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Tectonostratigraphic architecture and uplift history of the Eastern Yilgarn Craton.

Module 3: Terrane Structure, Project Y1-P763

Richard S. Blewett and Karol Czarnota

Record
2007/15

SPATIAL INFORMATION FOR THE NATION

Tectonostratigraphic architecture and uplift history of the Eastern Yilgarn Craton

Module 3: Terrane Structure, Project Y1-P763

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by

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Please note: Module 3 accompanies Module 1 (stratigraphy) and Module 2 (late basins) which are separately released due to confidentiality constraints.

Forward

This Geoscience Australia Record is a public domain release of the Module 3 structural study from the *pmd**CRC and AMIRA Y1-P763 project that concluded in November 2005. An eighteen month confidentiality period remained on this work and the results (this report) remained with the sponsors.

The report delivered to sponsors has been reproduced here with only minor editorial and technical improvements to meet Geoscience Australia production standards. Research into the structural evolution of the Eastern Goldfields Superterrane (EGST) continued in allied projects (Y2 and Y4) as part of the *pmd**CRC programme. The Y2 project Final Report was released into the public domain as Geoscience Australia Record 2006/05 (see https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=64019). At the time of writing this Forward (July 2007), the active Y4 *pmd**CRC project has been continuing the work from these previous projects. Therefore, some interpretations of the structure of the EGST presented in this report have changed. The latest publicly available thinking is presented in Blewett and Czarnota (2007). A table of comparison is included in this Forward to assist the reader. One of the enduring assets of this original Y1-P763 Final Report is the very extensive data holdings preserved in the appendices. The philosophy behind this original report was to clearly separate data from interpretation and this philosophy has aided us in continually improving our understanding of the structural evolution of the EGST. We hope the reader finds the data sections equally enduring and able to be built on for further improvements in understanding.

Richard Blewett and Karol Czarnota
July 2007

Blewett and Czarnota (2007)			Swager (1997)	Blewett et al. (2004b)	Miller (2006)
Minor contraction		D_7			
Minor extension		D_6	Collapse	Late D_e	
Dextral transpression		D_5	D_4	D_3	D_4
Sinistral transpression		D_{4b}	D_3	D_3	D_3
		D_{4a}	D_2	D_{2b}	D_2
Extensional doming	Stage 2 late basins	D_{3b}	D_E	D_{2e}	
	Stage 1 late basins	D_{3a}			D_1
Upright folding and reverse faulting		D_2	D_2	D_{2a}	
Extension with intermittent compression		D_1	D_E	D_e, D_1, D_{1e}	

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3.1.10 Spatial synthesis

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excel spread sheets of structural data
photographs,
structural synthesis diagrams and posters CorelDraw and pdf files.

Appendix 3.3: interactive pdf of Granite Study previously published as GA Record 2004/10

Appendix 3.4: Note books (scans of the 6 field note books)

[1] Modules 1 and 2 had appendices –Module 3 starts with Appendix 3.

Summary

- No structural difference between terranes.
- The only possible terrane accretion structures are the Ida Fault and the Hootanui Fault since the Ockerburry Fault is extensional.
- No D1 N-S compression, early isoclinal shallowly dipping structures are interpreted to be extensional in origin.
- Long-lived ENE-directed extension marked during D1 which formed the major basin architecture for the greenstone sequences.
- There is a strong extensional event (D3) which postdates D2 compression and forms and deforms the late basins.
- The crustal architecture (observed in seismic) is controlled by D1 and D3 extension. It is not a thin-skinned fold and thrust belt.
- The NNW-trending tectonic grain in the Eastern Yilgarn was set up as a result of ENE-directed D1 and D3 extension with local extension vectors controlled by the exhumation of granite domes in the footwall to NNW striking extensional shear zones. The folding which the late basins unconformably overlay may have formed during extension. Further work is required to examine if this hypothesis holds true for every case not just around the Lawlers Anticline.
- The N-S tectonic grain in the Eastern Yilgarn is a function of D2 and D5 dextral transpression which has dissected the NNW-trending extensional architecture.
- D2 and D3 are spatially inversely related, i.e. where D2 is present D3 is absent and where D3 is present D2 is absent. This poses the question as to the significance or pervasiveness of the D2 contractional deformation.
- P-T dihedra work has resolved D2 and D5 $\sigma1$ palaeostress to be predominantly ENE- to NE-striking. Contractional deformation is predominantly associated with strike-slip movement on N- to NNW-striking faults as opposed to thrusts.
- This study has recognised a N-S to NW-SE oriented low-strain contractional D4 deformation event. This deformation is typically expressed as either sinistral N- to NNW-striking faults or E-W striking N- and S-directed thrusts.
- Few events have the structural style and intensity necessary for significant crustal thickening.
- This study recognised that gold is present in extensional structures although the majority of Au deposits lay in contractional structures.
- Gold deposits located in ductile shear zones are typically localised in the highest strain regions of the shear zone typically located at its centre. These high strain areas are typically marked by the presence of shear related foliation boudinage.

Introduction

Many questions remain unanswered regarding the tectonic evolution of the Eastern Yilgarn, and a range of competing models have been proposed. These models include:

- Ensialic extensional rifts or basins (Archibald et al., 1978; Hallberg, 1986; Hammond and Nesbitt, 1992; Williams and Whitaker, 1993; Passchier, 1995; Hall, 1998),
- Convergent margin settings (Barley et al., 1989; Eisenlohr, et al., 1989; Swager et al., 1992; Witt, 1994),
- Accretionary models (Myers, 1995; Archibald, 1998; Krapěz et al., 2000), and
- Mantle plumes (Campbell and Hill, 1988).

Passchier (1995) and Swager (1997) both suggested that this range of tectonic models indicated a rather sketchy geological database, especially in areas away from the highly mineralised belts. One of the key geological inputs into any tectonic model, and the focus of this third module of the P763 project, is a new assessment of the structural history.

The approach taken in this study has been to focus on a transect across the entire Eastern Yilgarn, from the gneisses and granites east of Laverton to the Ida Fault (Fig. 1). The transect area is bound by latitudes –21ºS, –30ºS and longitudes 120ºE, 123º30'E, crossing the Burtville, Kurnalpi and Kalgoorlie Terranes and their bounding structures (faults).

Particular emphasis was made of the open pit exposures in the greenstone belts for much of the mesoscopic data collection. The open pits were selected because:

- they provide unique 3D exposure (all too rare in such a low-relief and weathered terrain),
- they are numerous,
- they occur in a range of lithologies (independent of weathering effects), and
- they occur at a range of structural levels and in a range of structural positions (core of folds, limbs, shear zones, within granite plutons).

The open pit studies were integrated with a separate Geoscience Australia study (Blewett et al., 2004a) of granites across the same transect area. At the macroscopic scale, use was made of solid geology maps and published outcrop maps, GA and GSWA point databases of structural readings, and recently released seismic reflection profiles with the central east part of the transect area.

The deliverables being reported against in this section of the P763 report include:

- The basic fault architecture and terrane boundary structures and their kinematics.
- An assessment of intra-terrane structural history and tectonic significance of terrane assembly
- An assessment of the match between seismic structure and surface geology
- Maps (posters) of structure in key domains

Regional Geology

Because the gold deposits of the Eastern Yilgarn are structurally controlled, structural geology and tectonics have been extensively studied in the region. This summary of previous work and the state of play prior to this study is drawing on the significant (regional) studies that describe more than an individual mine or map sheet.

Modern structural geology was not systematically applied to the Eastern Yilgarn until the studies of Platt et al. (1978) Archibald et al. (1979) and Swager (1989). These workers were the first to publish regional deformation event histories that were adopted as a framework by subsequent workers.

Prior to this however, Ellis (1939), Matheson (1939) and Prider (1945) described regional cross folding by E–W folds overprinting NNW–trending folds. Interestingly, these workers suggested that refolding was not only important for the location of the gold deposits, but also the metamorphic grade. The recognition of this set of E–W trending folds (overprinting what people today would call 'D2') remained until around Glikson (1971). After this time, the E–W trending folds (developed during a late N–S contraction) 'disappeared' from the literature.

The pronounced NNW-oriented structural trend of the Eastern Yilgarn ('D2' trend) is marked by the regional fault pattern and elongate granitoid bodies (Gee, 1979). The regional-scale faults form an anastomosing network of high-strain zones that bound a number of terranes or structural domains (Swager et al., 1992; Myers, 1997) that are elongate or lensoid in map pattern shape, and separate different greenstone successions. The characteristic map pattern of the Eastern Yilgarn was developed by a succession of compressional and extensional deformation events that have been interpreted as regional (province-wide) in extent. Swager (1997) summarised many of the interpretations of the regional deformation history, and it is this framework that is largely followed here.

Unlike other orogenic belts such as in the Proterozoic and younger terranes, no names have been proposed for the various orogenic events in the EGP or Yilgarn Craton. Rather, a nomenclature of D1 to $D4_{+}$ is most widely used (see Swager, 1997). Broadly, the recognised deformation (compressional history) involved early D1 recumbent folding and thrusting during N-S shortening, followed by E-W shortening through large-scale upright D2 folding and thrusting, then a period of strike-slip D3 faulting with associated folding, followed by continued regional D4 transpressive oblique and reverse faulting. Some authors have proposed early, intermediate, and late periods of extension throughout parts of this compressive history.

The greatest amount of debate in the literature is with regards to the early extensional and D1 compressional events. Swager and Griffin (1990) suggested that the D1 event involved large-scale stratigraphic repetition during N-S compression. For example, a regional-scale thrust duplex structure extends from Kambalda to Kalgoorlie and duplicates stratigraphy significantly. Regional 'D1' in the EGP is thought by many to have developed roughly E-W trending thrusts and folds as a result of N-S compression (e.g., Swager, 1997 and references therein).

More recent interpretations of this map pattern suggest that these so-called D1 thrusts are later. This new interpretation is based on the observation that F2 folds are transected by these 'D1' thrusts (Blewett, et al., 2004a). On a mesoscale, early recumbent folds (F1) are clearly refolded by upright N-S trending F2 folds (Swager and Griffin, 1990). D1 structures overprint the >2670 Ma Black Flag Group of the Kalgoorlie Terrane (Krape et al., 2000), providing a minimum age for this event. Recognition of D1 structures is important in understanding the final geometry of the area, and also in determining which fabric elements developed when, with respect to, the deformation chronology. Recognition of D1 contraction has been a long-standing problem in the northern Goldfields (see also Beardsmore, 2002; Wyche and Farrell, 2000), and it was not observed in this study. It is probable that all these D1 structures are extensional (an argument forwarded in this report).

A number of workers have suggested that early extension predated D1 thrusting and may represent the last stages of development of the actual basin in which the greenstones accumulated (e.g., Williams et al., 1989; Hammond and Nisbet 1992, 1993; Williams, 1993). Detailed work in the Leonora area led Passchier (1994) to suggest that the D1 recumbent folds may have formed in an extensional setting. Swager and Griffin (1990) suggested that the D1 event involved large-scale stratigraphic repetition during N-S compression. For example, a regional-scale thrust duplex structure extends from Kambalda to Kalgoorlie and duplicates stratigraphy significantly. Regional 'D1' in the EGP is thought by many to have developed roughly E-W trending thrusts and folds as a result of N-S compression (e.g., Swager, 1997 and references therein).

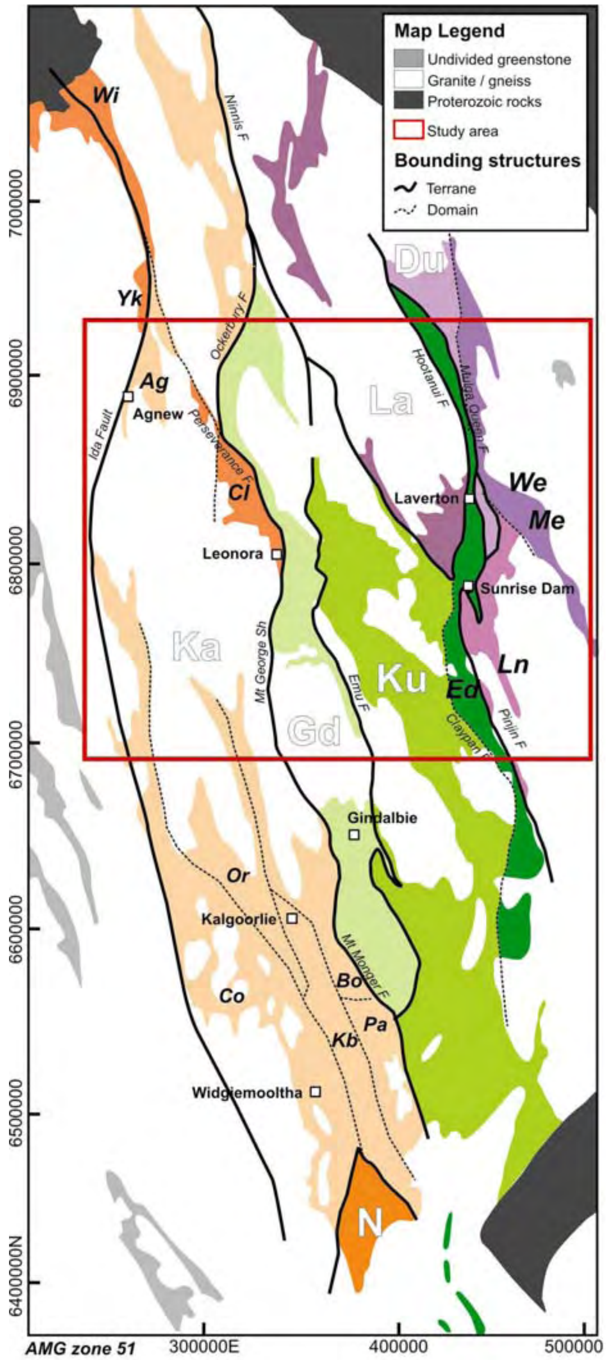


Figure 1. Location of study area in relationship to the Terranes and domains of the Eastern Yilgarn. Terranes and domains are modified from Barley et al. (2002). Terranes: N = Norseman, Ka = Kalgoorlie, Gd = Gindalbie, Ku = Kurnalpi, La = Laverton, Du = Duketon. Domains: Or = Ora Banda, Kb = Kambalda, Pa = Parker, Co = Coolgardie, Bo = Boorara. Domains (informal, this report): We = Mt Weld, Me = Merolia, Ln = Linden, Cl = Mt Clifford, Yk = Yakabindie, Ag = Agnew, Wi = Wiluna.

Swager (1997) interpreted the late siliciclastic basins (Kurrawang, Penny Dam etc) as being developed during extension after D1 and before 'D2', because they transect regional D1 structures and they are deformed by 'D2' (in his four-fold deformation chronology). This pre-D2 extensional phase was interpreted as oriented E-W, involving synclinal basins developed above roll-over anticlines. Other workers have described these basins as 'compressional' basins, developing synchronous with 'D2' (Liu and Chen, 1998; Chen et al., 2001).

The regional D2 deformation involved considerable E-W (ENE–WSW) crustal shortening, producing major regional-scale upright F2 folds, together with a pervasive metamorphic foliation (Swager, 1997). The widespread subvertical penetrative foliation is interpreted in most cases as a composite S1-S2 fabric, particularly outside the main shear zones. However, interpretation of the penetrative fabric across the Eastern Yilgarn as pure shear flattening has been shown by this study to be problematic. The regional F2 anticlines are best preserved, and can be traced over large distances, commonly with doubly plunging to horizontal fold axes (Fig. 1). The synclines are commonly more complex fault-related structures, with late siliciclastic basins locally defining the F2 synclinal hinge zones (in most workers terminology). Hammond and Nisbet (1992) suggested that the regional antiforms represented hangingwall anticlines developed during W-directed thrusting, and this view was thought to be consistent with the seismic data from Kalgoorlie (Goleby et al., 1993; Drummond et al., 2000), and the seismic data and 3D model developed for the Leonora-Laverton area (Blewett et al., 2002; Goleby et al., 2002). These workers suggested that the seismic data represent a classical fold-and-thrust belt such as the European Alps and North American Appalachians (Rodgers, 1995). This study suggests otherwise, and argues that the primary architecture was developed during mostly ENE-directed extension.

The regional 'D_2' event is considered by most workers to post-date the late siliciclastic basins. For example, the Kurrawang, Merougil, and Penny Dam basins lie in regional 'D_2' synclines in the southern part of the EGP (Swager, 1997; Krape et al., 2000; Weinberg et al., 2003). Similarly, in the Welcome Well area the Pig Well-Yilgangi basin is folded by the NW-trending Butcher Syncline (Gower, 1976) and is overprinted by a well-developed fabric interpreted as S_2 (Williams et al., 1989; Passchier, 1994; Liu and Chen, 1998; Stewart, 1998). Swager (1997) suggested D_2 was ca. 2665 Ma, while Krape et al. (2000) suggested that it was ca. <2650 Ma[2]. Weinberg et al. (2003) stated that it was after the deposition of the late basins and used Krape et al.'s (2000) young age of about 2655 Ma for 'D_2'. Swager and Nelson (1997) noted local extension (after 'D_2') of the high-grade granite-gneiss domains into their final uplifted positions relative to the lower grade greenstone belts. They suggested that this extensional event was syn- to post-main granitoid emplacement at ca. 2660 Ma. Wyche and Farrell (2000) described similar relationships along the Ockerburry Fault System in the northern Goldfields.

Continued regional D3 E-W shortening is particularly evident as late-stage foliations and sets of faults (Swager, 1989). Prominent, oblique faults, that crosscut and offset these late-stage structures, and interpreted as a separate D4 event by Mueller et al. (1988), have been attributed to a small rotation in the main shortening direction. The en-échelon F3 folds may show very steep plunges because they formed in already steeply tilted sequences. Hammond and Nisbet (1992) questioned the significance of the D3 sinistral strike-slip event. They proposed that most of the so-called late movements were rotated N-directed D1 thrusts that now recorded apparent sinistral kinematics. Recent seismic imaging (Goleby et al., 2002), and work on the 3D geometry of the major shear zones in the Leonora-Laverton area (Fig. 1) show that most shear zones dip moderately to shallowly to the east (Blewett et al., 2002), an apparently unlikely geometry for a significant strike-slip

[2] Krape et al. (2 000) interpreted the detrital zircon data to give a 10 m.y. younger maximum age for the late siliciclastic basins by using the youngest grain (2655±5 Ma) rather than the youngest statistical population (2665±5 Ma).

orogen. However, not all strike-slip motion is early and subsequently rotated. For example, some of the ca. 2640 Ma Low-Ca granitoids (post 'D_2') have intense subhorizontal L-tectonites with sinistral kinematic indicators (Blewett et al., 2004a).

Late-stage crustal scale extensional faulting is recognised on the Ida Fault (Fig. 1) by an abrupt eastward change in metamorphic grade, with exhumed high-grade rocks in the footwall to the west (Swager, 1997). Seismic reflection data reveal that about 5 km of downthrow to the east occurred across the fault (Goleby et al., 1993). The orientation of the Ida Fault, parallel to the D2 'compressional' structures, might infer extension or post-orogenic collapse following D2-D3 shortening. Blewett et al. (2002) and Goleby et al. (2002) noted a similar E-block down sense of extensional movement on domain-bounding faults in the Leonora-Laverton area seismic reflection data. The extensional movement on the Ida Fault is constrained as older than the stitching Clarke Well Monzogranite (2640 ±8 Ma: Nelson, 1997). This extensional movement was younger than peak metamorphism (Swager, 1997), and corresponded to a change in granitoid magmatism to the Low-Ca suite at the base of the greenstone sequences (Champion and Sheraton, 1997).

Interestingly, Swager (1997) outlined a series of extensional events between many of the contractional events, although he suggested that some of these were of local extent. Most workers tended to focus on the contractional event history, and neglected the extensional part of the history. Davis and Maidens (2003), and Blewett et al. (2004b) documented important extensional events during or just after the major 'D2' contractional event. Blewett et al. (2004a) suggested that 'D2' involved two contractional (D2a, D2b) events, separated by an extensional event (D2e) together with the deposition of the 'Late Basins', and that this more complex 'D2' was diachronous (younging to the west or southwest). The timing (diachroneity) and relationship of the 'Late Basins' to a regional D2e extensional event was a significant departure from the established Swager (1997) framework.

Post D3 compressional structures (D4) have been described as variably oriented kink bands and crenulation cleavages, as well as oblique-slip sinistral and dextral faults (Swager, 1997; Vearncombe, 1998; Chen et al., 2001). The NE-trending faults are mostly dextral, and the E- to ESE-trending faults are mostly sinistral, suggesting renewed E-W compression. Swager (1997) considered the D4 structures to be ca. 2620-2600 Ma.

Another feature of most structural studies in the Eastern Yilgarn was the emphasis on the greenstone. Many of the granites of the central Eastern Yilgarn are well-exposed, with granite pavements providing unique lateral continuity to map structures. This good exposure, coupled with recent high-resolution geochronology (Cassidy et al., 2002; Black unpublished GA data), allowed Blewett et al. (2004b) to erect a new event history that was better constrained in time. The granites were also useful as they are now exposed at a range of crustal levels and a range of regions in terms of the distribution of regional strain.

Peak metamorphic (low- to intermediate-pressure) conditions are considered to be related to late D_2/D_3 deformation (Swager et al., 1992). Binns et al. (1976) recognised both static and dynamic (shear zone) styles of metamorphism. The regional patterns they mapped (and supported by Hallberg, 1985) show lowest grades (greenschist and lower) in the internal (furthest from external granites) and thickest parts of the greenstone belts. Metamorphic grade (temperature) increases towards the margins of the greenstone belts. These regional patterns transect the domain boundaries, illustrating the relatively late or long-lived metamorphic event(s). More recently, Mikucki and Robert (2003) reported two metamorphic events, with a low pressure event associated with the late-stage Low-Ca granites.

This study

Rationale

In the past structural studies in the Eastern Yilgarn have focused on either; regional studies in poorly outcropping greenstone belts or detailed postage stamp studies within individual deposits. There has been a lack of truly regional systematic structural analysis. The aim of this study was to fill this gap and in so doing answer the questions posed by Module 3.

In order to conduct a regional systematic structural study a new approach was needed. It would not be enough to simply conduct traverses over the area since this would only duplicate previously conducted structural studies (e.g., Passchier, 1994) and would not be an efficient use of time since the few greenstone outcrops that exist are from a structural point of view, data poor. That is, in greenstone areas where there is outcrop, not much more than a regional foliation can be observed and even then the kinematics on that foliation is hard to determine. It was necessary to conduct structural work away from previously studied areas but in structurally data rich locations. This formed the rational for the granite structural study of Blewett et al. (2004a) and the Module 3 greenstone open pit study of Blewett and Czarnota (reported here).

