deposition of the greenstone sequence in the Eastern Goldfields. However, metamorphic core complexes generally have a constant stretching direction, controlled by the regional axis of maximum stretching, rather than a radial stretching as documented around the Raeside Batholith. We suggest that early extension was externally driven and characterized by generalized horizontal stretching. This triggered or accelerated buoyancy-driven granite doming, which tilted the greenstone overburden amplifying recumbent folds or nappes (Witt, 1994; Harris et al., 2002).

Other granitic domes of the Eastern Goldfields are associated with extensional features. Many of the extensional features around the Raeside Batholith are also found in the “Eastern Gneiss Complex” (Swager and Nelson, 1997). These include conformity with country rocks, dome-up sense of shear on normal shear zones, and sharp decrease in metamorphic grade away from the granite. Doming in this case is inferred to have started early, before D_2, but unlike the Raeside Batholith, final granite emplacement and extensional structures continued during the D_2 shortening phase. The Widgiemooltha dome, SSW of Kalgoorlie, is surrounded by a significant thermal aureole (Bickle and Archibald, 1984) strongly overprinted by D_2 folding, and also has an early history of extension (Archibald et al., 1978).

5.2. Ida Shear Zone and extension

The 500 km long Ida Shear Zone, separating the Kalgoorlie from the Southern Cross Terrane, is the largest single structure ascribed to an extensional event in the Yilgarn Craton (e.g., Swager et al., 1997). We studied it in four localities spaced over a distance of 150 km, from Mt Alexander to Davyhurst (Weinberg et al., 2002). The shear zone is within and parallel to a narrow high strain corridor of greenstones, which accommodated the indentation of competent granitic bodies on either side of the corridor. Several narrow zones of intense deformation were recognized in this corridor. The main shear zone is generally 100–200 m wide, and is typically along the contact between thinly bedded mafic–ultramafic rocks plus interbedded shales to the east, and massive pillow basalts to the west. The foliation consistently dips steeply to the east, and is generally accompanied by a gently S-plunging mineral lineation. A lack of asymmetries within the shear zone indicates that the deformation is primarily the product of intense pure shear, but local asymmetries suggested a dextral strike-slip component (Weinberg et al., 2002).

Metamorphic facies on both sides of the shear zone is similar, with mafic rocks throughout the Mt Ida and Mt Alexander areas and on both sides consisting of amphibole (hornblende or actinolite), plagioclase ($An_{50–90}$), ilmenite and titanite. Chlorite forms a minor, retrograde component and epidote is rare. Low to mid-amphibolite facies conditions is suggested by the rarity of epidote and absence of garnets in the mafic rocks (Weinberg et al., 2002). Spinifex and cumulate textures are preserved in ultramafic rocks, although the mineralogy is now metamorphic (serpentine + magnetite ± tremolite). Tomich (1956) reported amphibolite facies sedimentary rocks, which include garnet schists, and staurolite and andalusite schists, which decrease in grade with distance from granitoid margins.

Integrating the evidence from the exposed Ida Shear Zone and from the Iguana deposit described here, with that derived from the seismic image of the area (e.g., Swager et al., 1997), it appears that the Ida Shear Zone is in fact two distinct structures, and not a single normal listric fault. The Ida Shear Zone, exposed at the surface as described here, is a steep ductile shear zone related to intense deformation of supracrustal rocks, defining a D_2 zone of bulk shortening, similar to the Bardoc Tectonic Zone, a parallel high strain zone to the east (Morey et al., 2007). This steep ductile shear zone is an early structure and defines the boundary between the Kalgoorlie and Southern Cross Terranes. The seismic image recovered immediately south of the Iguana pit (above), defines a gently E-dipping plane associated with normal displacement of markers and interpreted to represent a late normal fault (e.g., Swager et al., 1997). This structure is referred to in the literature as the Ida Fault and we suggest that this is a result of a later event, possibly our D_5, that produced a new structure. We postulate that this event is recorded at the surface by the recumbent folds and gentle foliation at the Iguana deposit and overprints the steep high strain zones of the Ida Shear Zone.