Blewett et al. (2004b) documented structural overprinting relationships in granites from a variety of crustal levels, ages and structural domains. Most workers in the past had previously ignored granites even though they make up approximately 65% of the solid geology outcrop of the Yilgarn. Based on the shear volume of granites in the Yilgarn it is safe to say that an understanding of the style of deformation within the granites is necessary for a sound understanding of the geodynamics of the region. Furthermore granites are excellent recorders of complex deformation histories due to their mineralogy and episodic intrusion history (Fig. 2) which is suitable for SHRIMP dating and the development of good crosscutting relationships associated with sound kinematic indictors. The results from this study proved to be an indispensable foundation for the pit based greenstone study since it provided the only available geochronological constraints on the timing of structural events. However while the geochronology of the granite study was indispensable for the greenstone study the 3D outcrop in the pits was necessary to verify the results of granite study since this was predominantly based on 2D granite pavement outcrops.

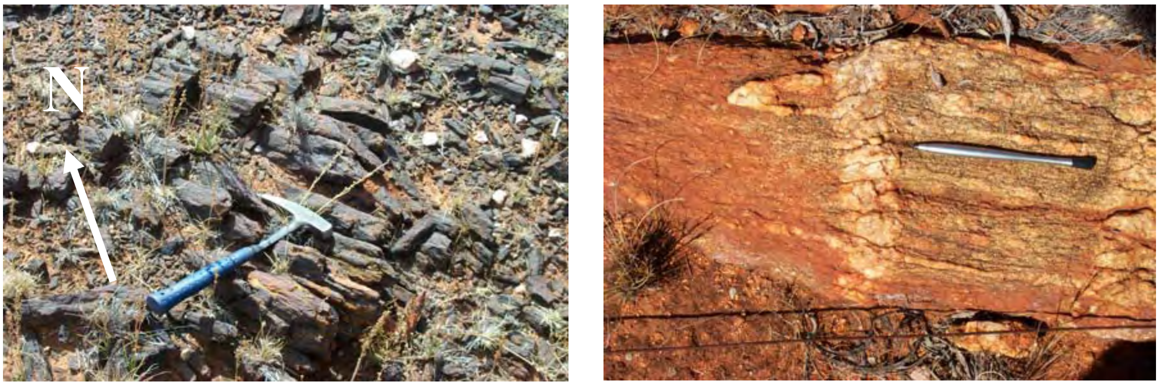


Figure 2: Field photograph comparing information available in regional greenstone and granite sites (near Wilbah Gneiss on Leonora 1: 250 000 sheet area). Both sites record E-W contraction, but the granites show that contraction involved a number of pulses as foliation generated by melting (leucosome) is isoclinally folded and overprinted by a leucocratic dyke which is cut by a foliation parallel to the axial planar fabric of the earliest fold. The main fabric in the greenstones is therefore likely a composite of a number of events, but the evidence for this is enigmatic at best.

The greenstone open pit work focused predominantly on non-operating mines where pits had been washed by cyclones and the geology was clearly visible. While a number of pits which were studied had been the focus of individual examinations in the past, a systematic study of structures across numerous deposits along a broad transect across the Eastern Yilgarn had not been previously attempted. Furthermore the location of historical pits in various structural settings was ideal to solving the Module 3 question of inter/intra-terrane structural histories. The approach of examining structures within pits to determine a regional structural history is based on the premise that economic deposits are not structurally anomalous areas. That is the volume of rock which makes up the deposit was not immune to the regional palaeostress fields. This assumption then permits the interpretation of typically complex structural histories observed within a deposit as regionally significant. The high degree of correlation between the granite and greenstone studies verifies that this assumption is valid and points out the benefit of preforming two largely independent studies which can be used to cross verify results.

Figure 3: Major advantage of the pits is the fresh exposure with multiple cross cutting relationships visible and mappable across large areas.

Theory

Overview

Both the granite and greenstone studies are based on a similar approach/methodology of determining structural event histories outlined in Figure 4. This method involves a three step process where cross-cutting relationships are observed and recorded at sites within a pit, then multiple sites from a pit are synthesised to produce an event history which is then correlated with other event histories determined at separate pits. In the case of the granite study the Step 2 of the method is omitted since the site location and the 'pit' location are one that is they are a particular granite pavement outcrop. The degree of interpretation and the scale of interpretation increases from Step 1 to 3. The compilation of a structural event history for any one pit or granite site in steps one and two is relatively straight forward. However the correlation of events from one pit to another, in Step 3, is not a trivial matter. The question becomes how can the event history from one pit which is typically only 300 m wide be correlated with another which may be up to 50 km away, with little to no outcrop in between? This is a problem common to all structural geologists in any regional study. In this study switches in palaeo-stress direction have been used as the means to correlate event histories with one another. Due to the 2D outcrop of granite pavements it was only possible to infer the most likely palaeo-stress direction necessary to form a particular structure. In the greenstone study 3D pit exposures (Fig. 3) were used to constrain the palaeostress necessary to form the observed structures in 3D through the application of a modified P-T dihedra method. In the following section a systematic overview of the modified P-T dihedra method is presented as it relates to each of the three steps in the methodology.

However before moving on it is important to state explicitly that the following method is based on the observation/assumption that there has not been large scale rotations of early structures following the first major deformation event i.e. regional D2. The observation/assumption that there has not been large scale rotation of structures is based on the uniformity of foliation directions in regional data sets. Figure 4 is an extract of all foliation trends in the study area from GA and GSWA databases, which shows a uniformly NNW trending foliation and hence supports the proposed assumption. Further more the large degree of correlation between the event histories observed at individual sites as presented in the Central Eastern Yilgarn Deformation Banner (Appendix 3.1.1) further verifies this approach.

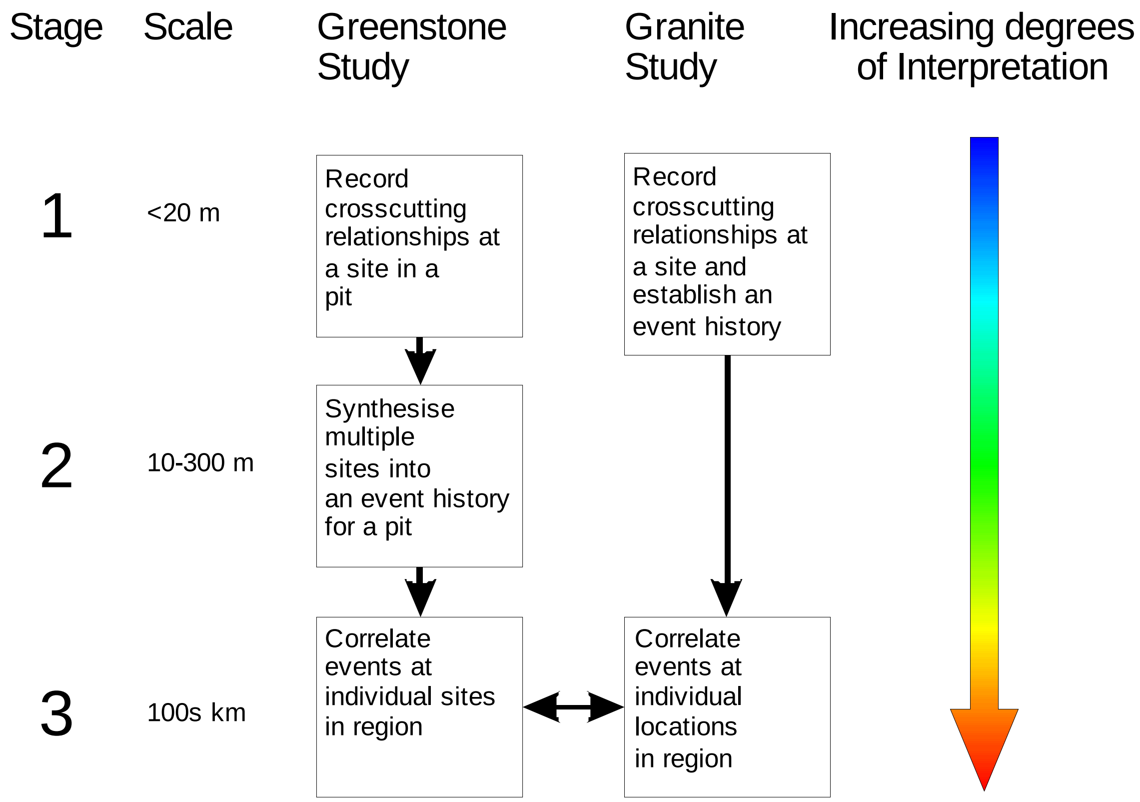


Figure 4: The approach used to construct structural event histories.

Step one

Structural crosscutting relationships were documented at discrete sites within a pit. A site typically consisted of a section of the pit wall and down ramp where individual structures could be followed and their relationship with other structures observed. Typically a site was 10-30 m wide. The overprinting structural event history at any one site was compiled into a structural 'stratigraphic' column where in the oldest structures are displayed at the bottom and the youngest at the top (see Fig. 6i). In cases where cross cutting relationships for a particular structure could not be determined, a dotted line has been used to indicate the upper and lower timing constraints. All structures within a structural stratigraphic column have been displayed as either P-T dihedra, planes or lines in lower hemisphere equal area stereonet plots. The range of structures observed during the study and the construction of P-T dihedra are outlined in Figure 8.

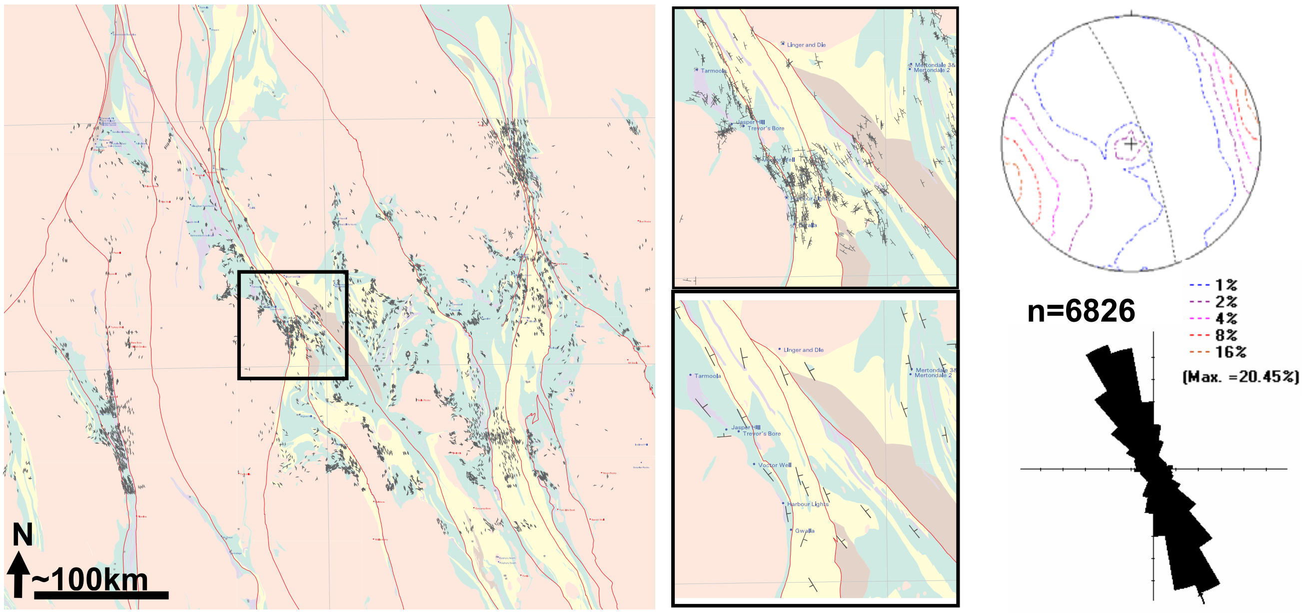


Figure 5: Regional foliation data for the study area with a close up of the Leonora area showing a consistently NNW trending foliation direction.

P-T dihedra

All fault/shear zone data from which a movement vector along a plane could be determined have been displayed as P-T dihedra. This method was initially developed by Angelier and Mechler (1977) (for English see Angelier (1984)) as a means of inverting brittle fault slip data to constrain the quadrants (or dihedra) in which σ_1 (dilation or P dihedral) and σ_3 (compression or T dihedral) lie, analogous to earthquake focal mechanisms (Fig. 7). A P-T dihedra plot is established by plotting the plane of the fault on an equal area lower hemisphere stereonet and the movement vector on the fault plane. The axillary to the fault plane is then constructed by plotting a plane which lays perpendicular to the movement vector and passes through the pole to the shear plane (Fig. 8). The right dihedra method of stress inversion is based on the Wallace-Bott assumption (Wallace, 1951; Bott, 1959) that any slip on a fault plane is parallel to the maximum resolved shear stress on the plane. There has been some controversy in the literature as to whether the P-T dihedra method resolves stress or strain (Twiss and Unruh, 1998). Recent studies by Blenkinsop (in press) indicate that the P-T dihedral method does resolve stress and hence the Wallace-Bott assumption holds true for large data sets even though experiments show violations of the Wallace-Bott assumption caused by fault interactions (Pollard et al., 1993).

Historically this method has only been applied to brittle fault slip data (i.e. faults with slickenlines) presumably due to the method's origin in seismological studies. However if the Wallace-Bott assumption holds true this method can be applied to any fault/shear data for which a movement vector along a shear plane can be resolved and hence in this study it has been applied to ductile structures. The reservation of applying the P-T dihedra method to ductile structures stems from a concern that at high strains there is a lot of rotation of structures within a shear zone. However the rotation of structures such as boudins and fold axes occurs within a consistently oriented shear zone and typically towards a well established stretching lineation, hence the orientation of the shear plane and lineation can be confidently used to construct P-T dihedra.

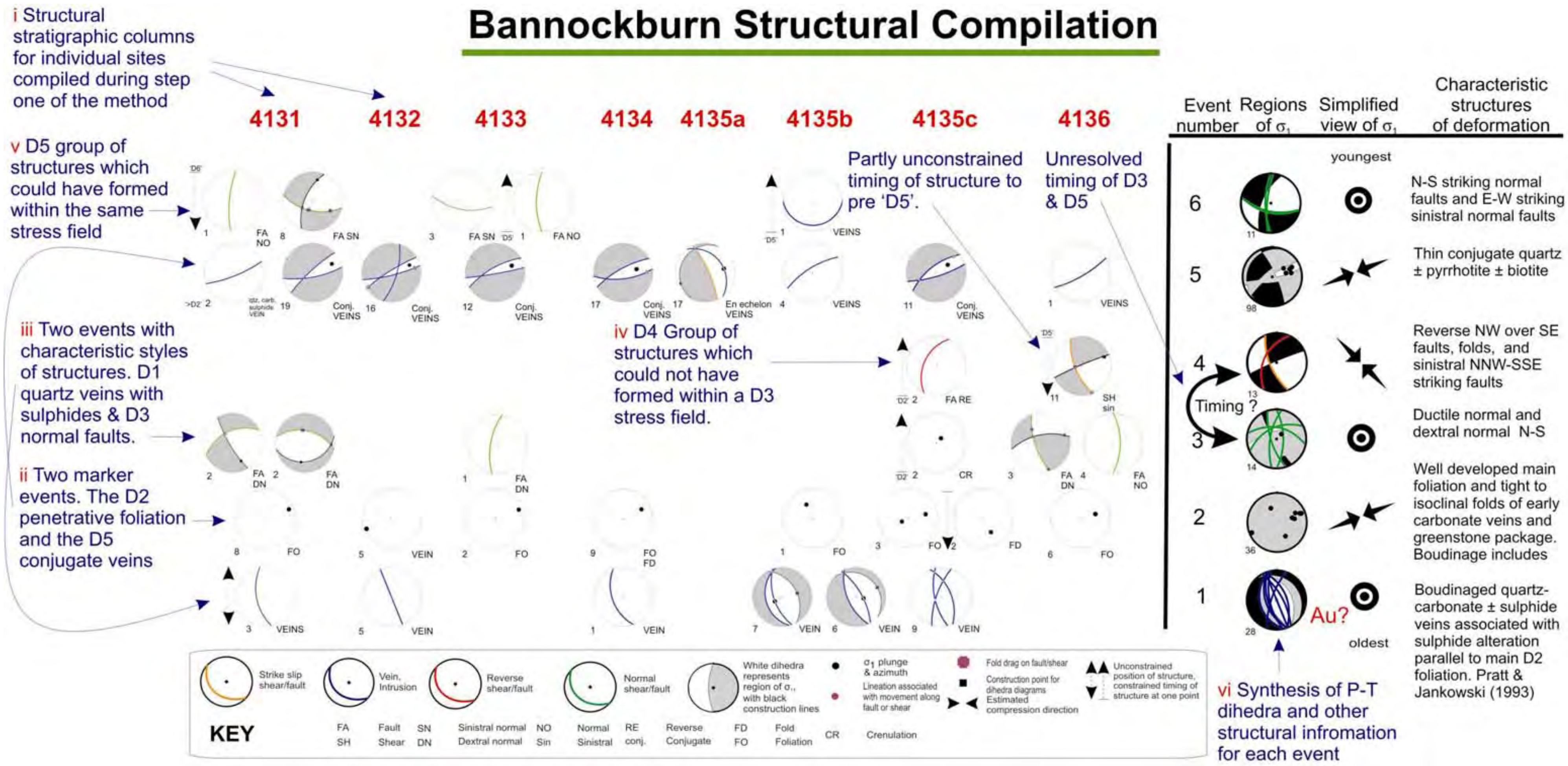


Figure 6: Bannockburn structural compilation as an example of the methodology used in this study. See Appendix 3.2 and therein for detailed syntheses

During the course of the study the approach of constructing P-T dihedra for brittle structures changed. Initially a set of co-genetic structures at a site was averaged and one P-T dihedral was constructed. Later in the study individual P-T dihedra were constructed for individual structures in order to more tightly define the regions of σ1 and σ3. However ductile shear zones and foliations continued to be averaged throughout the duration of the study in order to smooth out the natural variations in foliation orientations. Examples of P-T dihedra construction for various types of structures observed during the course of field work are show in Figure 8.

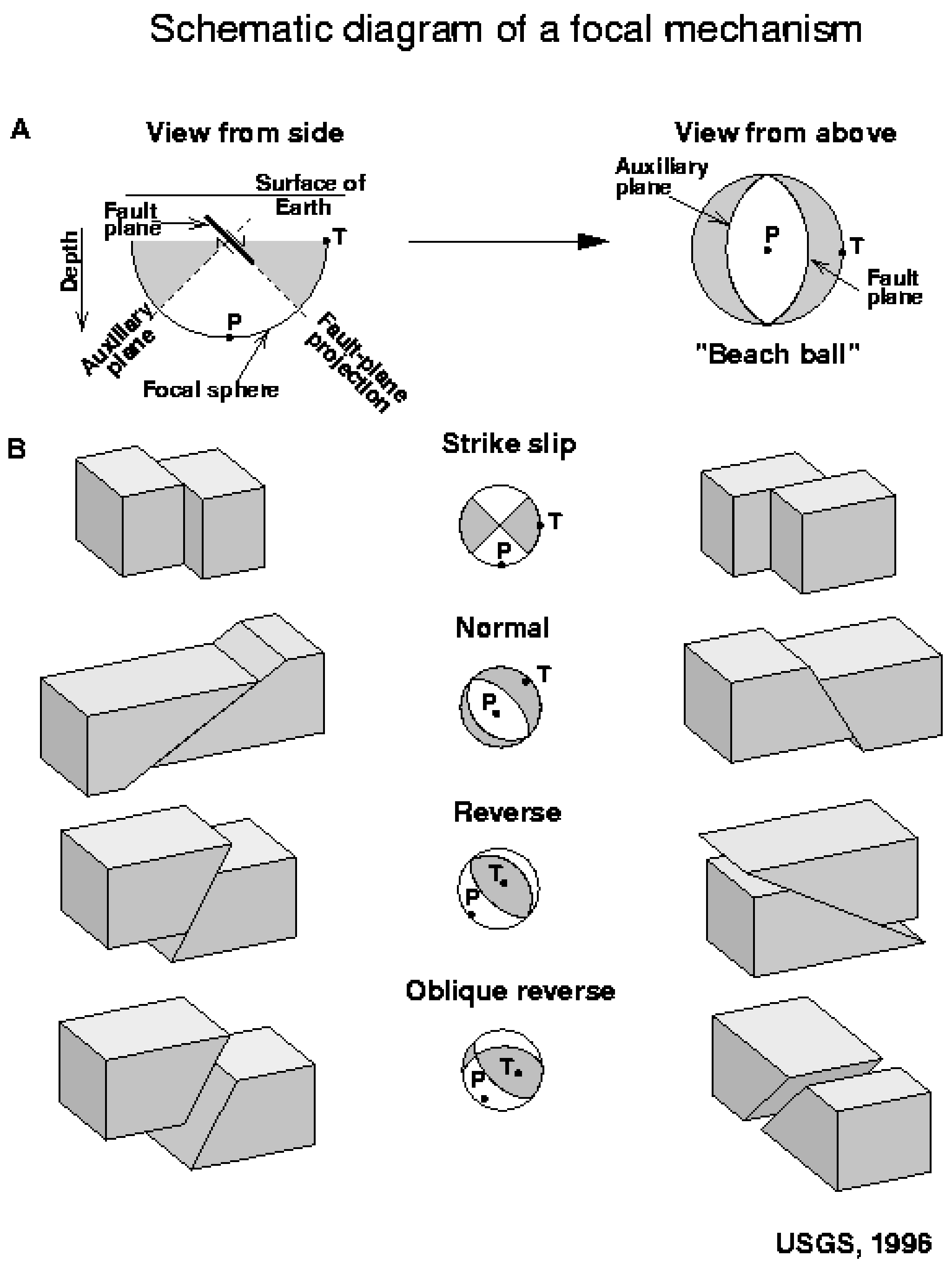


Figure 7: Simplified P-T dihedra (stereonets) and the representative end-member fault classes. Compression (σ1 or the P) is located in the white areas of the stereonet to make the fault move accordingly.

Planes

It is not possible to construct P-T dihedral for all structures. Tension veins, dykes, sills and faults for which a movement vector could not be determined were displayed as planes. In the case of tension veins it can be assumed that σ_1 lies within the plane of the vein. For faults, the approximate orientation of σ_1 can be estimated however this is not as rigorous as P-T dihedra.

Lines – the special case of foliations and folds

Foliations and folds are inherently hard to interpret. In this study co-planar foliations with extensional, strike-slip, reverse and pure flattening all parallel to axial planes of regional folds have been observed, albeit at different locations. These fabrics have been typically interpreted as S2 flattening planes, and used to correlate events across wide areas. This difference in foliation genesis makes the task of interpreting the significance of any one foliation, which can not be easily associated with a sense of shear, extremely difficult.

At the beginning of the study all foliations, for which a sense of shear was not observed, were assumed to be related to pure flattening and have been displayed as poles to the foliation plane which was intended to approximate the orientation of σ_1. However a re-examination of boudin photographs according to the classification of Goscombe et al. (2004) has shown that the majority of foliations are in fact shear fabrics. In the cases where a foliation has been reinterpreted, changes have been made to the respective structural synthesis. However, in many cases there was insufficient data to re-evaluate the nature of the foliation and hence these foliations are still displayed as poles to the foliation plane.

Step two

Once a structural stratigraphic column was established for each site within a pit, each of the sites were correlated with one another. This was done by linking structures together based on their morphology and the stress field in which they formed. The first step was to identify a particular structure/s that was common in the pit and use it as the marker event to correlated between sites (eg. a penetrative foliation see Fig. 6ii). The second step was to correlate similar styles of structures with similar kinematics together (eg. all early quartz veins associated with sulphides see Fig. 6iii). After this stage there were relatively few structures left. The palaeostress field of these structures was examined to see if they could have formed contemporaneously during the already defined events, while remaining bound by the observed cross-cutting relationships (see Figure 6iv & v). All P-T dihedra from within a correlation class (or event) were then combined to define the possible regions of σ_1 and σ_3 as defined by the overlap of individual P-T dihedra (see Fig. 6vi).

The correlation of structures in step two is based on the pit scale (up to 1 km^2 area) assumption that stress is uniform and invariant over the duration of any one deformation event. This assumption is verified by the general lack of structures which can not be correlated with other structures of a similar style. Very occasionally there are minor outlying brittle structures represented by a few readings which are hard to correlate with any other structures. These may be attributed to fault interactions or stress transfer and have been identified as a problem in stress inversion in the past. However with large enough data sets these structures become insignificant[3] in determining the regional palaeostress directions. The one exception to this rule is New Holland where thrust-related veins cut downwards into their footwall. Therefore, the P-T dihedra constructed for the thrusts and

[3] Each pit has anything from 100 to 500 measurements and observations (see Excel spreadsheets in Appendix 3.2)

the related extension structures do not overlap. This is most likely a function of the rheology of the regionally distinct sandstone the deposit occurs in.

Step three

In Step 3, the synthesised structural event histories determined in Step 2 (Fig. 6vi) are correlated with one another. At this point our methodology diverges from classical P-T dihedra stress inversion studies (e.g., Angelier and Mechler, 1977) which correlate all structures based on the absolute direction of stress determined by overlapping individual P-T dihedra. Such an approach assumes that the regional stress is uniform and invariant during any one event over the whole study area. While this assumption is safe on the pit scale it is not valid on the regional scale hence the absolute orientation of stress vectors has not been used to correlate individual events with one another. Instead it is the pattern of stress switching which has been used to correlate events within one another. In conjunction with the pattern of stress switching limited geochronological constraints have also been used along with regional map patterns. In the case where there were insufficient events observed in a pit to make a certain correlation as the timing of an observed structure the ambiguity in the location of the structure is shown on the Central Eastern Yilgarn Deformation History Banner (Appendix 3.1.1).

Initially instead of palaeostress switching patterns unique structures such as the penetrative 'D2' fabric were used to correlate between pits. However through the course of the study it was shown that this fabric could not be used to correlated between pits since at various deposits this uniformly NNW striking fabric displayed normal, reverse, strike-slip and pure shear kinematics hence the penetrative fabric can not be assumed to have necessarily formed in the same event. Based on this observation events were correlated based on the pattern of palaeostress switching which is dependant on identification of a unique sequence of palaeostress switches used as a marker sequence. The unique pattern of palaeostress switching used in this study is the switch from: extension to NNW-SSE compression followed by NE-SW compression. This pattern has worked well however it is primarily based on the presence of what is typically a moderate- to low-strain deformation and hence caution should be taken in placing too much emphasis on correlations based on a very low-strain NNW-SSE compressional event. Furthermore this pattern can be used to correlate events in areas where extension is not recorded. In these areas we see a switch from ENE-WSW compression to NNW-SSE compression and back to NE-SW compression. To resolve this problem, map patterns were used to determine the relative timing of the early extension and compression events. The observation that Late Basins overlay a pre-folded sequence yet sit in the hangingwall to extensional shear zones has been used to constrain the timing of D3 extension to after the D2 compression.

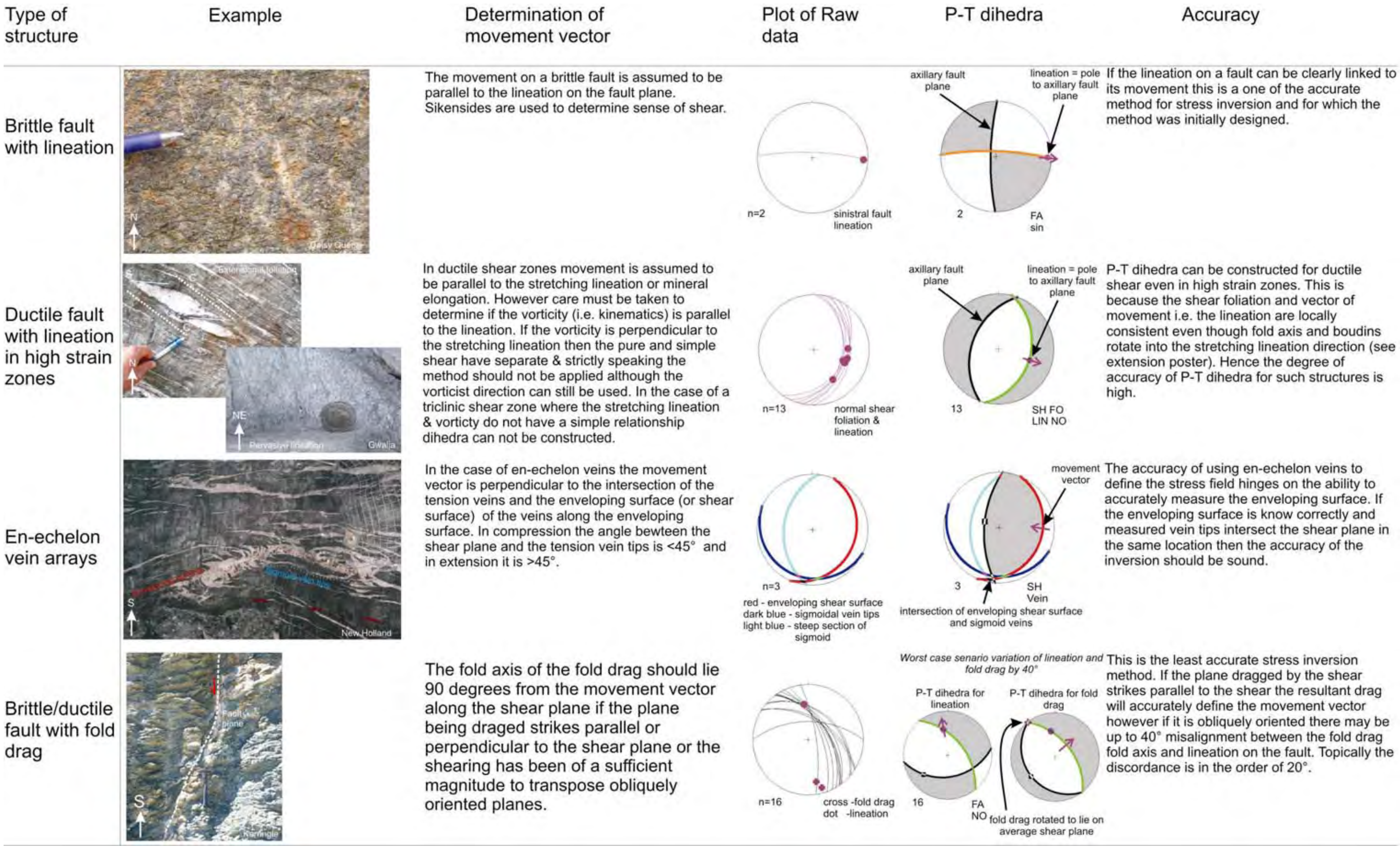


Figure 8: Case examples and explanation of the modified PT-dihedra method (Czarnota and Blewett, 2005) applied to the Eastern Yilgarn

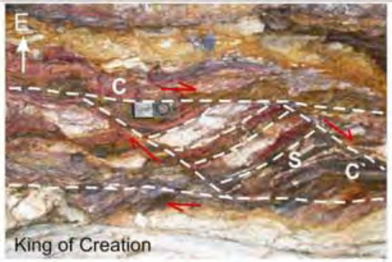
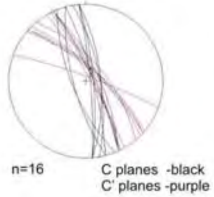
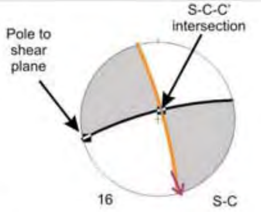
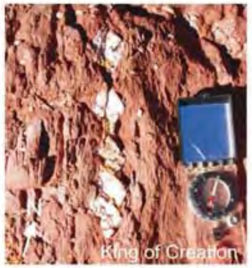
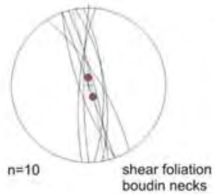
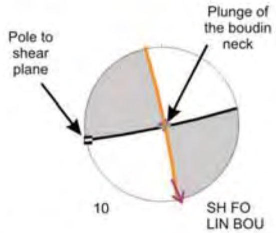
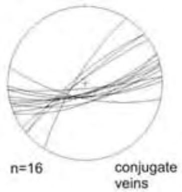
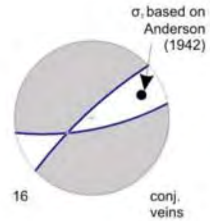
Type of structure	Example	Determination of movement vector	Plot of Raw data	P-T dihedra	Precision of P-T dihedra construction from structure
S-C or S-C' fabric in shear zone	 	Sense of shear on the C or C' plane is 90° away from the S-C-CP intersection along the C or C' plane, hence the axilary to the fault plane passes through the point of intersection and the pole to the shear plane.	 	 	Since it is possible to gather lots of S-C measurement pairs the resultant accuracy is good.
Boudinage in shear zone	 	Sense of shear can be determined using boudins based on the criteria of Goscombe et al. (2004). If the boudin material lies within the shear plane then the vector of movement is perpendicular to the plunge of the boudin neck within the shear plane.	 	 	Accuracy is dependent on the material being boudinaged laying entirely within the shear foliation plane.
Conjugate veins/faults	 	In the case of conjugate veins where a lineation is present data should be reduced for individual planes as for brittle faults with lineations. In the special case where a movement vector can not be determined on a fault plane however a conjugate relationship can be determined the region between the two shear planes is inferred to host σ_1	 	 	Low accuracy determination of σ_3.

Figure 8 continued: Case examples and explanation of the modified PT-dihedra method (Czarnota and Blewett, 2005) applied to the Eastern Yilgarn

Figure 9: Location of field sites (blue-pits and red-granites) with fault systems and major anticlines and granite batholiths named.

Structural history of the terranes of the Eastern Yilgarn Craton

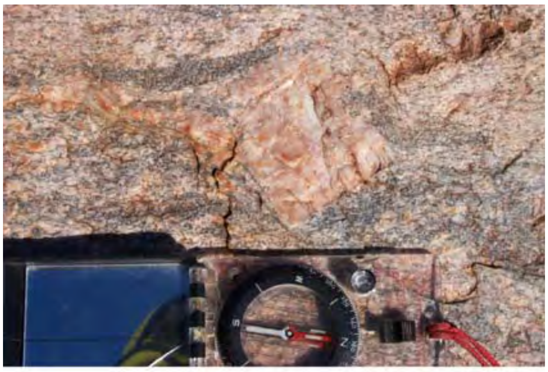
The following section summarises the deformation history of each terrane from east to west (Burtville, Kurnalpi, Kalgoorlie), by describing each of the key data sites (granite pavement and greenstone pit), as well as the terrane boundaries and major fault systems. The summaries are based on detailed work that is presented in Appendix 3, and includes raw data (Excel files), jpeg photographs, facsimile copies of the 6 field note books (pdf), posters of stress inverted pits (pdf and CorelDRAW version 12 originals), and the granite study (CD of Blewett et al., 2004a). The colour A3 atlas is a 'thumbnail' supplement to the printed report, and most full colour posters are designed for A0 plotting.

Burtville Terrane

The Burtville Terrane is the most easterly of the Eastern Yilgarn terranes, and is bound to the west by the Hootanui Fault System (locally as the Barnicoat East Fault). To the east, the terrane is concealed by Proterozoic and younger basinal sedimentary rocks. Much of the terrane consists of 'external' granite and gneiss with protoliths as old as 2770 Ma (Cassidy et al., 2003), with narrow greenstone belts at Yamarna, Mt Sefton and to the east of Laverton. Three gold deposits (Keringal, Mikado, and King of Creation) were studied, together with nine granite sites (Isolated Hill, Surprise Rocks, Ivor Rocks, Ironstone Point, Moon Rocks, Mt Denis, Barrett Well, Hanns Camp, Two Lids Soak). Many of the granite sites have old (~ 2675 Ma and older) High-Ca granite/gneiss 'basement' and younger (~2640 Ma) Low-Ca granite intrusions. These two age populations neatly bracket much of the deformation, providing temporal control for events before and after the intrusions.

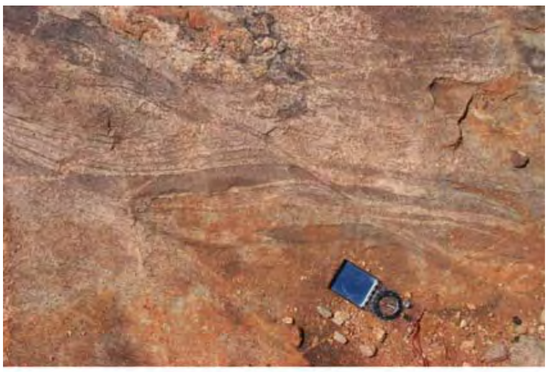
Isolated Hill

Isolated Hill is the most easterly site of the study, and is located ~150 km east of Laverton in the Great Victoria Desert. All structural elements (Blewett et al., 2004a) are younger than the two phases of granite dated (2681±4 Ma and 2663±7 Ma). The dominant fabric element developed during NW–SE contraction is a strong L–S tectonite plunging shallowly south. A sinistral component of shear is recorded on the S–planes (see photograph). A later ductile dextral overprint shows stress switch to NE–SW contraction. Minor faulting overprints the two ductile events.



Surprise Rocks

Surprise Rocks are located SE of Laverton on the Minigwal 1:250K sheet. The oldest phases at Surprise Rocks are 2765 Ma High-Ca granite gneiss, with extensive leucosome sheets and biotite-rich banding. The age of metamorphism unknown, but it is likely around 2675 Ma. The gneissosity is isoclinally folded about recumbent folds that verge south, possibly related to extension(?). These folds are refolded into Type II interference patterns by upright N–S trending folds, and overprinted by dextral extensional shear zones (see photograph). A series of ductile to semi-ductile sinistral shears are overprinted by Low-Ca granite dykes that were intruded into E–W sinistral shear zones at 2645±6 Ma (Blewett et al., 2004a).



Ivor Rocks

Ivor Rocks are located 55 km ENE of Laverton on the road to Yamarna. The oldest phases are 2690±10 Ma and 2670±10 Ma High-Ca granite gneiss with extensive leucosome sheets and biotite-rich banding (Dunphy et al., 2003). The age of metamorphism unknown, but based on regional melting events, is likely around 2675 Ma. The gneissosity is isoclinally folded about recumbent folds that verge south, possibly related to extension(?). These recumbent folds are refolded into Type II fold interference patterns by upright N–S trending folds. Extensional C' dextral shear zones are associated with granite dykes. Sheets of Low-Ca granite are overprinted with sinistral shears that transpose some of the earlier dextral shear zones (Blewett et al., 2004a).

Ironstone Point

Ironstone Point is located 50 km ESE of Laverton. High-Ca granodiorite (2668±4 Ma) (Dunphy et al., 2003) hosts a strongly penetrative NNW–striking foliation which is overprinted by a series of younger phases of granite dykes. Low-Ca granite dykes and larger bodies, dated at 2638±2 Ma (Dunphy et al., 2003), host a well-developed foliation and shallow south–southeast plunging stretching lineations (Blewett et al., 2004a).

Mount Denis

Mount Denis is located more than 60 km SE of Laverton on the Coglia–Merolia road. This site is complex of at least eight separate phases of granitoid intrusion, and multiple switches in inferred palaeostress. The gneissic protolith has a date of 2770±4 Ma (Dunphy et al., 2003), and has been intruded by various phases of granite sills and dykes. The first penetrative fabric is a pronounced flat-lying gneissosity with a shallow north-plunging lineation. The age and kinematics of this event is uncertain, but is possibly due to an extensional event at around 2675 Ma. The gneissic fabric is overprinted by a crenulation cleavage and associated sinistral shears. At least phases of additional granite and pegmatite are then overprinted by N–S trending sinistral shears and associated syn–tectonic granite dykes. A stress switch to NE–SW contraction developed dextral shear zones and emplacement of Low-Ca granite dykes at 2650±8 Ma. These dykes and earlier shear zones were then overprinted by NE–trending dextral shear and subsequent minor sinistral reworking (Blewett et al., 2004a).

Moon Rocks

Moon Rocks is located SE of Laverton. The oldest phases at Moon Rocks are 2732±16 Ma High-Ca granite gneiss (Keith Sircombe, unpublished GA data), with low-angle leucosome sheets and biotite-rich shears defining the S1 fabric. The gneissosity is isoclinally folded about recumbent folds, and like other gneissic sites in this terrane, is possibly related to extension(?). These folds are refolded into Type II interference patterns by upright NNW–trending folds, and overprinted by intense NNW–trending dextral shear zones and associated melt/intrusion along the shear planes during NE–SW contraction. Co–planar sinistral shears overprint the earlier dextral shears and represent a major palaeostress switch to NW–SE oriented contraction. These sinistral shears are also accompanied by granite dykes, and at the latest stages by Low-Ca granite dykes dated at 2637±7 Ma along WNW–trending dextral shears (Keith Sircombe, unpublished GA data). The final stages of NW–SE contraction occurred with minor semi-ductile crenulations and sinistral shears (Blewett et al., 2004a).

Barrett Well

Barrett Well is a series of gneissic outcrops located 10 km east-northeast of Edjudina station. A biotite monzogranite dyke, dated at 2675±2 Ma (Swager and Nelson, 1997), overprints a gneissosity and leucosome sheets (sills). This is an important observation as it provides a minimum age constraint on gneissic fabrics across the region. Many of the gneisses have been dated at around 2675 Ma (Cassidy et al., 2003), suggesting the Eastern Yilgarn underwent significant metamorphism and melting at this time. The gneissosity is isoclinally folded about recumbent folds, and like other gneissic sites in this terrane, is possibly related to extension(?). These folds are refolded and crenulated by upright north–trending folds, and overprinted by intense NNW– to north–trending dextral shear zones NNE–SSW contraction. A palaeostress switch to NW–SE contraction resulted in sinistral reworking, transposition and boudinge. Minor dextral shearing during E–W contraction records the last brittle–ductile movements (Blewett et al., 2004a).

Hanns Camp

The Hanns Camp Syenite is located around 5 km east of Laverton. It was emplaced at 2664±2 (Cassidy et al., 2003), probably during regional extension. The syenite has a pronounced flat–lying mylonitic foliation (see photograph to right) with a NNW to SSE movement direction. It is not clear whether this foliation developed during a contractional event (as interpreted by Blewett et al., 2004a), or an extensional one (as favoured here). The mylonitic fabric is overprinted by spaced N– and NNW–trending sinistral shear zones and open to tight upright folds that developed during NW–SE contraction. Later minor dextral shears reflect a switch to NE–SW contraction, with the final event NE–trending kink bands of the main penetrative foliation (Blewett et al., 2004a).

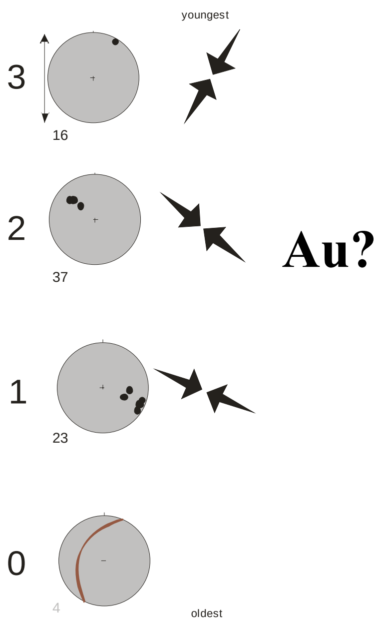
Two Lids Soak

The main gneissic phase at Two Lids Soak, located 30 km NE of Yarrie, has been dated at 2672±2 Ma (Swager and Nelson, 1997). The granite host was metamorphosed and a sheet–like gneissic fabric developed, probably during regional extension. Sheath–like isoclinal folds of the 'S1' gneissic fabric are upright and plunge gently to the north and NNW. The folds are partly transposed by S–C mylonites and associated boundinage during sinistral shear under NW–SE contraction. A palaeostress switch to NE–SW contraction resulted in the dextral reworking of the earlier fabrics and offset of dyke markers. Minor open folding and NW–trending sinistral faults likely reflect late–stage E–W contraction.

Mikado

The Mikado is a small gold deposit south of the old workings of Burtville. The deposit is hosted in weathered talc schist. Three phases of deformation have been defined (Fig. 10). The first fabric is a steeply to moderately WNW–dipping penetrative foliation across the entire rock mass, developed during NW–SE contraction. The main ‘S1’ foliation is overprinted by a spaced crenulation that is locally very intense (see photograph below), as the result of ongoing NW-SE contraction. This ‘D2’ event is thought to be the gold event. The final ‘D3’ event was the development of a fine-spaced crenulation cleavage, which is particularly well-developed at the NNE side of pit. This foliation is interpreted to reflect contraction (flattening) under a NE–SW contractional event.

Figure 10: Summary structural stratigraphy of Mikado.