5.3. Timing of gold mineralization

There are strong arguments to support a relatively late, syn-D_3–D_4 major phase of gold mineralization during the Kalgoorlie Orogen (e.g., Groves et al., 1995, 2000). However, like others who argued for protracted mineralization (Bateman et al., 2001; Witt, 2001; Davis and Maidens, 2003; Bucci et al., 2004), this work concludes that gold was deposited from the earliest D_{1e} event to D_5, arguably the latest event of the Kalgoorlie Orogen, thus bracketing most of the post-greenstone deposition history of the Kalgoorlie Terrane.

Acknowledgments

We would like to thank Gerard Tripp, Anthony Morey and Frank Bierlein for vigorous discussions during fieldwork, and Steve Wyche and Tom Blenkinsop for thorough and helpful reviews.

References

Archibald, N.J., Bettenay, L.F., Binns, R.A., Groves, D.I., Gunthorpe, R.J., 1978. The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia. Precambrian Res. 6, 103–131.

Bateman, R.J., Hagemann, S.G., McCuaig, T.C., Swager, C.P. (Eds.), 2001. Protracted gold mineralization throughout Archaean orogenesis in the Kalgoorlie camp, Yilgarn Craton, Western Australia: structural, mineralogical, and geochemical evolution. World-class gold camps and deposits in the eastern Yilgarn Craton, Western Australia, with special emphasis on the Eastern Goldfields Province, Record 2001/17. Western Australia Geological Survey, pp. 63–98.

Bickle, M.J., Archibald, N.J., 1984. Chloritoid and staurolite stability: implications for metamorphism in the Archaean Yilgarn Block, Western Australia. J. Metam. Geol. 2, 179–203.

Blewett, R.S., Cassidy, K.F., Champion, D.C., Henson, P.A., Goleby, B.S., Jones, L., Groenewald, P.B., 2004. The Wangkathaa Orogeny: an example of episodic regional 'D2' in the late Archaean Eastern Goldfields Province, Western Australia. Precambrian Res. 130, 139–159.

Bucci, L.A., McNaughton, N.J., Fletcher, I.R., Groves, D.I., Kositcin, N., Stein, H.J., Hagemann, S., 2004. Timing and duration of high-temperature gold mineralization and spatially associated granitoid magmatism at Chalice, Yilgarn Craton, Western Australia. Econ. Geol. 99, 1123–1144.

Davis, B.K., 2002. Scotia-Kanowna Dome, Kalgoorlie Terrane: deformation history, structural architecture and controls on mineralisation. Applied structural geology for mineral exploration and mining. Field Guide, Kalgoorlie, Western Australia, pp. 1–57.

Davis, B.K., Maidens, E., 2003. Archaean orogen-parallel extension: evidence form the northern Eastern Goldfields Province Yilgarn Craton. Precambrian Res. 127, 229–248.

Davis, B.K., Hickey, K.A., Rose, S., 2001. Superposition of gold mineralization on pre-existing carbonate alteration: structural evidence from the Mulgarrie gold deposit Yilgarn Craton. Aust. J. Earth Sci. 48, 131–149.

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J., Williams, P.R., Sheraton, J.W., Heinrich, C.A., 1993. Archaean crustal structure from seismic reflection profiling, Eastern Goldfields, Western Australia. Aust. Geol. Surv. Org. Rec. 15, 54.

Groves, D.I., Batt, W.D., 1984. Spatial and temporal variations in Archaean metallogenic associations in terms of evolution of granitoid-greenstone terrains with particular emphasis on the Western Australian Shield. In: Kröner, A., Hanson, G.N., Goodwin, A.M. (Eds.), Archaean Geochemistry: The Origin and Evolution of the Archaean Continental Crust. Springer-Verlag, Berlin, pp. 73–98.

Groves, D.I., et al., 1995. Lode gold deposits of the Yilgarn block: products of late Archaean crustal-scale overpressured hydrothermal systems. In: Coward, M.P. (Ed.), Early Precambrian Processes. Geological Society of London Special Publications, London, pp. 155–172.

Groves, D.I., Goldfarb, R.J., Knox-Robinson, C.M., Ojala, J., Gardoll, S., Yun, G.Y., Holyland, P., 2000. Late-kinematic timing of orogenic gold deposits and significance for computer based exploration techniques with emphasis on the Yilgarn Block, Western Australia. Ore Geol. Rev. 17, 1–38.

Hallberg, J.A., 1986. Archaean basin development and crustal extension in the northeastern Yilgarn Block, Western Australia. Precambrian Res. 31, 133–156.