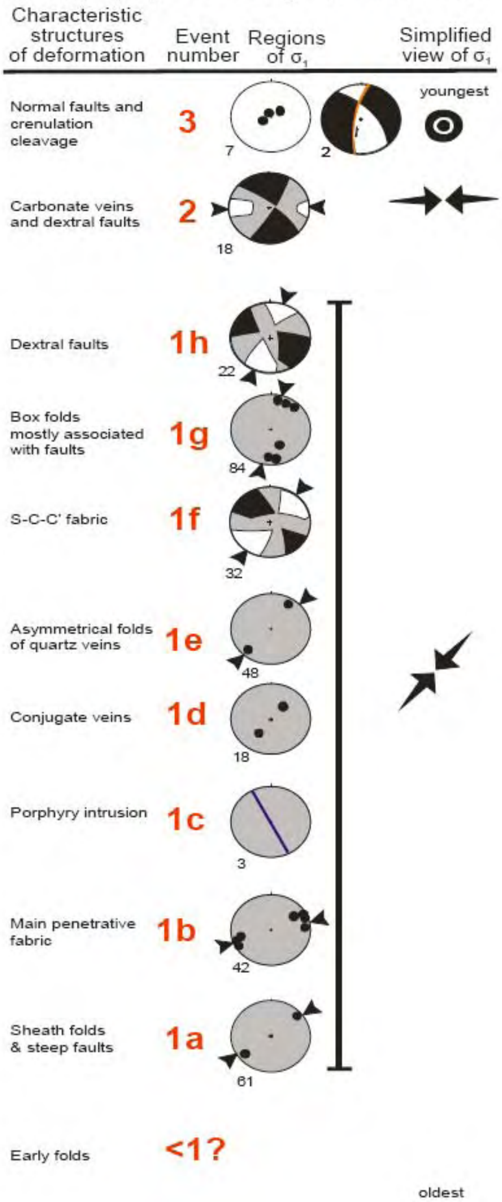


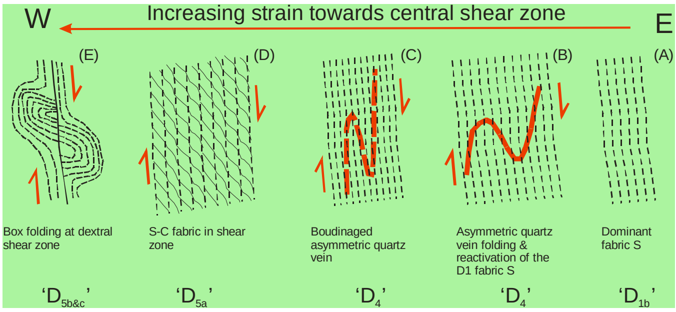
Key Point:
Good evidence for mineralisation during NW–SE contraction

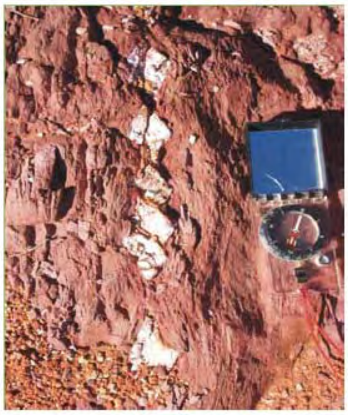
King of Creation

The King of Creation deposit is located 53 km north of Laverton, on the eastern limb of the Mt. Margaret Anticline in greenschist facies greenstones. Strain increases towards a major dextral shear zone within the centre of the pit, and which is assumed to have hosted gold mineralisation. Kinematically the pit is simple with one progressive period of NE–SW contraction developed as foliations (flattening and shear fabrics), sheath folds, veins, S–C–C’ mylonites, boudins, mullions, and more discrete faults and conjugate veins. A NNW–trending porphyry dyke was also emplaced into this sequence. Strain is highly partitioned into a narrow NNW–trending corridor (mineralised), some 50 m wide (see inset sketch). The centre of the shear zone records multiple phases of deformation and transposition under a significant dextral régime (Fig. 11), while in contrast the margins of the pit are strained only with a single penetrative dextral shear foliation. At the centre of the pit horizontal and vertical lineations are present, consistent with transpressional shearing. This dextral transpressional event was the principal control on gold mineralisation. A late extensional collapse completes the sequence of events.

Figure 11: Summary structural stratigraphy of King of Creation.







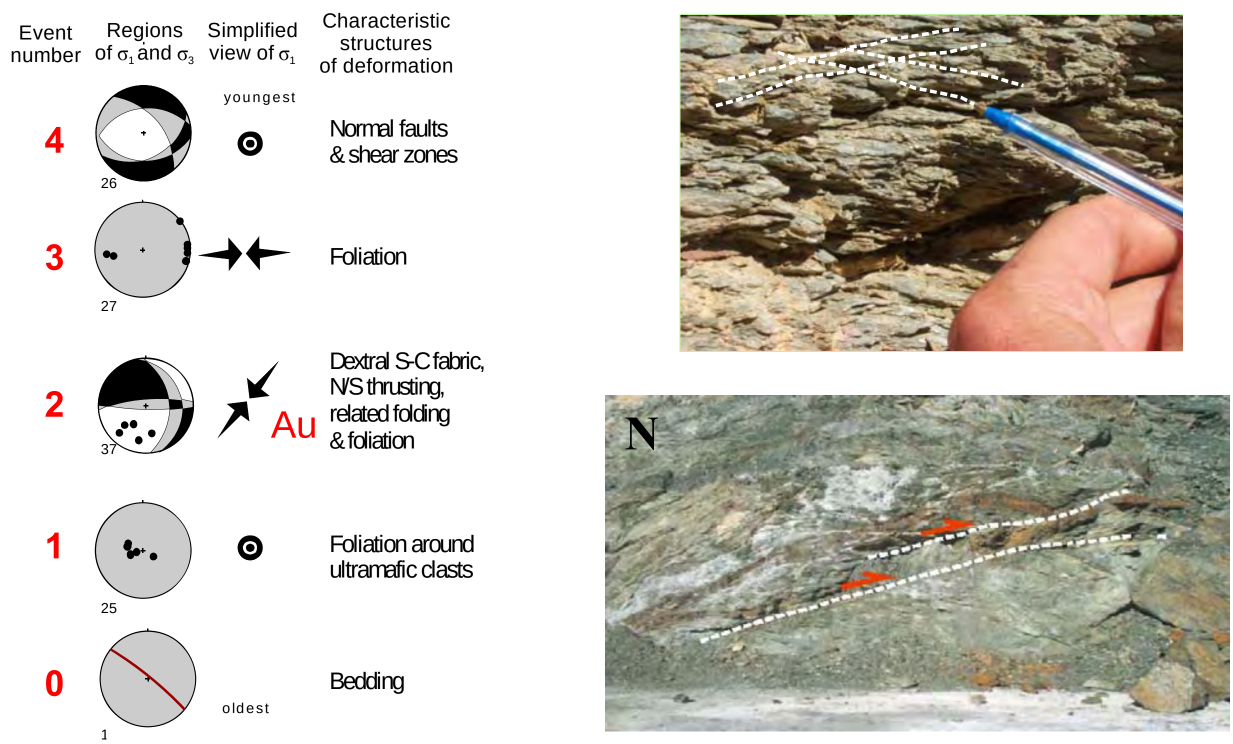
Dextral shear Domino Boudins (Goscombe et al. 2004) in regional fabric implying it is a dextral shear fabric.

Key Point:
1. Intense strain partitioning in dextral shear zone and development of complicated structures during progressive deformation.
2. Regional NNW trending foliation in pit is actually a dextral shear foliation which poses the question what is the regional NNW trending foliation in the Yilgarn?

Keringal

The Keringal Au deposit is located 37 km SSE of Laverton, and lies on the terrane boundary of the Burtville and Kurnalpi Terranes (Hootanui Shear Zone). Rock types include ultramafic conglomerate, and schist, basalt, as well as lamprophyre and porphyry dykes. Mineralisation occurs in E-W trending shoots, and they developed during the local ‘D2’ event. The main foliation in the pit is a low–angle anastomosing series of fabrics (see upper photograph), that likely developed by a vertical flattening field (extension). At some sites a sequence of overprinting low–angle fabrics is recorded. Overprinting the main penetrative foliation is a series of N–S trending moderately E–dipping dextral strike–slip faults and SW–directed thrusts (see lower photograph). These dextral faults and thrusts mark an inversion of the earlier extension, and developed during NE–SW contraction which resulted in mineralised shear and extension veins. A later overprinting flattening foliation dips steeply east or west and is associated with an E–W contractional event. The final deformation event was close to uniaxial extension with the development of a series of brittle normal faults having a variety of transport directions (see also Davis and Maidens, 2003).

Figure 12: Summary structural stratigraphy of Keringal



Key Point:
Development of strong horizontal early fabric and NE over SW thrusting.

Kurnalpi Terrane

The Kurnalpi Terrane is the central terrane of the Eastern Yilgarn, and is bound to the east by the Burtville Terrane and to the west by the Kalgoorlie Terrane. The bounding faults are the Hootanui and Ockerburry Fault Systems respectively. Other major faults include the Celia, Mertondale, Keith–Kilkenny, and Emu Faults.

The structural synthesis is based on detailed studies of eighteen mines (Winditch, Phoenix, Gladiator South, Telegraph, Lancefield, Jupiter, Transvaal, Westralia, Porphyry, Mt Nambi, Mt Redcliff, Mertondale, Celtic, Linger and Die, Puzzle, Butterfly, Dragon, and Parmelia) and eight granite sites (Murphy, Bernie Bore, Yarrie, Outcamp Bore, Pindinnis, Bulla Rocks, Rainbow, and Mullenberry). Most of these granites are internal granites, and intrude older greenstone sequences, and have thus been emplaced into higher structural levels than the external granites. The linkage between the structural stages of the internal and external granites provides valuable constraints on the distribution of strain through the crust. The internal granites also acted as buttresses, and are themselves commonly only weakly deformed. The Porphyry deposit is both a mine and a granite site, and Yarrie was a small gold digging within a granite site.

Mine and granite sites were selected on the quality of outcrop (although this was sometimes less than brilliant) and at a range in structural level and position with respect to major shear zones and regional folds. The 01AGSNY1 regional seismic reflection line from the *pmd**CRC transects the entire terrane, and provides additional geometrical constraints on the architecture of the major fault systems.

A self consistent pattern of events/stages and their timing has been defined fro the Kurnalpi Terrane. The Kurnalpi Terrane (in this study area) is dominated by the Mt Margaret Anticline (Fig. 9), a S–plunging upright fold cored by a multiphase batholith and with sheared limbs to the east by the Hootanui Shear Zone (Laverton tectonic zone), and to the west by the Celia Shear Zone (tectonic zone). Beardsmore (1999) described the kinematics of the east limb as dextral and the west limb as sinistral. This study confirms these observations, but suggests that they occurred at different stages (see below in this section). The western margin of the terrane is marked by the Ockerburry Fault System, a major E-dipping extensional fault.

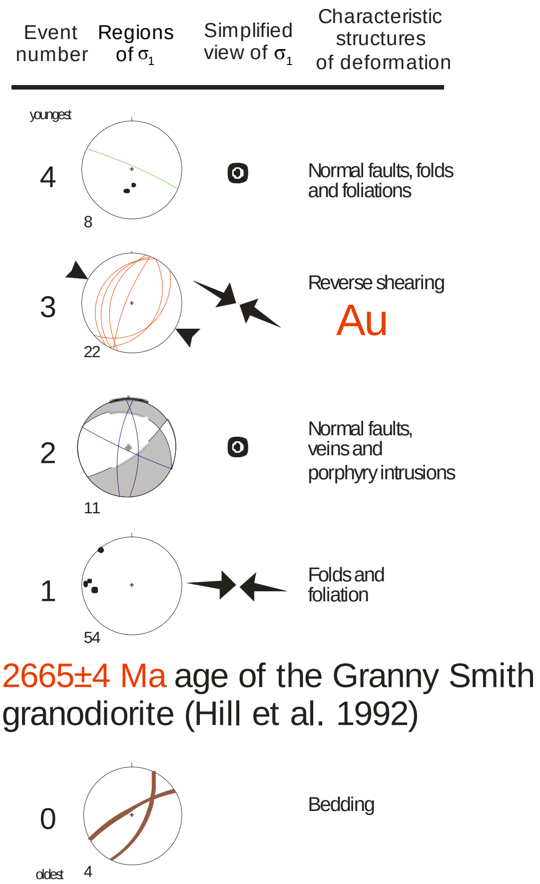
The Kurnalpi Terrane was deformed by a series of what appears to be long–lived extensional stages associated with granite emplacement, interspersed with short–lived contractional stages. As was the case for the Burtville Terrane, the classical 'D1' N–S contractional event of Swager (1997) appears absent in the Kurnalpi Terrane. Others have inferred its existence (e.g., Ojala, 1995; Liu and Chen, 1998; Beardsmore, 1999). However, Beardsmore (1999) suggested also suggested that the earliest folds and foliations around the Mt Margaret Anticline could have been extensional in origin, and been later folded during the development of the regional anticline.

Windich

The Windich Au deposit is located in the Laverton area 22 km S of Laverton within the Granny Smith Camp. The deposit is located at contact between metasedimentary rocks of the Granny Smith Basin and the Granny Smith Mafic-type granite. The structural history involved four main events. Both the granodiorite and adjacent sedimentary rocks are well-foliated, with upright open folds are developed in the greenstones. These structures were developed during E–W contraction after 2665±4 Ma (age of granodiorite from Hill et al., 1992). Gold was localised along NE–striking reverse faults during NW–SE oriented contraction following an intermediate Stage of extension (Fig. 13). The latest Stage was extensional, with normal faults down throwing to the NNE, and crenulations and folds with sub–horizontal axial surfaces (see also Davis and Maidens, 2003).

The position of the Windich pit on the SE corner of the granodiorite resulted in a strain shadow from the major dextral stage of shearing along the eastern margin of the Kurnalpi Terrane (see Keringal, King of Creation, Phoenix, Gladiator and Murphy). This favourable location under a NE–SW contractional event may have resulted in extension, and the Stage 4 extension may be part of this event.

Figure 13: Summary structural stratigraphy of Windich



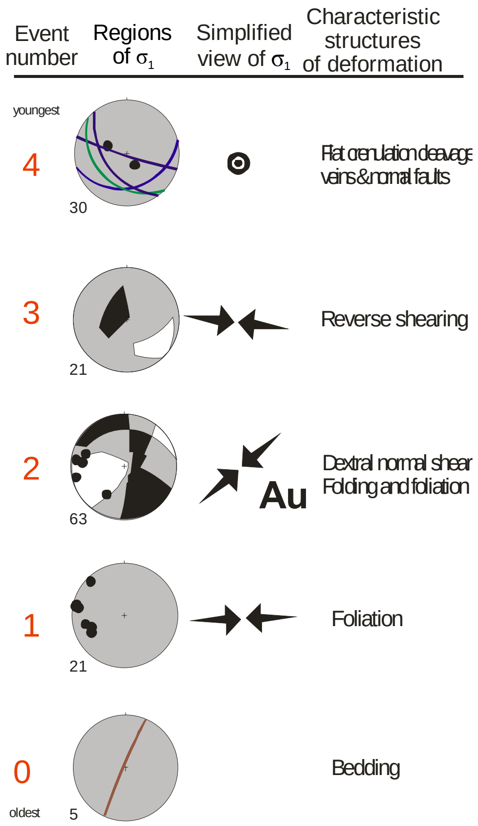
Key Point:
Gold is associated with NW–SE contraction, and subsequent dextral reactivation was largely absent because this location was in a strain shadow.

Phoenix

The Phoenix gold deposit is located 22 km south of Laverton, and lies on the Childe Harold Fault. It is situated on the western edge of the Granny Smith Basin on the Laverton Shear Zone. Gold is hosted within dextral–normal shear reactivation of boundary between Granny Smith (first stage) basin sediments on the east and dolerite and basalts of the older mafic sequence on the west.

Four deformational stages have been defined at Phoenix. The first involved the development of a pervasive steeply dipping foliation in all rocktypes. This stage folded(?) the stratigraphy into its steep attitude, and may have involved an element of thrusting to the west. The second stage was associated with gold deposition(?) and is recorded by strongly partitioned dextral shearing with folds that are locally transposed (see photograph below). The Stage 3 deformation overprint involved a return to W-directed reverse faulting during E–W contraction. The final stage was extensional, with the development of low-angle crenulations, normal faults and minor quartz veins (Fig. 14).

Figure 14: Summary structural stratigraphy of Phoenix



Transposed folds during dextral shear

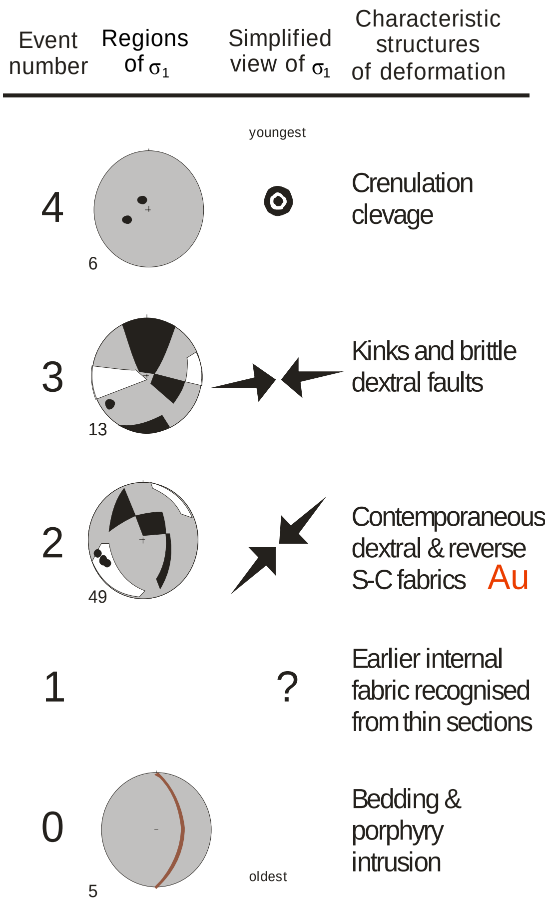
Key Point:
Gold is associated with NE–SW contraction during dextral transpression shear.

Gladiator South

The Gladiator South pit is located ~ 5 km west of Laverton along the Childe Harold Fault. Most of the pit is hosted by reddened polymictic conglomerate with rounded mafic clasts. Porphyry dykes locally occur. The pit is dominated by a well–developed penetrative foliation and shallowly dipping stretching lineation. The dominant kinematics is dextral–reverse for the Stage 2 deformation. Internal foliations in the microlithons between shear planes attest to an earlier fabric that is now largely transposed.

Gold is interpreted to have been deposited during the dextral–reverse shearing stage. Less intense brittle reverse and dextral faults that developed during E–W contraction overprint the main fabric in the pit. The last stage of deformation is the development of low-angle crenulations probably developed during extension.

Figure 15: Summary structural stratigraphy of Gladiator South



Dextral reverse shearing

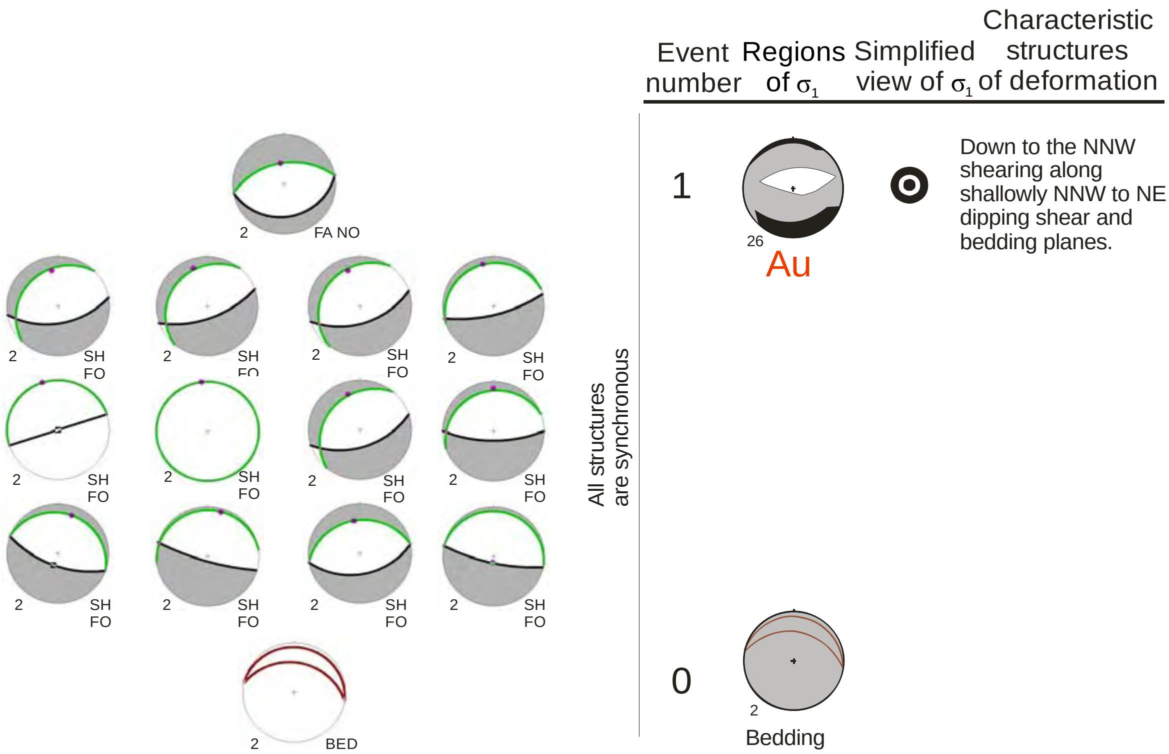
Key Point:
Good evidence for strain partitioning into strike–slip (dextral) and reverse (NE–over–SW) shear.

Sunrise Dam

Sunrise Dam is a multi-million ounce deposit located in the southern Laverton district. The deposit is complex and there is debate over the structural history. The traditional understanding is that the early recumbent folds and thrusts are related to D1 thrusting (N-S), and these are overprinted by upright F2 folds, which are parasitic to the larger Spartan Anticline to the east (Newton et al., 2001). Interpretation of the sense of shear has been described as both sinistral and dextral. Little mention is made of the extensional history.

Figure 16 is a PT-dihedra analysis of the mapping of a wall in the pit by Davis (2003). Davis noted extensional geometries including S-C fabrics (Fig. 17). Davis also noted that the main gold-bearing shears had top to the NW sense of shear, which on NW-dipping shear planes is extensional. The resolved PT-dihedra from Davis's work also indicate that the main fabric is extensional with down to the NNW shearing on shallowly dipping shear planes and layering (Fig. 18).

Figure 16: Summary structural stratigraphy of Sunrise Dam



Structural information from Brett Davis talk to GSA WA division 1 July 2003

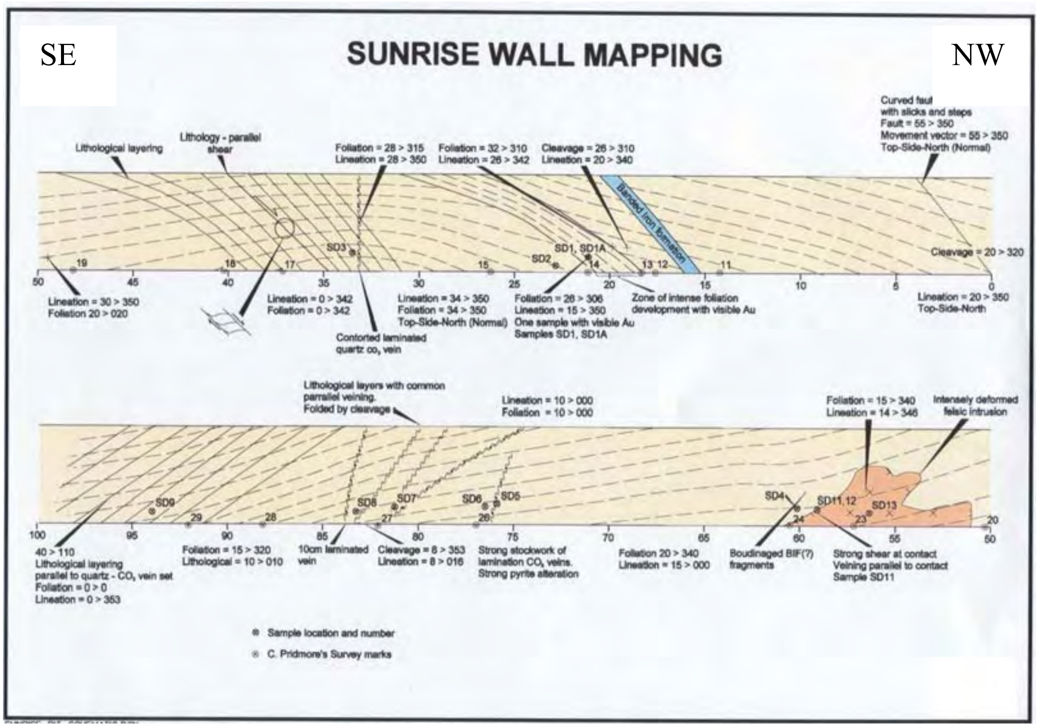


Figure 17: Detailed sections (after Davis, 2003) of a Sunrise wall from which the PT-dihedra analysis was constructed. Note extensional S-C fabric elements in the inset of the upper wall.

Figure 18: Down to the north S-C extensional shearing on the Sunrise Shear (waterfall outcrop). This is the gold event described by Davis (2003)?

Key Point: Down to the NW extension, possibly associated with gold

Murphy

The Murphy granite is a High–Ca type granite located ~60 km NNW of Laverton. It lies on the eastern margin of the Mt Margaret batholith, in proximity to the Hootanui Fault System (Blewett et al., 2004a).

The emplacement age is imprecisely interpreted as around 2670 Ma (Cassidy and Champion, 2003). The oldest stage of deformation at Murphy is a well–developed gently-dipping mylonitic fabric with a north–directed transport direction (see photograph). The mylonites may have developed during extension as interpreted elsewhere in the granites. The mylonitic fabric is isoclinally folded by upright N–S trending Stage 2 folds, which are overprinted and partly transposed by dextral shear bands. A suite of NE–trending aplite and pegmatite dykes overprint Stage 2 and earlier elements, and are themselves cut by conjugate semi–ductile faults during E–W contraction. A switch to N–S contraction during Stage 4 developed more discrete sinistral and dextral conjugate fault arrays.

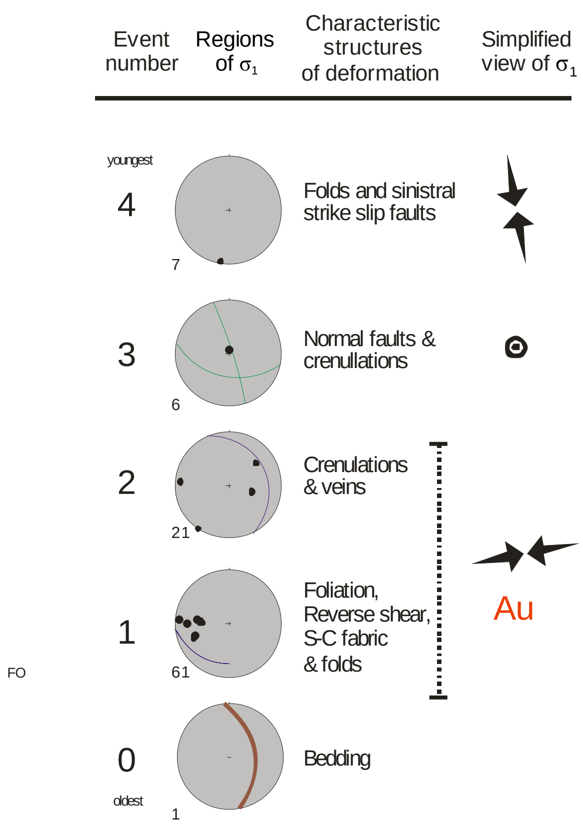
As with much of the eastern part of the Kurnapli Terrane, a stage of intense dextral shearing, developing narrow high–strain zones during NE–SW contraction. The final stage was a series of very low–displacement E–W sinistral faults and associated quartz veining and haematite alteration.

View north of gentle dipping main foliation (associated with extension?)

Telegraph

The Telegraph pit is located 5 km north of Laverton in sheared and flattened pillow basalts. Gold was deposited during the first stage of E–W contraction in a series of west–directed thrusts. The thrust planes are curviplanar and dip moderately to the east. Strain is partitioned into zones of intense flattening which transforms ovoid pillow structures into cigar–shaped lenses (see photograph below) and ultimately mafic schist with no primary distinguishing features. Progressive contraction developed crenulations of the primary foliation, and these Stage 1 and 2 fabric elements are overprinted by normal faults and crenulations with low–angle axial surfaces during extensional Stage 3 deformation. The final stage of deformation was the development of E–W trending folds and NE–trending sinistral strike–slip faults during N–S contraction (Fig. 19).

Figure 19: Summary structural stratigraphy of Telegraph



Flattened pillows – upward facing

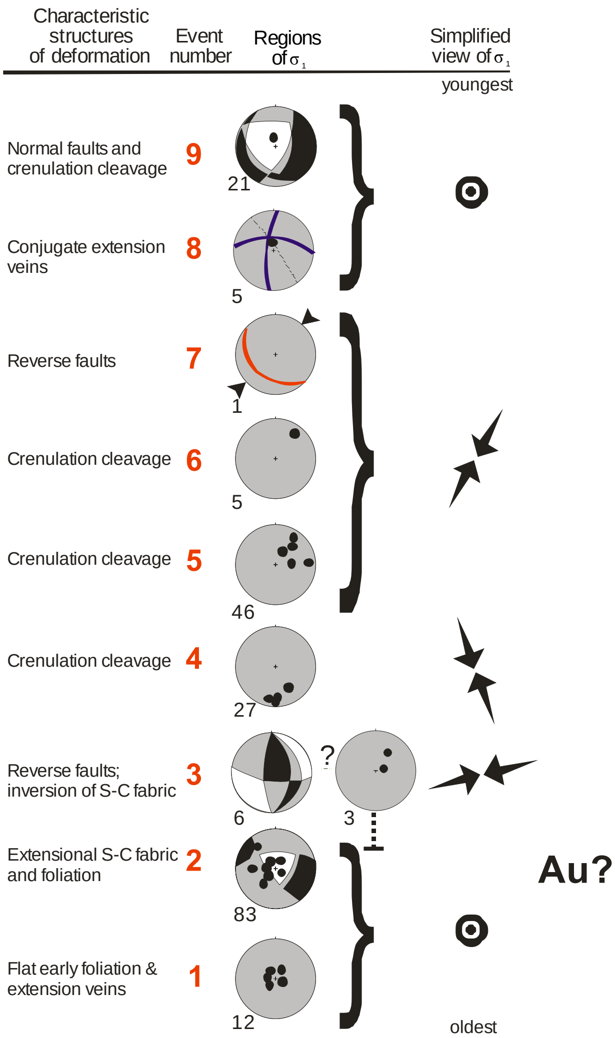
Key Point:
Good evidence for strain partitioning with east–facing pillows deformed into west–directed thrusts.

Lancefield

The Lancefield Au deposit is located 8 km NNW of Laverton. It is situated at the south eastern edge of the amphibolite grade granites of the Mt. Margaret Anticline (Fig. 8) within greenstones (ultramafic schist) with an underlying domal granitoid intrusion (Hronsky, 1993). Gold is hosted within two low-angle E- to SE-dipping shear zones that are defined by 'shale' or 'chert'. In many localities about the Eastern Yilgarn these 'sediments' are shear zones.

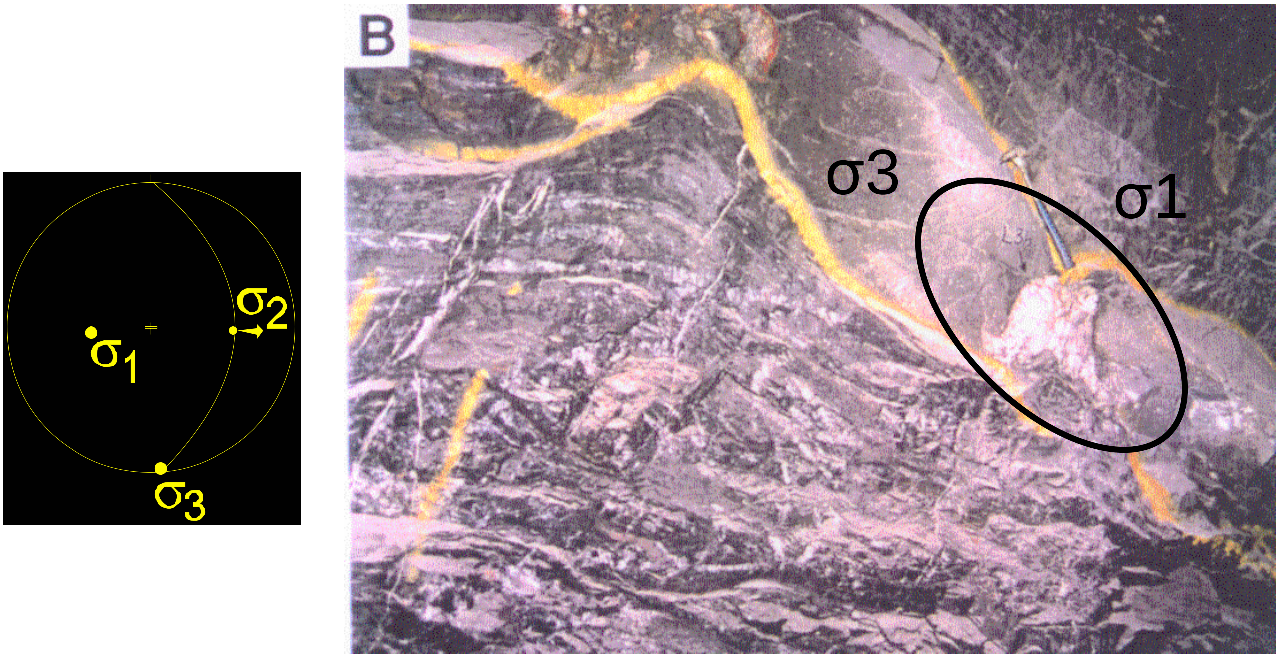
Gold was deposited during a retrogressive stage, with temperatures of 325ºC (±50) compared to the peak metamorphic temperatures of 450ºC and pressures of 1.5 (±0.5) kbars (Hronsky, 1993). This suggests that peak metamorphism occurred early during the extensional development at Stages 1 and 2, with retrogressive mineralisation occurred during the inversion and Stage 3 contraction which was oriented E–W (*cf*. Hronsky, 1993). The principal fabric element of the pit is dominated by the Stage 2 extensional foliation (see photograph) with a movement vector being consistently down to the ESE or SE (Fig. 20). The Stage 4 and later sequence of events is defined as ~N–S contraction followed by NE–SW contraction, which represented as a series of successively overprinting crenulations. The last stage was the development of low–angle crenulations and normal faults during extension or vertical flattening (Fig. 20).

Figure 20: Summary structural stratigraphy of Lancefield

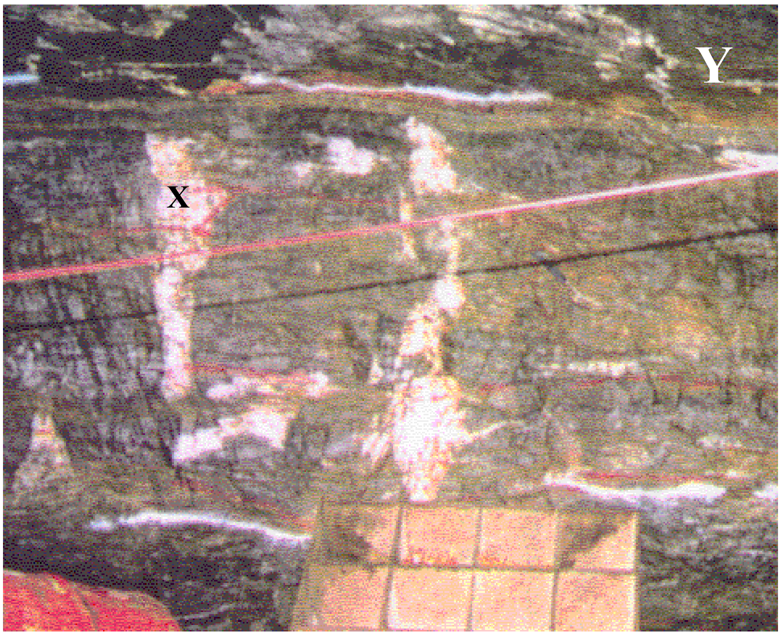


View north of S-C fabrics showing extension

Key Point:
Good evidence for widespread extension down to the south–east and inversion by E–W contraction



View east down the boudin neck (parallel to σ2). These high–grade gold veins are developed in the extension zones between boudin necks. This is an extensional gold event (down to the south) movement (data and photograph re–interpreted from Hronsky, 1993)



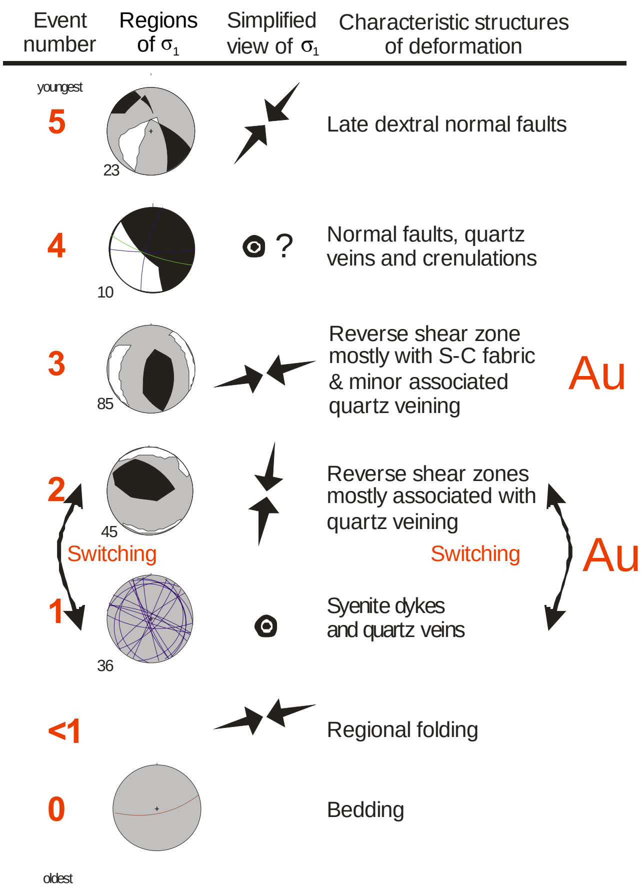
High–grade extension veins (X) cut across the gently dipping mylonitic fabric (30º to 090). Note the folded extensional veins in the upper right of the photograph (Y), consistent with ongoing vertical flattening (photograph reinterpreted from Hronsky, 1993)

Jupiter

Jupiter is a spectacular gold deposit located 28 km SW of Laverton, on the western limb of the Mt. Margaret Anticline in steeply dipping (south younging) greenschist facies pillow basalts that were intruded by quartz-alkali-feldspar syenite and quartz-feldspar porphyry dykes and stocks.

The pillow basalts face south and are folded about the Mt Margaret Anticline, which was developed during E–W contraction. Extensive syenite dykes and stocks intrude this folded sequence, with dykes distributed radially about the centre of the pit (Fig. 21). The first contractional stage was oriented N–S and was overprinted by many of the syenite dykes. Ongoing contraction resulted in reactivation as well as neo-formed N–over–S and S–over–N thrusts overprinting the syenites (Fig. 21). Some dykes show ductile offsets indicative of magma being emplaced into active contractional shear zones (see photograph). At least four different syenite phases were observed. Quartz veining and intense alteration was common at this time, and this was likely a gold event. Stage 3 contraction followed with NE–SW contraction developing west–directed thrusts and associated minor veining. This stage 3 thrusting is also interpreted to be a gold event on the basis of the attitude of the gold envelopes (During et al. 2000). A stage of normal faults, quartz veins and crenulations record the collapse and extension of the system (Fig. 21). The final stage of deformation was a set of normal–dextral faults. The Jupiter pit is a likely analogue of Wallaby in terms of syenite dynamics and regional N–S contraction (John Miller personal communication, 2005).

Figure 21: Summary structural stratigraphy of Jupiter



Key Point:
Classic example of syenite emplaced during contraction and magma pressure developing dyke swarms capable of overcoming regional N–S contraction and gold.

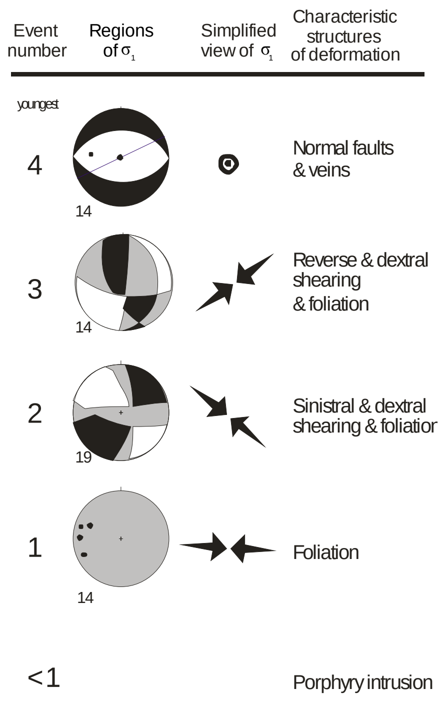
Transvaal

The Transvaal pit is located in the Mt Morgan's gold camp on the western limb of the Mt Margaret Anticline, and marks the eastern influence of the NNW–trending Celia Fault System. The pit is located 2 km NNE of the main Westralia pit (see below), and comprises steeply east–dipping (to overturned) basalts intruded by quartz–feldspar porphyry. The porphyry dykes are conjugates, with a N–trending set and a NNE–trending set. Mineralised shear zones are localised along the NNE–trending dyke margins (Beardsmore, 1999). Gold appears to have developed during NE–SW contraction in dextral and reverse movements on the shear zones.

The structural history of Transvaal (Fig. 22) involved the regional folding during E–W contraction of the basalt host, together with the intrusion of porphyry dykes and the development of a steeply east–dipping penetrative foliation in dyke and basalt. The dykes may have been emplaced during regional contraction, like Jupiter, but under an E–W contractional field. The second stage developed N–S faults along the margins of the porphyry (and locally E–W dextral faults) under a NNW–SSE contraction. The third stage involved dextral reactivation of the steeply east–dipping faults, together with E–over–W reverse faulting. This third stage is interpreted to be a gold event. The final stage was extensional with the development of brittle normal faults and crenulations.

On the basis of previous unpublished company reports, Beardsmore (1999) described shallow north–dipping reverse faults to overprint the mineralisation. These reverse were not observed in this study, although moderately to gently dipping north–dipping normal faults were (which overprint mineralisation). It could be that the reverse kinematics were 'misidentified' and these are the Stage 4 normal faults. Alternatively, the north–dipping reverse faults could have developed during Stage 2 NNW–SSE contraction and involved a component of sinistral motion. If this is the case, then our interpretation of Stage 3 gold is in error.

Figure 22: Summary structural stratigraphy of Transvaal



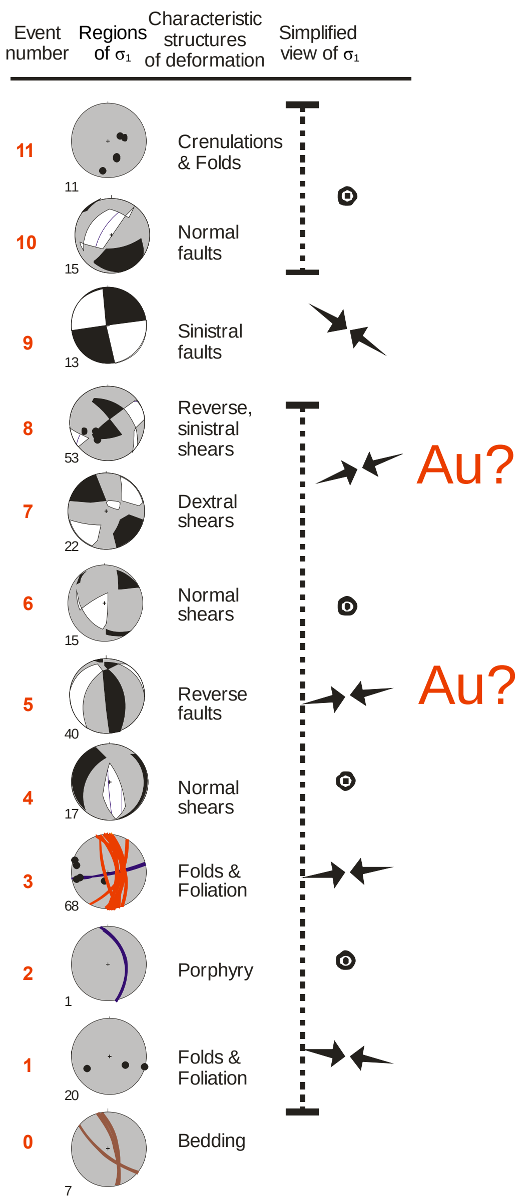
Key Point:
Example of focussed shearing along porphyry margins, and localisation gold within these shears

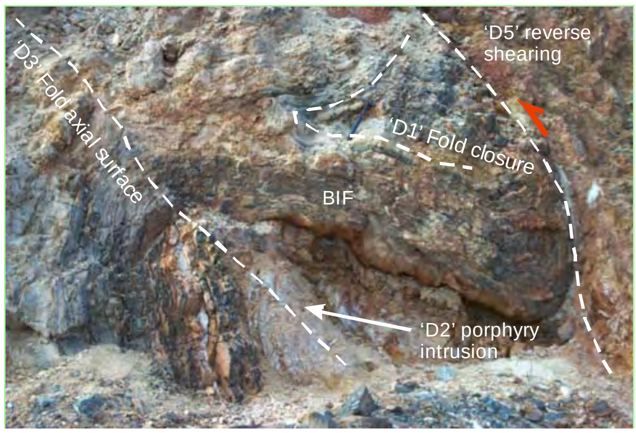
Westralia

The Westralia pit is the largest in the Mt Morgan's district, and it produced nearly 1 million ounces of gold (Vielricher et al. (1998). Gold is hosted by thin steeply NE–dipping BIF and porphyry dykes, in a mainly tholeiitic basaltic sequence. Talc–chlorite schists after komatiite occur in the west and lamprophyre dykes are also common in the pit (Beardsmore, 1999).