Hammond, R.L., Nisbet, B.W., 1992. Towards a structural and tectonic framework for the central Norseman–Wiluna greenstone belt, Western Australia. In: Glover, J.E., Ho, S.E. (Eds.), The Archaean: Terrains, Processes and Metallogeny, vol. 22. Geology Department (Key Centre) & University Extension, University of Western Australia, Perth, pp. 39–50.

Harris, L.B., Koyi, H.A., Fossen, H., 2002. Mechanisms for folding of high-grade rocks in extensional tectonic settings. Earth Sci. Rev. 59, 163–210.

Kent, A.J.R., Cassidy, K.F., Fanning, C.M., 1996. Archean gold mineralization synchronous with the final stages of cratonization, Yilgarn Craton, Western Australia. Geology 24, 879–882.

Knight, J.T., Groves, D.I., Ridley, J.R., 1993. The Coolgardie Goldfield, Western Australia: district-scale controls on and Archaean gold camp in an amphibolite facies terrane. Miner. Deposita 28, 436–456.

Krapez, B., Brown, S.J.A., Hand, J., Barley, M.E., Cas, R.A.F., 2000. Age constraints on recycled crustal and supracrustal sources of Archaean metasedimentary sequences, Eastern Goldfields Province, Western Australia: evidence from SHRIMP zircon dating. Tectonphysics 322, 89–133.

Martyn, J.E., 1987. Evidence for structural repetition in the greenstones of the Kalgoorlie District, Western Australia. Precambrian Res. 37, 1–18.

Micklethwaite, S., Cox, S.F., 2004. Fault-segment rupture, aftershock-zone fluid flow, and mineralization. Geology 32, 813–816.

Morey, A., Weinberg, R.F., Bierlein, F., 2007. Multiple gold mineralisation events within the Bardoc Tectonic Zone, Eastern Goldfields Province, Western Australia. Miner. Deposita. 42, 583–600, doi:10.1007/s00126-007-0125-7.

Mueller, A.G., Harris, L.B., Lungan, A., 1988. Structural control of greenstone-hosted gold mineralization by transcurrent shearing: a new interpretation of the Kalgoorlie Mining District, Western Australia. Ore Geol. Rev. 3, 359–387.

Passchier, C.W., 1990. Report on the geology of the Leonora area, Western Australia. BMR Record 1990/59, p. 29.

Passchier, C.W., 1993. The nature of high-strain zones in the Laverton–Leonora area, Western Australia. BMR Record 1992/53, p. 24.

Passchier, C.W., 1994. Structural geology across a proposed Archaean terrane boundary in the eastern Yilgarn craton, Western Australia. Precambrian Res. 68, 43–64.

Platt, J.P., Allchurch, P.D., Rutland, R.W.R., 1978. Archaean tectonics in the Agnew supracrustal belt, Western Australia. Precambrian Res. 7, 3–30.

Ridley, J., Mengler, F., 2000. Lithological and structural controls on the form and setting of vein stockwork orebodies at the Mount Charlotte Gold Deposit. Kalgoorlie. Econ. Geol. 95, 85–98.

Skwarnecki, M.S., 1988. Controls on Archaean gold mineralization in the Leonora District, Western Australia. In: Ho, S.E., Groves, D.I. (Eds.), Recent Advance in Understanding Precambrian Gold Deposits. The University of Western Australia, Perth, pp. 109–135.

Skwarnecki, M.S., 1990. Sons of Gwalia. 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. Geology. Department (Keycentre) and University Extension, University of Western Australia, Perth, pp. 149–151.

Swager, C.P., 1994. Geology of the Dunnsville 1:100,000 sheet. Geological Survey of Western Australia, Explanatory Notes.

Swager, C.P., 1997. Tectono-stratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia. Precambrian Res. 83, 11–42.

Swager, C., Griffin, T.J., 1990. An early thrust duplex in the Kalgoorlie–Kambalda greenstone belt, Eastern Goldfields Province, Western Australia. Precambrian Res. 48, 63– 73.

Swager, C.P., Nelson, D.R., 1997. Extensional emplacement of a high-grade granite gneiss complex into low-grade greenstones, Eastern Goldfields, Yilgarn Craton, Western Australia. Precambrian Res. 83, 203–219.