Westralia is close to the Celia Shear Zone and it provides a likely proxy for its kinematics. The structural event history appears complex (Fig. 23), but is simply reflecting a pulsing orogen. Eleven discrete stages have been identified on the basis of overprinting relationships. The early history, Stage 1 to Stage 8 inclusive, involves west–directed thrusting and dextral faults switching with extension under a predominantly E–W contractional event (see photograph). This behaviour may be a function of how thrusts propagate (surging and/or post motion relaxation?). Gold timing is poorly constrained within this complex contraction–extension interplay. Stage 9 sees a switch to NW–SE contraction, with minor sinistral strike–slip faults, and was followed by typical late collapse with development of normal faults and flat–lying crenulations.

Figure 23: Summary structural stratigraphy of Westralia





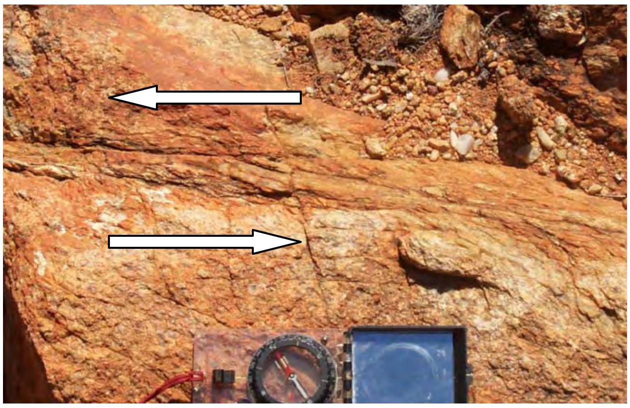
View north of complex folds and thrusts at Westralia

Key Point:
Good example of the complex interplay between contraction and extension (rapid switching) in a thrust régime

Bernie Bore

The Murphy granite is a High–Ca type granite located ~20 km NW of Mt Morgan's district. It lies on the western margin of the Mt Margaret batholith, in proximity to the Celia Shear Zone. Details of the structural history of this site may be found in Blewett et al. (2004b). The emplacement age has not been determined, but from age–constrained granites with a similar chemistry, it is likely to be about 2660 Ma (Dave Champion, pers comm. 2003). The oldest stage of deformation at Bernie Bore is a well–developed steeply dipping schistosity in greenstone country rock. The granite is deformed by a strong shallowly-dipping mylonitic foliation (see photograph above) that is interpreted to have developed during extension (as interpreted elsewhere in the granites). The stretching lineation plunges gently to the SE. If features at Bernie are a proxy for movements on the Celia Shear Zone, then a dextral–normal movement is inferred at this time. The mylonitic fabric steepens as the fault is approached, consistent with a normal component on shear on this fabric (and similar in style and geometry to the S-C like architecture observed in the seismic data—see later). The last stage of deformation was minor NW–trending sinistral strike-slip faults with decimetre-scale offsets.

Yarrie



The Yarrie Monzogranite is a little deformed High high-field-strength granite (High-HFSE) that was dated at 2714±21 Ma (Black et al. in press). The site is located at a series of minor abandoned gold mines (Byer Well which is 15 km SE of Porphyry mine), and are part of the so-called Wallaby Line (Swager, 1995). Mineralised zones are associated with narrow (1-3 m wide) sinistral shear zones (see photograph right) that strike NNW and have shallow north-plunging stretching lineations (Blewett et al., 2004a). Much of the host granite is only weakly deformed at this site and deformation is strongly partitioned into narrow high-strain zones.

Swager (1995) described a similar foliation and lineation throughout the pluton, and also steep contact parallel foliations with down-dip lineations. He also suggested that contraction was ENE-WSW oriented, but is interpreted here (and by Blewett et al., 2004a) as NW-SE.

Porphyry

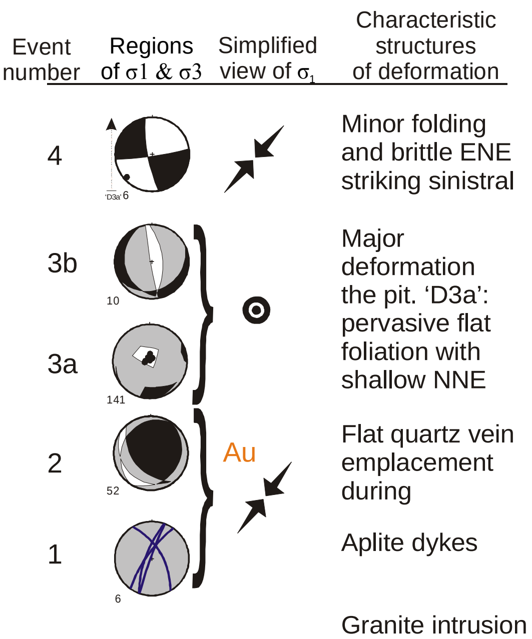
The Porphyry deposit is hosted by the Porphyry Quartz Monzonite pluton, a 2-3 km wide by 4.5 km long pluton dated at 2667±4 Ma (Hill et al., 1992). An age of 2657±8 Ma has also been determined and the interpretation here is that the older age is likely to be influenced by inheritance (as it acquired by SHRIMP 1 without cathode-luminescence).

Gold is hosted in the Porphyry and Million Dollar shear zones, which dip 20-25° to the east, and are 1-20 m in width. The shear zones cut the eastern intrusive contact with andesitic volcanic rocks, with the Million Dollar shear zone around 350 m structurally above the Porphyry shear zone. The highest gold grades occur as en échelon lenses in narrow mylonitic zones up to 10 cm thick that 'step-up' the shear zone (Allen, 1987; Weatherstone, 1990). The Porphyry (1936-1943) and Million Dollar (1984-1989) mines yielded 480 kg and ~4000 kg of gold respectively.

Allen (1987) was not confident in determining the kinematics of the shears, although he suggested a component of sinistral reverse shear. The S-C-C' relationships of this study clearly demonstrate that the main penetrative mylonitic foliation ('S3') was extensional in origin, with a mostly down to the east and southeast sense of shear. This extensional foliation overprints the main porphyritic granite, a phase aplite dykes and the low-angle auriferous quartz veins. The dykes ('D1') and veins ('D2') were developed during NE-SW oriented contraction, resulting in thrusting of the veins and the en échelon array of lodes.

The extensional event can be subdivided into two discrete stages with σ1 almost vertical (Figure 24). The first stage ('D3a') was manifest as the main low-angle mylonitic foliation, and the second stage ('D3b') was more discrete steely dipping normal faulting. Minor folding/crenulation ('D4'), together with sinistral and reverse (cf. Allen, 1987) faults overprint all earlier fabric elements.

Figure 24: Summary structural stratigraphy of Porphyry



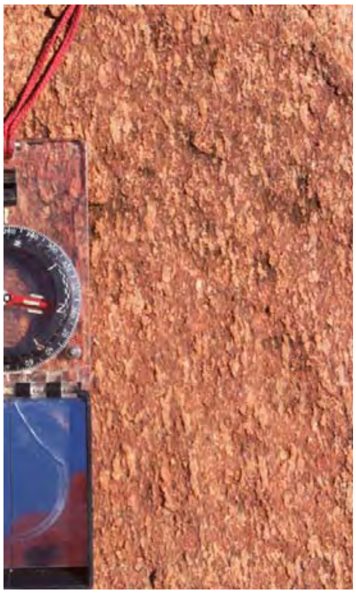
Down to the east extensional shearing (D3a)

Key Point:
Good example of complex interplay between contraction and extension (rapid switching) in a thrust régime

Outcamp Bore

Like Yarrie Monzogranite, the Outcamp Bore Tonalite is a little deformed High high-field-strength granite (High-HFSE) that was dated at 2710±6 Ma (Black et al. in press). The site is located 25 km NNW of the Porphyry gold mine. Deformation has been localised into 1-2 m wide sinistral high-strain shear zones that strike NNW and have a shallow NNW-plunging lineation. The deformation event producing this shearing was likely due to a contraction vector oriented NW-SE. The outcrop is located between the Keith-Kilkenny and Celia shear zones, and probably correlates with similar sinistral movements on these faults and on nearby sites such as Bernie Bore and Yarrie.

Pindinnis



The Pindinnis Granite site is located around 13 km SSW of the Yundamindera homestead. Two phases of granite that are within error have been dated. Fletcher et al. (2001) dated a host phase of High-Ca granite at 2664±5 with a penetrative flattening foliation that dips steeply north and contains a shallow E-plunging lineation. The penetrative foliation overprints a phase of thin pegmatite dykes. Metre-wide, fine-grained, N-S trending High-Ca granite dykes overprint the 'S1' foliation, and was dated at 2667±4 Ma (Fletcher et al., 2001). The age of the foliation is likely to be around 2665 Ma. The event causing this foliation is unknown, but on regional considerations elsewhere, is likely to be extensional.

Minor NE-SW striking ductile sinistral shear bands and later brittle-ductile NNW-trending dextral shears overprint the dyke and are likely the result of ~N-S contractional deformation after 2665 Ma.

Bulla Rocks

Bulla Rocks is a relatively undeformed High-Ca granite that was emplaced at 2660±5 Ma (Black et al. in press), and it intrudes the central part of the Kurnalpi Terrane. The centre of the batholith is located about 20 km NW of the Yundamindra homestead, between the Keith-Kilkenny and Celia Shear Zones. The base of greenstones is complex dome and basin shape with an primary antiformal axis that trends NW and pitches along this vector abut an ENE-trending 'secondary' axis. Gravity data show that Bulla Rocks is a large gravity low, and it is exposed at an erosion level below the base of the greenstones. The cluster of three batholiths in this central part of the Kurnalpi Terrane mark a domical apex between batholiths to the NW and the SE (Fig. 9).

The high magnetic rim of the Bulla Rocks Batholith cross cuts a texturally diffuse (on magnetic data) pluton on its western margin. This magnetically diffuse pluton appears to cross cut the Pig Well-Yilgangi Late Basin (Whitaker and Blewett, 2002). The Pig Well-Yilgangi Late Basin is younger than the maximum depositional ages detritus of 2664±3 Ma and 2664±4 Ma (see Module 2), and is older the Yilgangi monzogranite 2656±4 Ma (see Module 2), and Bulla Rocks 2660±5 Ma.

Deformation at the site observed in this study was limited to minor normal faulting, with down to the north offsets.

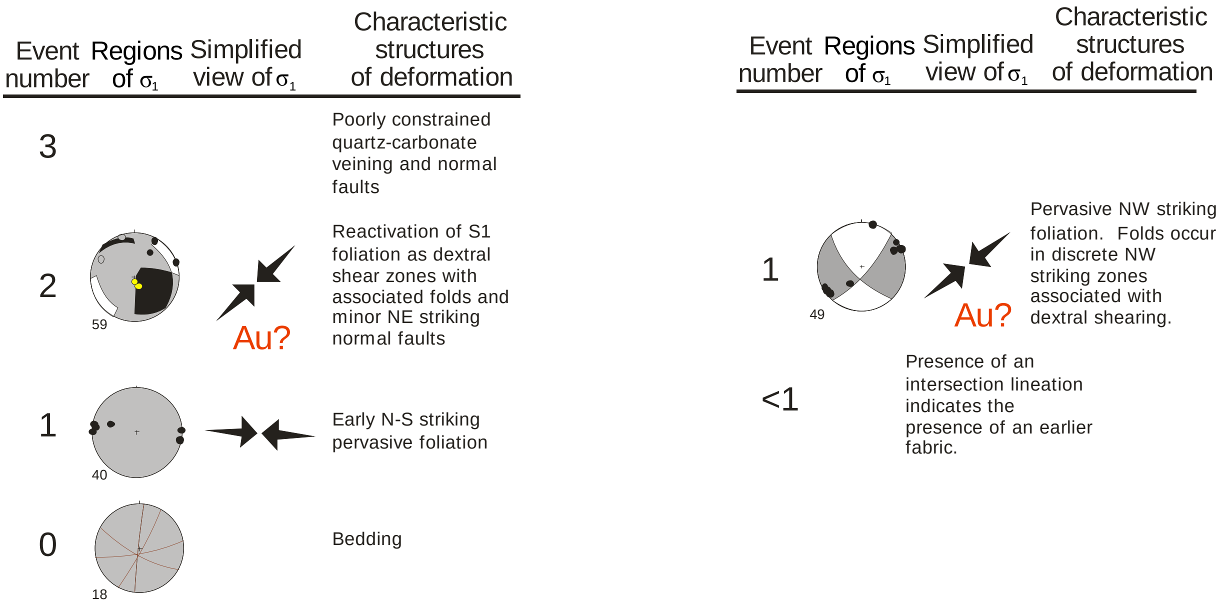
Nambi and Mt Redcliffe

The Mertondale line of deposits includes Mertondale (1 to 5), Mt Redcliffe and Nambi, and they lie along the Mertondale Shear Zone which is up to 500m wide and 65 km long. The Nambi open pit gold mine is a small deposit located on the northern extension of the Mertondale district of deposits. Around 32,000 oz of gold were extracted from Nambi and 58,000 oz from Mt Redcliffe (Fox, 1998). The Mertondale Shear Zone is a splay of (or is cut by) the Keith-Kilkenny Shear Zone to the W and SW, and is located in the centre of a narrow greenstone belt that plunges south.

The Nambi and Mt Redcliffe pits expose highly sheared and altered mafic volcanic, felsic volcanoclastic, and metasedimentary rocks (including carbonaceous slate). Mineralisation is broadly stratabound in two sub-parallel zones, and is localised around the contact between quartz-sericite schist and chlorite schist.

The geological event history (Fig. 25) is characterised by the development of a penetrative foliation that dips steeply and strikes approximately N-S to NW-SE. This foliation is interpreted to be the result of ~E-W contraction resulting in flattening strains. Further deformation is revealed as tight to isoclinal folds (see photograph above) that occur in discrete NW striking zones associated with dextral shearing during NE-SW contraction. This shearing is interpreted to be the mineralising event, and is consistent with the characteristic 'Z-folding' of the local stratigraphy (Fox, 1998). The last events are poorly constrained normal faults and quartz carbonate veins.

Figure 25: Summary structural stratigraphy of Nambi and Mt Redcliffe



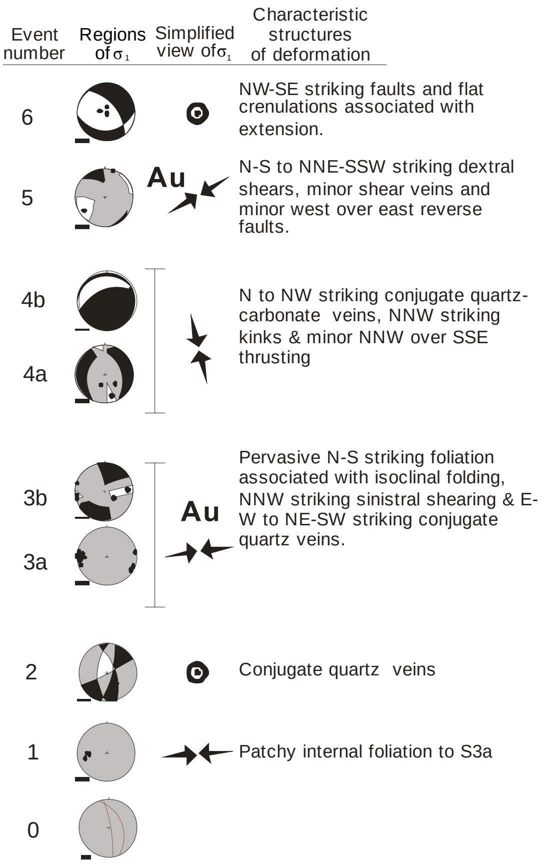
Key Point:
Late-stage dextral gold

Mertondale

The Mertondale group of gold deposits is located 30 km NE of Leonora. Mineralisation is localised along high strain shears at basalt-porphyry contacts in the N-S striking Mertondale 3 & 4 pit and along lower strain shear zones within the E-W striking Mertondale 2 pit (Nisbet & Williams, 1990). Au is associated with quartz, carbonate and silicic alteration. Nisbet and Hammond (1989) and Nisbet (1991) recognised that the area has been affected by two major deformations each related to gold. They described an early sinistral shearing event followed by a dextral shearing event on NNW striking faults. This study supports this result while demonstrating a greater level of complexity in the structural history (Fig. 26).

The structural stratigraphy of the Mertondale group of pits comprises up to main six events (Fig. 26), although this can be simplified into an early stage of ENE-contraction and associated extensional switches and gold, followed by a NNW-SSE contraction, and a return to ENE-WSW contraction (and gold) and final stage of extension. The main penetrative fabric is the 'S3a' schistosity, which is axial planar to isoclinal folds. This 'D3' event was also accompanied by sinistral shearing (*cf.* Nisbett, 1991). The 'D4' stage was low-strain with NNW-SSE contraction, and the system returned to ENE-WSW contraction with dextral shearing and west-over-east reverse faulting. This 'D5' event in the Mertondale group of pits likely correlates with the main gold events and dextral shearing in the Nambi and Mt Redcliffe pits along strike to the north.

Figure 26: Summary structural stratigraphy of Mertondale



'D5' quartz carbonate veining in dextral fault plane. View S at site 4101i.

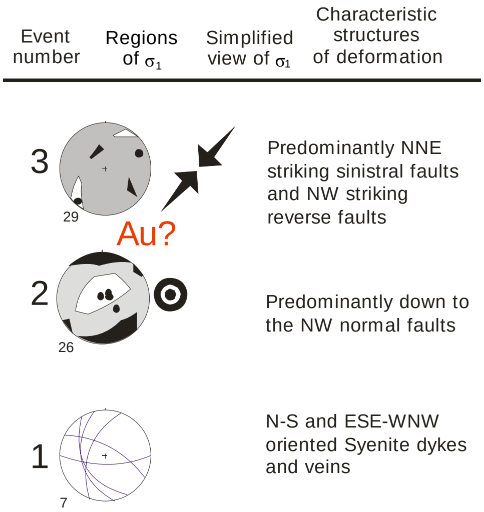
Key Point:
Two gold events associated with ENE-WSW contraction (high-strain) separated by low strain NW-SE contraction

Celtic

The Celtic deposit is located around 5 km north of the Teutonic Bore VHMS mine. It is a small satellite pit supplying gold to the Tarmoola operations further south. It is located at the contact with greenstones and granite/syenite on the western margin of a large granite batholith, adjacent to the Keith-Kilkenny shear zone (Fig. 9). The host rock is a dolerite with sills and dykes of magma-mingled syenite and granodiorite, with well-developed net-vein textures displayed.

There were no obvious pre-granite fabrics developed in the dolerite host rock. Syenite and granodiorite (Mafic-type granite) were emplaced as sills and dykes, with dyke trends mostly N-S and ESE-WNW. The host dolerite and granite were subjected to an extensional event with the development of S-C fabrics and normal faults and shear zones with mostly down to the NW sense of shear. Gold was probably deposited in the third stage, with NE over SW directed reverse faulting and associated NNE-striking sinistral faults (Fig. 27).

Figure 27: Summary structural stratigraphy of Celtic



Top to the SW reverse faulting (thrusting) in the Celtic pit

Extensional S-C fabrics in dolerite

Key Point:
Gold associated with NE-SW contraction post extensional shearing

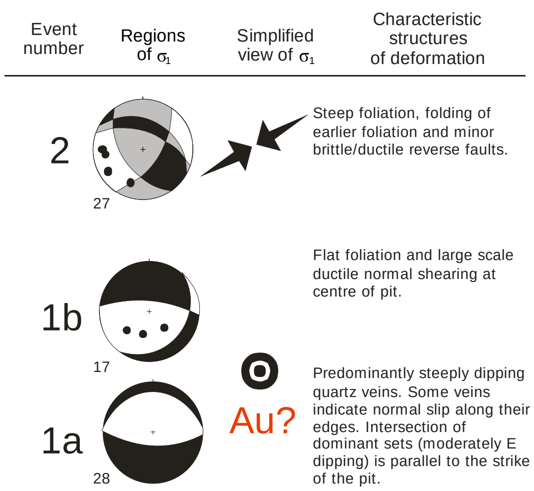
Linger and Die

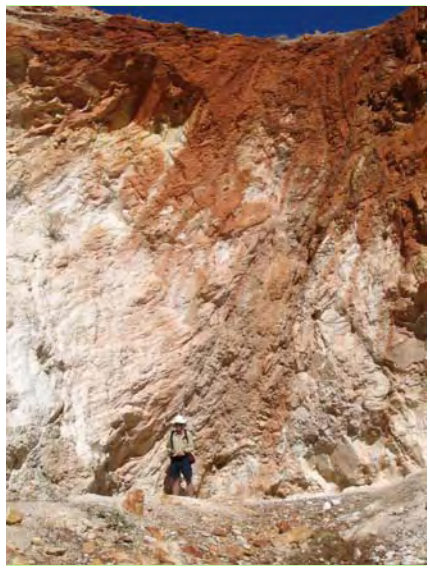
Linger and Die is located 28 km north of Leonora and produced 2000 ounces of gold from 1,400 tonnes of ore from 1897. Mining in the 1980's extracted 2007 tonnes at an average grade of 11.77 g/t; the ore being mined from small pits along the old line of historical workings.

The deposit is located just to the east of the Keith-Kilkenny shear zone. The prominent fabric elements in the pit indicate extensional movements, down-to-the-east, consistent with interpretation of the seismic reflection data further south along strike. Gold appears hosted in quartz veins associated with normal or extensional movements. These veins are overprinted by discrete normal faults that strike E-W and down-throw to the north, and a low-angle foliation. Both normal faults and the attitude of the foliation are consistent with a sub-vertical $\sigma 1$ (extension). The normal faults overprint the shallowly dipping foliation and drag it into steeper attitudes (see photograph). A steep foliation and localised strike-slip faults were developed during local ’D2’ NE-SW contraction, and these overprint the extensional fabric elements and gold (Fig. 28).

Elsewhere along the Keith-Kilkenny shear zone, and the Leonora region in general, extensional deformation and extensional gold is common. The timing of the main ‘D1’ extensional event (and therefore gold) is considered later than Swager (1989) ’D2’, and this extensional event represents a regional collapse across the Eastern Goldfields (see Regional Correlation poster). The contractional event at Linger and Die (local ‘D2’) is interpreted to be equivalent to ‘D3’ in the Swager (1989) terminology.

Figure 28: Summary structural stratigraphy of Linger and Die





Key Point:
Gold is likely extensional and associated with development and deformation of the Pig Well late basin

View east of main shear zone in weathered granite. Foliation drag is concave down, consistent with normal drag down to the north-east on the shear zone. Foliation intensity is greatest within or close to the shear zone

Rainbow

The Rainbow Granite Complex is an undated Low-Ca granite site 100 m east of the greenstone contact marked by the NNW-trending Emu Fault. The oldest Low-Ca granite in the Kurnalpi Terrane is the nearby Donkey Rocks Monzogranite, which has an age of 2650 ± 3 Ma (Dunphy et al., 2003).

The Rainbow Granite Complex is overprinted by weakly developed N-S to NNW-trending ductile dextral shear zones with S-C fabrics and aligned feldspar phenocrysts. The likely kinematics of the Emu Fault post Low-Ca granite emplacement (~2650 Ma?) was dextral. The last event was the development of brittle low-displacement (few cms) sinistral faults that trend ~E-W (Blewett et al., 2004a).

Mullenberry

The Mullenbery Granite is an undated High-HFSE type granite located around 15 km NW of the Meningina homestead. The youngest granite of this type in the Kurnalpi Terrane is the Weebo Granodiorite, which has an age of 2658±6 (Nelson, 1997). Most are older being around 2690 Ma. This is a high-level intrusion with miarolytic cavities common (Blewett et al., 2004a).

The first stage is recorded as a steeply dipping NNW-trending mylonitic foliation with biotite that has rare sinistral kinematic indicators. This penetrative foliation is overprinted by subparallel equigranular granite dykes that are themselves overprinted by E-W trending sinistral shears. These three stages likely were developed during E-W or NE-SW contraction. A switch to ~N-S contraction is recorded during the fourth stage with the development of widespread NNW-trending dextral shear zones (with individual mylonite zones up to 5 cm thick). A return to ~E-W contraction is recorded by WNW-trending sinistral shear zones and associated shallow plunging stretching lineations (see photograph). The final stage is brittle fractures filled with vein quartz (Blewett et al., 2004a).

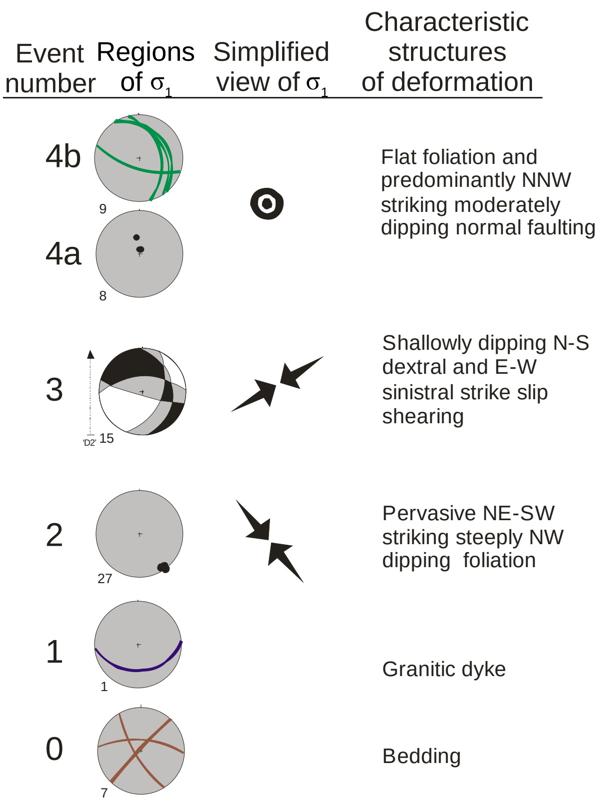
Key Point:
The Emu Fault is inferred to have moved by early flattening and thrusting (?) with a component of sinistral shear, followed by dextral shear, and finally a return coaxial shortening. The extensional movements inferred from map patterns were not observed in the granite sites visited.

Puzzle

The Puzzle deposit is located ~ 5km east of the town of Kookynie, on the NW margin of the Kookynie granite. The granite is a High HFSE-type, and has been dated at <2643 ±14 Ma (GA unpublished data). The granite intrudes pillowed basalts, and Late Basin sediments which include black shales and conglomerates with rounded clasts porphyry clasts (see photograph below)

A steeply NW-dipping pervasive foliation is developed across the pit, and is interpreted to represent a NW-SE shortening event (Fig. 29). The stress field rotated into a stage of deformation that was dominated by NE-SW contraction, and was manifest as N-S dextral and E-W sinistral faults. The final stage resulted in extension and collapse, and was developed as sub-horizontal foliations and normal faults (most down to the NE).

Figure 29: Summary structural stratigraphy of Puzzle



Key Point:
The age of the granite at <2643±14 Ma provides a maximum age for the switch to NW-SE contraction. This is the likely regional 'D4' event.

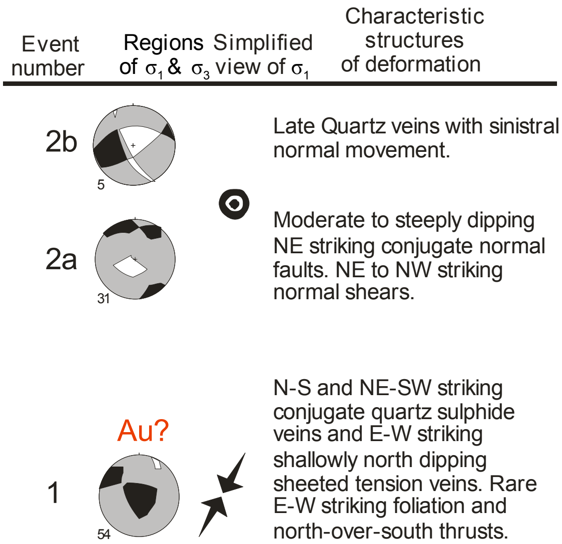
Butterfly

Butterfly is a small, relatively low-grade, gold deposit located approximately 40 km south of Leonora in the Kookynie district. The deposit is hosted by a predominantly fine-grained mafic sequence (pillow basalt and dolerite) on the southern limb of an east-plunging box-fold like syncline.

Mineralisation lies within the ~30º NE-dipping Butterfly Shear from which some 35,000 tonnes @ 7.7 g/t Au were mined in the early 1900's. Subsequent drilling (post mid-1980's) revealed the Shear to be mineralised into several high-grade shoots over a 250 m strike length and a down-dip up to 100 m. Mining achieved a maximum depth of 70 metres below surface, with the deposit containing 190,000 tonnes at a grade of 2.6 grams per tonne for 14,800 recoverable gold ounces. Ore was trucked to Sons of Gwalia for processing.

The structural geology is relatively simple with a series of conjugate NE- and N-striking gold-bearing quartz veins, and associated shallowly dipping extension veins, developed during a NNE oriented contractional event (Fig. 30). Localised north-over-south thrusts overprint earlier developed veins under this régime. A prominent extensional event overprints the contractional foliations and veins. These are both brittle and ductile, with significant foliation drag locally adjacent to discrete normal faults. The earliest stage of extension (‘D2a’) was to the north and south, and later stage (‘D2b’) was extended to the east and west.

Figure 30: Summary structural stratigraphy of Butterfly



View east-northeast of conjugate vein arrays and acute bisector extension vein constraining σ1 to a shallow ~N-S to NNE-SSW orientation.

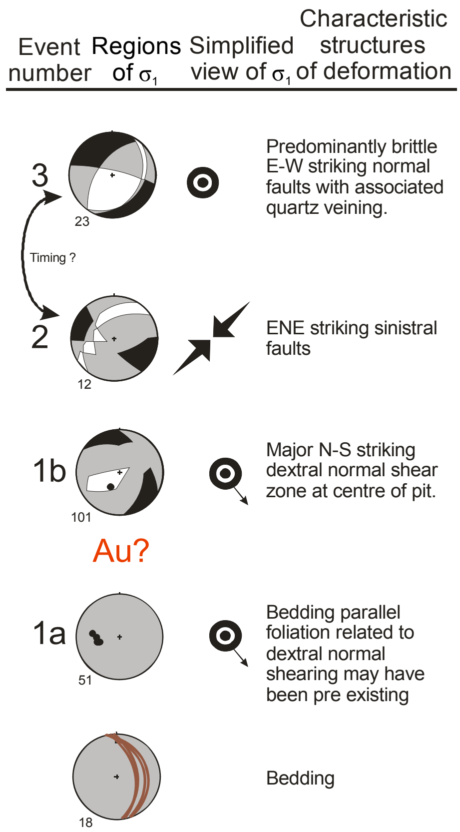
Key Point:
Butterfly lies on the southern limb of a regional E-W syncline and may have developed as a shear-related structure on the Emu Fault during the main NNE-SSW contraction. Regionally, this event is dextral.

Dragon

The Dragon deposit is one of the Mt McClure group of gold deposits located along the western margin of the Kurnalpi Terrane (Fig. 9). The deposit is hosted in a shear zone contact between an ultramafic footwall to the west and basalt and sedimentary rocks to the east. In the Kalgoorlie Terrane granites to the west, Wyche and Farrell (2000) indicated that the main the fabric elements (their S2) was related to the emplacement of the granites. Presumably these fabrics are extensional.

The stratigraphy and shear zones dip moderately to steeply east (Fig. 31). The main foliation is a composite S-C-C' fabric, and it records a dextral-normal sense of shear. The fabric elements comprise an S1b layer-parallel foliation (that may have been pre-existing), that was reworked by the D1b dextral-normal shears. The stretching lineations on the C-planes plunge moderately to the SE, and the S-C intersection lineations and F1b drag folds of the S-planes plunge gently to the NE. The most intense zone of fabric element development is well exposed in central shear, at the contact between the ultramafic rocks and the rest of the stratigraphy. Fine-scaled crenulations have subhorizontal axial planes and gentle fold hinge plunges. Overprinting the main extensional fabric elements are brittle ENE-striking sinistral faults and E-W striking normal faults. The temporal relationship between these two events is uncertain.

Figure 31: Summary structural stratigraphy of Dragon



Down to the east S-C fabrics and drag folds (view N)

General view north of the moderate E-dip of the shear zone

Key Point:
The western margin of the Kurnalpi Terrane is dominated by dextral-normal deformation for the main fabric forming event.

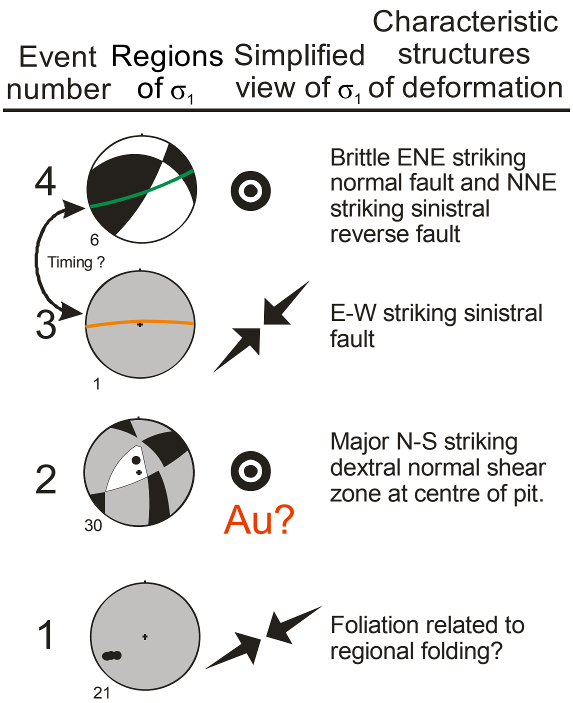
Parmelia

The Parmelia deposit is one of the Mt McClure group of gold deposits located along the western margin of the Kurnalpi Terrane (Fig. 9). The deposit is hosted in steeply E-dipping shear zone within a black shale horizon that has been intruded by porphyries.

The host rocks in the western side are polymict cobble conglomerate with rounded clasts of granite and quartz veins. The main Stage 1 foliation in the pit ('S1') dips parallel to layering, both dipping moderately to steeply to the ENE. Overprinting this main fabric is a Stage 2 N-S striking dextral-normal shear zone with associated S-C fabrics (see also Fig. 31). The genesis of the 'S1' fabric is uncertain, it may be related to the regional folding/tilting of the stratigraphy (Fig. 31). However, in the Kalgoorlie Terrane granites to the west, Wyche and Farrell (2000) indicated that the main the fabric elements (their S2) was related to the emplacement of the granites. Presumably these fabrics are extensional.

The later stages of deformation were brittle and involved NE-SW contraction, although this was not a pervasive stage (Fig. 32). The last stage was likely extensional (collapse), although the robustness of these last events is not particularly high.

Figure 32: Summary structural stratigraphy of Parmelia



Steeply E-dipping shear in black 'shale' at centre of Parmelia pit

Key Point:
The western margin of the Kurnalpi Terrane is dominated by dextral-normal deformation for the main fabric forming event.

Kalgoorlie Terrane

The Kalgoorlie Terrane is the westernmost terrane of the Eastern Yilgarn, and is bound to the east by the Kurnalpi Terrane and to the west by the Youanmi Terrane (Southern Cross). The bounding faults are the Ockerburry and Ida-Waroonga Fault Systems respectively. Other major faults include the Kunanalling, Bardoc, and Perseverance, Koonoonooka, and Mt McClure Fault Systems (Champion, 2005).

The structural synthesis is based on detailed studies of twenty one mines (Gwalia, Harbour Lights, Victor Well, Trevor's Bore, Jasper Hill, Tarmoola, Slaughter Yard, North Well, Bannockburn, Yunndaga, Mt Owen, Fairyland, Sunrise Birthday, Lawlers East, Daisy Queen, Genesis, Glasgow Lass-Hidden Secret, Redeemer, North Cox, Bottle Creek and Bellevue) and thirteen granite sites (Pink Well, Poison Creek, Pepperil Hill, Wilbah, Mars Bore, Waroonga, Turkey Well, Riverina, and Top Well). The undated Anderson and Marshall Creek granites are 'internal granites' intruding the supracrustal sequence. The granites at the Daisy Queen and Lawlers East deposits are high-level intrusions into the base of the Lawlers greenstone belt. The other sites are 'external granites', and represent lower structural levels than the 'internal granites' and their host greenstones, so the deformation in these granites is 'reflected' in the deformation in the greenstones. The linkage between the structural stages of the 'internal' and 'external granites' provides valuable constraints on the distribution of strain through the crust.

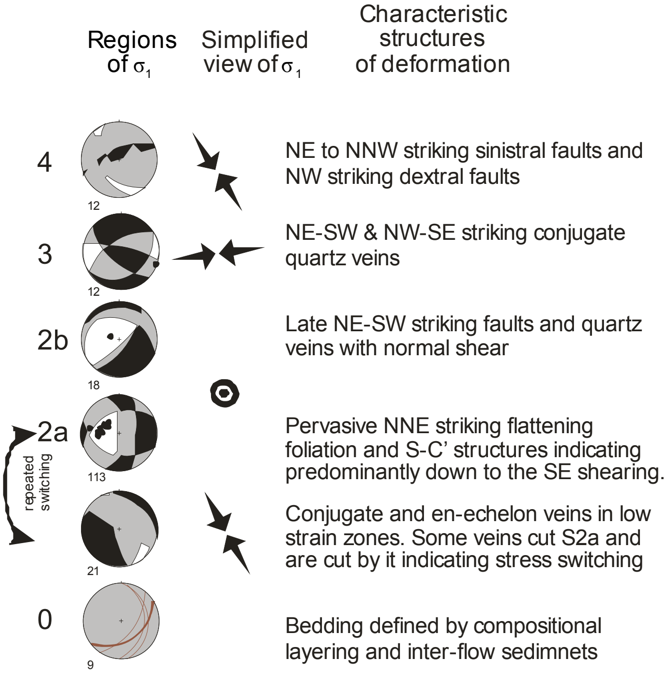
Mine and granite sites were selected on the quality of outcrop (although this was sometimes less than brilliant) and at a range in structural level and position with respect to major shear zones and regional folds. The 01AGSNY1 regional seismic reflection line from the *pmd**CRC only intersects the easternmost margin of the terrane, and provides geometrical and kinematic constraints on the Ockerburry Fault System.

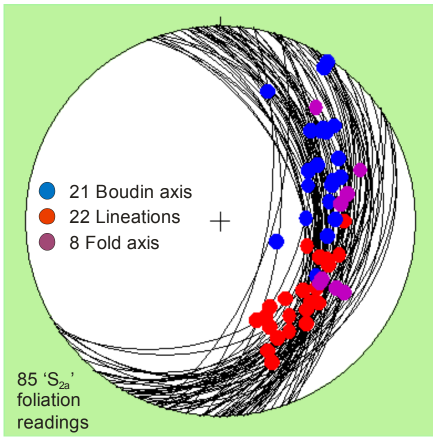
Gwalia

The Gwalia Au deposit is located 3 km south of Leonora. It is situated along the Ockerburry Shear Zone locally know as the Sons of Gwalia Shear Zone (SGSZ) recognised by Williams et al. (1989) as a east dipping extensional detachment separating amphibolite and greenschist facies rocks.

The SGSZ is expressed as a pervasive foliation ('D2a') within the Gwalia pit (Fig. 33). The deposit is hosted in a sequence of tholeiitic pillow basalts and minor interflow sediments. The ore body lies within the 'S2a' foliation in a chlorite sericite schist with numerous quartz carbonate veinlets (Coates, 1993) and plunges down to the SE parallel to the lineation. 'D2a' folds of early quartz-carbonate conjugate veins locally display cleavage refraction through the veins, but most have an axial planar S2a fabric. Some folded veins have conflicting senses of vergence indicating that the axial planer foliation contains a strong flattening component of strain. Across the pit, the 'L2a' boudins and fold axes rotate towards the stretching lineation suggesting the presence of sheath folding related to normal down to the SE shearing along high strain zones. The main shearing fabric also hosts a crenulation in the microlithons between the P-domains. Consistent S-C and C' planes at a range of scales indicate extensional tectonic mode. Extension is clearly recorded in the 01AGSNY1 seismic line across the pit, and the strong reflectivity extends eastwards for >5 km, suggesting that this region is a broad-scale extensional margin to the terrane.

Figure 33: Summary structural stratigraphy of Gwalia





Plot of all 'S2a' foliations overlain with all 'D2a' lineations, boudins and fold axis.

Key Point:
The dominant fabric elements are extensional and evidence for E-W contraction (classical D2) is either totally overprinted or was never developed and this has largely been an extensional system.

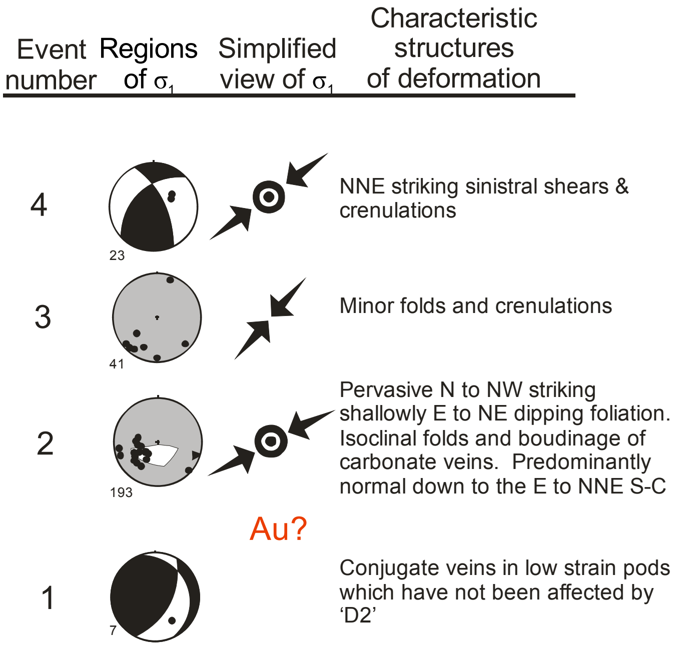
Harbour Lights

The Harbour Lights deposit was discovered in 1896 and is located ~5km north of the Sons of Gwalia deposit. The deposit is hosted in an east-facing sequence of amphibolite, komatiite, and High-Mg basalt that was intruded by granite to the west. Metamorphism in the host rocks is mid to upper greenschist facies, with retrogression along shear zones.

Down-to-the-east extensional shear zones host gold in altered basalt and talc schist. Ore forms as shoots that plunge steeply (parallel to the pronounced lineation) and others have a shallow plunge. Extensional deformation post-dated peak metamorphism. Extensional deformation was progressive, with many sites showing a succession of events. Typically the main foliation is an S-C composite fabric that cuts and is cut by veins (Fig. 34). Veins and the foliation become progressively folded, transposed and boudinaged, and overprinted by steep east-down C’ shear bands. Minor crenulation cleavages and strike-slip faults (with or without veins) overprint the dominantly extensional fabric elements. Stretching lineations are dominantly down-dip and fold hinges pitch towards the linear trend suggestive of the development of sheath folds. Boudin axes are generally orthogonal to the lineation.

Like other deposits along the eastern margin of the Raeside Batholith, there is little evidence for significant E-W contractional events (classical ‘D2’). The main fabric and lineation, as well as gold mineralisation, are post-’D2’ (classical contractional) events. The northern and eastern margin of the Lawlers Anticline has a similar geometry/history (see later). Seismic reflection data through Sons of Gwalia and the Pig Well Late Basin, as well as the post peak metamorphic timing of extensional shearing, support this hypothesis.

Figure 34: Summary structural stratigraphy of Harbour Lights



Down to the east extensional shearing of flattened and boudinaged quartz veins

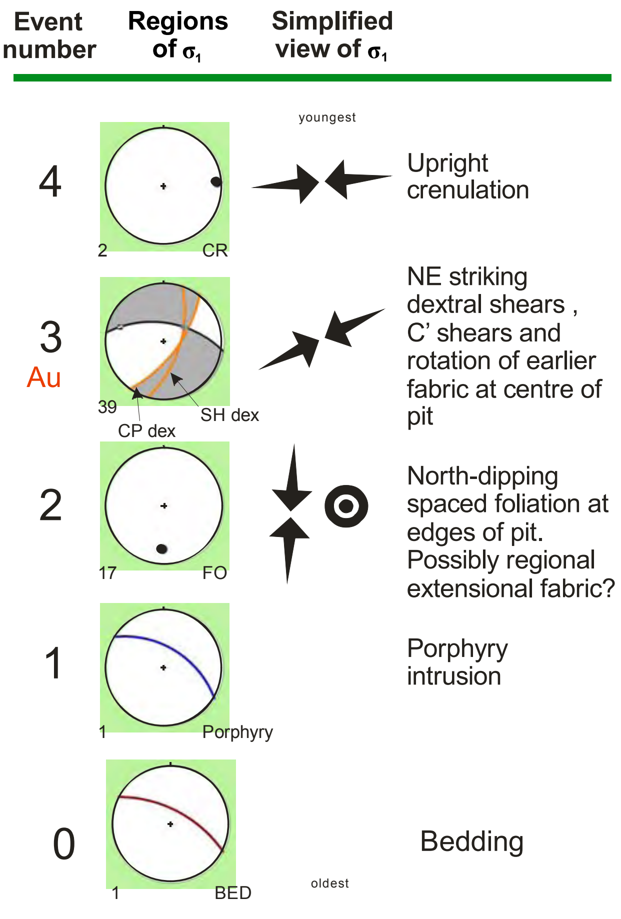
Key Point:
The dominant fabric elements are extensional and evidence for E-W contraction (classical D2) is either totally overprinted or was never developed and this has largely been an extensional system.