Swager, C.P., Witt, W.K., Griffin, T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., Wyche, S., 1992. Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia. In: Glover, J.E., Ho, S.E. (Eds.), The Archaean: Terrains, Processes and Metallogeny, vol. 22. Geology Department (Key Centre) & University Extension, University of Western Australia, Perth, pp. 107–122.

Swager, C.P., Goleby, B.R., Drummond, B.J., Rattenbury, M.S., Williams, P.R., 1997. Crustal structure of granite-greenstone terranes in the Eastern Goldfields, Yilgarn Craton, as revealed by seismic reflection profiling. Precambrian Res. 83, 43–56.

Tomich, S.A., 1956. Summary Report on the geology of a portion of the Mt. Ida district, North Coolgardie Goldfield. Geological Survey of Western Australia. Ann. Rep., 18–20.

Vanderhor, F., Witt, W.K., 1992. Strain partitioning near the Keith–Kilkenny fault zone in the central Norseman–Wiluna Belt, Western Australia. BMR Record 1992/68, p. 13.

Vearncombe, J.R., 1992. Archaean gold mineralisation in a normal-motion shear zone at Harbour Lights, Leonora, Western Australia. Mineral. Deposita 27, 182–191.

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

Weinberg, R.F., Groves, D.I, Hodkiewicz, P.F., Van der Borgh, P., 2002. Hydrothermal systems, giant ore deposits and a new paradigm for predictive mineral exploration. AMIRA Project P511, Yilgarn Atlas, vol. 3, unpublished: pp. 140–170.

Weinberg, R.F., van der Borgh, P., Moresi, L., 2003. Timing of deformation in the Norseman–Wiluna Belt, Yilgarn Craton, Western Australia. Precambrian Geol. 120, 219–239.

Weinberg, R.F., Hodkiewicz, P., Groves, D.I., 2004. What controls gold distribution in Archean Terranes. Geology 32, 545–548.

Weinberg, R.F., van der Borgh, P., Bateman, R.J., Groves, D.I., 2005. Kinematic history of the Boulder–Lefroy Shear Zone and controls on associated gold mineralization, Yilgarn Craton, Western Australia. Econ. Geol. 100, 1407–1426.

Williams, P.R., 1998. Geology, structure, and gold resources of the Leonora 1:100,000 Sheet, W.A. AGSO Record 1998/9, p. 71.

Williams, P.R., Currie, K.L., 1993. Character and regional implication of the sheared Archaean granite-greenstone contact near Leonora, Western Australia. Precambrian Res. 62, 343–365.

Williams, P.R., Whitaker, A.J., 1993. Gneiss domes and extensional deformation in the highly mineralised Archaean Eastern Goldfields Province, Western Australia. Ore Geol. Rev. 8, 141–162.

Williams, P.R., Nisbet, B.W., Etheridge, M.A., 1989. Shear zone, gold mineralization and structural history in the Leonora district, Eastern Goldfields Province, Western Australia. Aust. J. Earth Sci. 36, 383–403.

Witt, W.K., 1993. Gold mineralization in the Menzies–Kambalda region, Eastern Goldfields, Western Australia. Geological Survey of Western Australia, Report 39, 165 p.

Witt, W.K., 1994. Geology of the Melita 1:100,000 Sheet. In: Explanatory Notes. Geological Survey of Western Australia, p. 63.

Witt, W.K., 2001. Tower Hill gold deposit, Western Australia: an atypical, multiply deformed Archaean gold–quartz vein deposit. Aust. J. Earth Sci. 48, 81–99.

Witt, W.K., Davy, R., 1997. Geology and geochemistry of Archaean granites in the Kalgoorlie region of the Eastern Goldfields, Western Australia: a syn-collisional tectonic setting? Precambrian Res. 83, 133–183.

Witt, W.K., Swager, C.P., 1989. Structural setting and geochemistry of Archaean I-type granites in the Bardoc–Coolgardie area of the Norseman–Wiluna Belt, Western Australia. Precambrian Res. 44, 323–351.

Witt, W.K., Vanderhor, F., 1998. Diversity within a unified model for Archaean gold mineralization in the Yilgarn Craton of Western Australia: an overview of the late-orogenic, structurally controlled gold deposits. Ore Geol. Rev. 13, 29–64.

Zhou, T., Phillips, N., Denn, S., Burke, S., 2003. Woodcutters goldfield, gold in an Archaean granite, Kalgoorlie, Western Australia. Aust. J. Earth Sci. 50, 553–569.