Victor Well

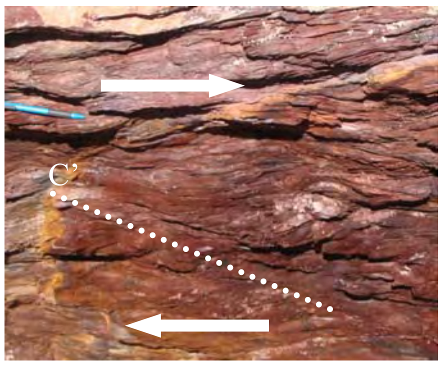
Victor Well is a small pit 3-4 m deep and 25 m long, located 17 km NNW of Leonora. Au is hosted in a quartz-vein bearing N-S striking dextral shear zone which cross cuts the regional E-W trending fabric and lithology (basalt and porphyry) observed in the walls of the pit. The first penetrative fabric overprints the porphyry and basaltic host rock and its genesis is uncertain. It is possible that the fabric represents the regional extensional fabric that wraps around the Raeside Batholith.

The 'S2' E-W trending fabric has been rotated into the central 'D3' dextral shear zone, which is characterised by a pervasive shear fabric and the development of cross cutting C' dextral shear bands (see photograph). This dextral shearing stage is associated with quartz veins and the gold event, and is interpreted to be related to NE-SW regional contraction (Fig. 35). The last stage of deformation is recorded by sparsely developed steeply dipping N-S trending crenulations.

Figure 35: Summary structural stratigraphy of Victor Well



General view south of Victor Well pit. The width of the dextral shear zone is limited to the narrow slot in the pit's centre.



View west dextral S-C-C' kinematic indicators

Key Point:
Dextral overprint of probable extensional fabric on northern margin of the Raeside dome. The dextral shearing is the gold event, and related to regional NE-SW contraction.

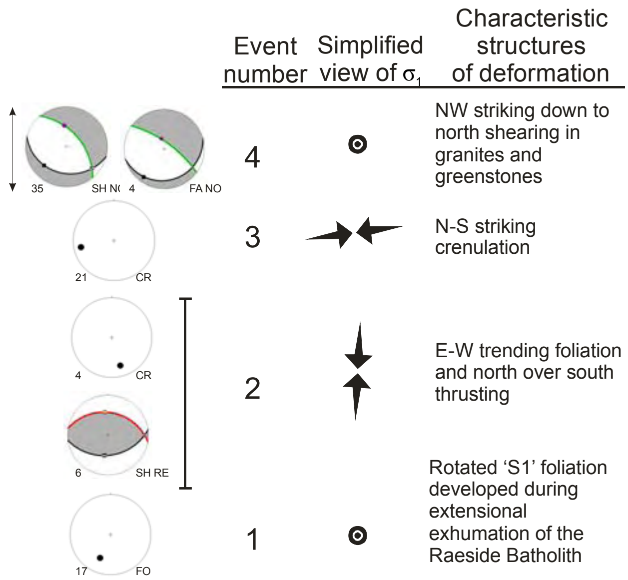
Trevor’s Bore

Trevor’s Bore is a small satellite pit of the Tarmoola operations on the NE margin of the Raeside Batholith. Granite is exposed on the southern flanks of the pit and intensely foliated chlorite schist after basalt is exposed on the northern flanks.

Four stages of deformation are recorded in the pit (Fig. 36). The first stage of foliation is a likely extensional fabric that has been overprinted by Stage 2 N-over-S thrusts and reverse faults. The stage 3 fabrics comprise a locally intense steeply dipping N-S crenulation cleavage. The final stage is a series of ductile spaced extensional shear bands that down-throw the sequences to the NE (see photograph). The stage of gold in this pit is unknown, but is likely to be during stage 1 extension, on the basis of a similar relationship to Harbour Lights, Tower Hill and Gwalia (see above).

This site is along ‘strike’ of the extension-dominated shear systems of the Leonora area. On this basis, it is probable that the main penetrative extensional fabrics in the pit (local ‘S1’), are part of the same event. Unlike Leonora to the south, this site has steeply E-dipping crenulations (‘S3’) that were likely developed during E-W shortening. A question of regional correlation is raised as to whether these ‘S3’ fabrics are the regional or classical ‘D2’ (Swager, 1997), or are they equivalent to Swager ‘D3’?

Figure 36: Summary structural stratigraphy of Trevor’s Bore



View south east of Stage 4 extensional shear bands in granite

Key Point:
N-S contraction follows extension with thrusting and crenulation of ‘S1’

Jasper Hill

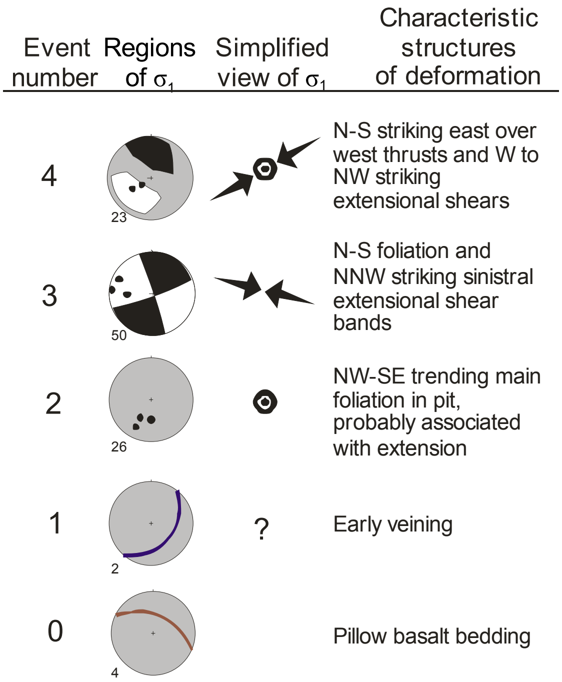
Jasper Hill is a small satellite pit for the Tarmoola operations, and is located near the NE margin of the Raeside Batholith. The deposit is hosted in a sequence of variably deformed mafic rocks, locally displaying pillow structures in the low-strain domains. The sequence is right-way-up, younging to the NNE.

The main penetrative foliation (WNW-striking) in the pit ('S2') is shear fabric with S-C microstructures indicative of sinistral shear. A well-developed moderately N-plunging lineation is associated with this fabric. This is likely to be the stretching lineation as the S and C plane intersection plunges south. The kinematics of this Stage 2 event suggests oblique sinistral slip during approximately NW-SE contraction. This Stage appears to be responsible for much of the flattening at this locality.

More difficult to reconcile is the nature of the earlier Stage 1 fabric. This foliation is best expressed in the eastern and western pit walls, were a well-developed foliation dips moderately to steeply to the NE or NNE (Fig. 37). The early veining is associated with the pillow lavas, and many are developed around pillow rims. The relations between original layering (pillows) and the veins become transposed into parallelism with large amounts of flattening strains.

The final stage of deformation occurred following a switch to NE-SW contraction, with the development of N-S striking east over west thrusts and W- to NW-striking extensional shears (Fig. 37). The timing of gold deposition at this locality is unknown.

Figure 37: Summary structural stratigraphy of Jasper Hill



View NE of pencil intersection lineation between Stage 2 and Stage 3 foliations.

Key Point:
Sinistral shearing is uncommonly (regionally) strong in this location, and is a function of NW-SE contraction following an extensional event

***Tarmoola*[4]**

The Tarmoola gold deposit is located ~30 km north of Leonora, on the northern end of the Raeside dome. The deposit is 'cored' by a trondhjemite with diorite dykes dated at 2667±8 Ma (Lance Black unpublished GA data). This study has elucidated five phase of deformation, and as with other deposits in the area, has a significant component of extensional deformation (see Swarneki, 1988; Vearncombe, 1992).

The first fabric(s) are developed in the greenschist facies mafic and ultramafic rocks that host the trondhjemite. These 'S1' fabrics are preserved as steeply dipping, E-W striking, penetrative foliations. Their interpretation is uncertain. The second event involved the development of extensional shear planes (C' bands) and a low-angle foliation, especially well developed in the talc schists. Sigma 1 was subvertical during 'D2' with extension off to the NE and SW. Gold is hosted in conjugate sets of en échelon quartz veins (see photograph below). Maximum vein thickness is obtained at an angle to the acute bisector of the conjugate vein pairs.

Modelling by Duuring et al. (2001) showed that the presence of a pre-existing foliation facilitated shear failure, and this is provided by the 'S2' fabric. Contraction is well constrained with σ1 oriented just south of east and σ3 oriented orthogonal to this. Some gold veins are deformed by a second extensional event, that locally rotated conjugate vein arrays (see photograph). This 'D4' extensional event involved mostly down to the south transport with σ1 again vertical. The final event was the development of north-over-south thrusts and shear veins, together with more steeply dipping sinistral faults and ~N-trending normal faults.

View north east of a principal Au-bearing shear vein and associated veins developed during 'D3' thrusting overprinted by 'D4' extensional shear zones (4122). Movement sense is down to the north east. Host lithology is talc schist.

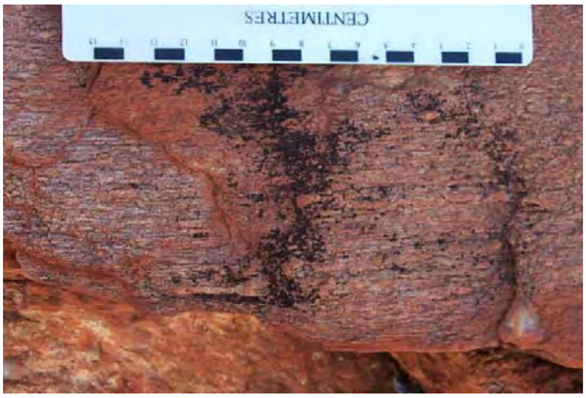
Key Point:
This study suggests that Tarmoola's deformation history is not particularly different to the regional events found in the area. The structures at Tarmoola show good evidence for switching between extension and compression.

[4] See the Tarmoola poster in the Appendix (it is too large to display here)

Anderson

The Anderson Granite is an elongated Low-Ca type granite pluton located to the west of the Ockerburry Shear Zone. No age has been established for this pluton, but typically ages of ca 2640 Ma have been determined for these types of granite (Cassidy et al., 2003).

The southern margin of the pluton is highly attenuated, and this is reflected in the well-developed L-S tectonite at outcrop scale. The main fabric is an intense L-S tectonite (defined by quartz ribbons with a shallow plunge and a NNW-SSE strike (see photograph right). No kinematic indicators have been determined. A narrow fine-grained biotite fabric overprint the quartz ribbons at an acute angle. The final stage is localised brittle tension gash-like veins.



Marshall Creek

The Marshall Creek granite is a High-Ca type granite located to the west of the Ockerburry Shear Zone. No age has been established for this pluton, but typically ages of ca 2665 Ma have been determined for these types of granite (Cassidy et al., 2003).

The main deformation event recorded at this site is a shallowly dipping mylonitic foliation (see photograph) with a well-developed SE-plunging lineation. The genesis of these fabric elements is unknown, however on the basis of regional considerations it was likely an extensional event. The second stage of deformation is recorded by localised NE-trending dextral faults. These likely developed during NNW-SSE or N-S contraction.

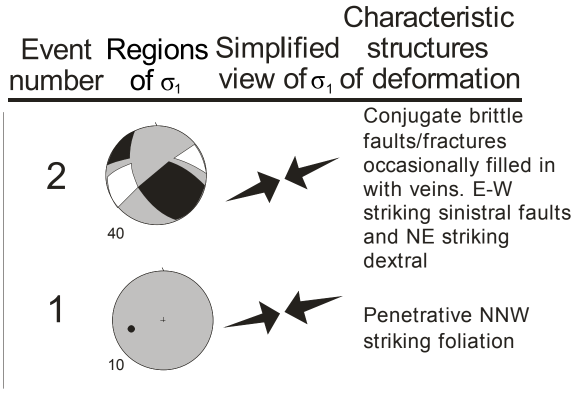
Key Point:
Although undated, these granites provide likely timing constraints on extension as the younger Low-Ca granite does not record it. The intensity of the L-S tectonite illustrates the intense partitioning of strain into the region of the younger Anderson Granite following this extension.

Slaughter Yard

The Slaughter Yard is a small pit at the northern end of a series of N-trending pits (including North Well and Bannockburn) along the western margin of the Leonora greenstone belt. The pit is located ~12 km north of Bannockburn, and is deeply weathered with limited access. The lithologies are mostly fine-grained pale-coloured phyllite and schist.

The structural geology of Slaughter Yard is relatively simple, with a penetrative NNW-trending (steeply E-dipping) foliation (see photograph below) overprinted by conjugate brittle faults with local vein infill. Both the ductile and more brittle deformation stages are interpreted to be the result of ongoing ENE-WSW contraction (Fig. 38). The region here appears to be one of flattening. Gold was presumably deposited during the later brittle stages in the various vein-filled faults.

Figure 38: Summary structural stratigraphy of Slaughter Yard



View SE of main penetrative 'S1' fabric in the phyllites

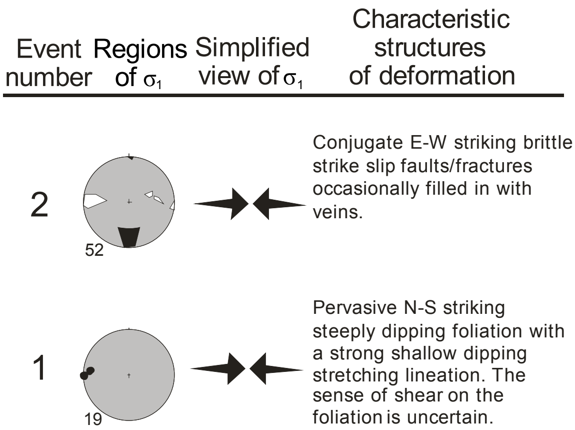
Key Point:
A simple deformation sequence implying ongoing flattening during ENE-WSW contraction.

North Well

The North Well pit is the central deposit along the Bannockburn to Slaughter Yard line of workings. The pit is located ~5 km north of Bannockburn. The pit is less weathered than the Slaughter Yard workings and the pit appears to be located along the sheared contact between a siliceous polymictic conglomerate and fine-grained basaltic rocks. Conglomerate clasts are well rounded and comprise porphyry and metamorphic detritus.

The structural geology of the North Well pit (like Slaughter Yard to the north) is relatively simple. The main fabric in the pit is a penetrative L-S tectonite in the conglomerates with clasts being stretched out to 10:1 (see photograph). This lineation plunges gently (10-15º) to the south, and is parallel to elongated and stretched minerals. There is little evidence for the sense of shear on the main fabrics. The stepped nature and deformation of passive markers such as flattened porphyry clasts suggest dextral. However, top to the west shearing is indicated by S-C relationships (see photograph), with the S-C intersection pitching parallel to the main shallow south-plunging stretching lineation. This implies some component of transpression with a coupled dip-slip (reverse) and strike-slip (dextral) kinematics. A tightly constrained E-W contractional Stage 2 event is recorded by reduction of the conjugate brittle faults (Fig. 39). Sigma 3 at this stage was likely shallowly plunging to the south (parallel to the stretching lineation), consistent with a strike-slip component to the regional stress field.

Figure 39: Summary structural stratigraphy of North Well



View south of S-C relationships suggest top to the west shear

View east of intense flattening of clasts in polymictic conglomerate

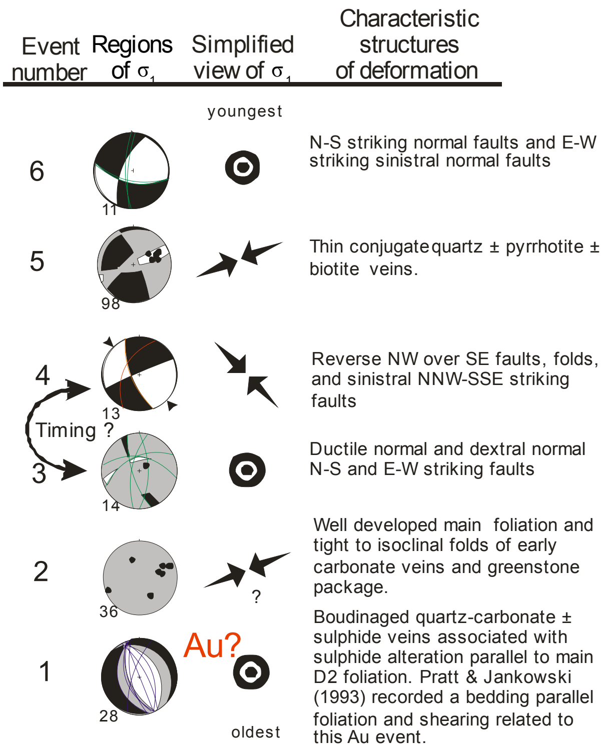
Key Point:
A simple deformation sequence implying dextral transpression and intense flattening during E-W contraction.

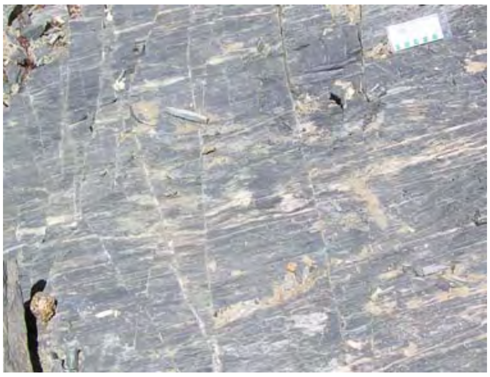
Bannockburn

The Bannockburn Au deposit is located 67 km NW of Leonora. It is situated half way between the Bardoc and Ockerburry shear zones, and is the southern pit in a N-S line of workings at the western side of the Leonora greenstone belt. Gold is located in folded quartz-carbonate-arsenopyrite-chlorite-biotite lodes hosted within metamorphosed intermediate and high-magnesium basalts and minor quartz-carbonate -pyrrhotite veins (Pratt and Jankowski, 1993). The major structure has been inferred to be a NNW-SSE trending syncline.

The main penetrative fabric in the pit is associated with isoclinal folds and intense flattening. Examination of oriented drill core shows that the main fabric has extensional kinematics. Gold is interpreted to be early in the sequence of events and is associated with boudinage (similar to the Leonora deposits?). Although the timing of the Stage 3 and Stage 4 is unknown, it is likely that extension dominated the early history up to the switch to NW-SE contraction at Stage 4. The Stage 4 event comprised reverse faults with transport to the SE, and sinistral faults that trend NNW-SSE. If these styles of structures are correctly coeval, then local σ1 was likely NW-SE oriented (Fig. 40). The change to ENE-WSW contraction is well constrained by numerous conjugate vein and fault pairs. These faults were associated with quartz-biotite veins. The final stage saw a collapse of the system with brittle-ductile normal faults developed.

Figure 40: Summary structural stratigraphy of Bannockburn





Conjugate veins and faults in the west wall of the pit

Key Point:
One of the few pits in which the type sequence of timing events is observed:1. early foliation forming ENE-WSW compression, 2. exte sion, 3. NW-SE compression, 4. ENE-WSW compression.

Twin Hills

The Twin Hills site is located SW of Leonora in the centre of a batholith. The oldest phase of High-Ca granite at the site has been dated at 2803±3 Ma (Dunphy et al., 2003), providing a maximum age for all deformation stages (Blewett et al., 2004a).

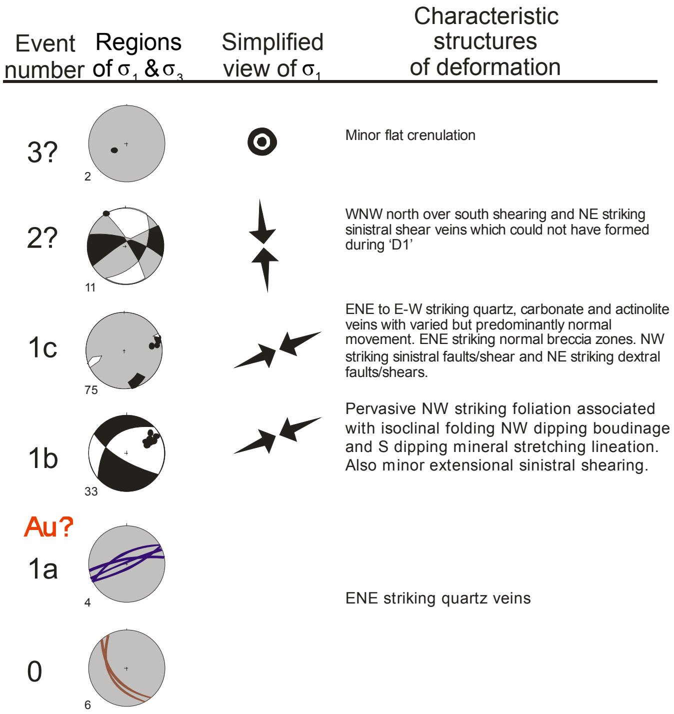
As with other granite sites, Twin Hills has a prolonged history of deformation and magmatism, with increasing embrittlement towards younger stages. The first stage elements comprise steeply E-dipping gneissic foliation with a weakly developed subhorizontal lineation. The original attitude and mode of generation of this early fabric is unknown. Two stages of aplite and pegmatite dykes overprint the gneissic fabric. A weak N-S trending fabric of unknown affinity overprints the dykes during the second stage. Rare dextral mylonitic shear zones also strike ~N-S (see photograph right). During the fourth stage, a series of spaced and locally intense ductile sinistral shear zones were developed synchronous with the emplacement of NNW-trending granitic dykes. This change from dextral to sinistral reflects a likely switch in palaeostress from NE-SW to NW-SE contraction. The fifth stage is recorded by brittle dextral faulting. Two more stages of brittle faulting overprint all fabric elements.

Yunndaga

The Yunndaga gold deposit is located ~6 km south of Menzies along the northern part of the Bardoc tectonic zone. The deposit is hosted by clastic sedimentary rocks and carbonaceous shale, along with a central dolerite-gabbro dyke, which is a chlorite schist locally. Gold was mostly mined from a quartz-carbonate vein along the pit centre, which is the western dolerite-sedimentary rock contact. Alteration in the dolerite includes quartz, biotite, arsenopyrite, and pyrrhotite (Morey et al., 2007). Actinolite and quartz define alteration along margins of ENE-striking extension veins in the chlorite schist.

Two major contractional events (’D1’ and ‘D2’) and a late extensional event (’D3’) deformed the area (Fig. 41), with gold associated with the first event(s). The main fabric (’D1’) elements were developed under a horizontal ENE-WSW contraction, with $\sigma 3$ plunging very shallowly to the SE. Up to five separate ‘phases’ of deformation have been recorded for the ‘D1’ event (see poster in Appendix 3). These are considered to be progressive or punctuated events that developed all under the same resolved stress. Quartz dominated veins were developed at every phase or stage of this ‘D1’ event, however it is not known if they are all gold bearing. Morey et al. (2007) described the main mineralised zone to be overprinted by the main penetrative fabric, suggesting this was developed as a shear vein during ‘D1a’ deformation.

Figure 41: Summary structural stratigraphy of Yunndaga



View west of Stage 1b isoclinal folded veins and actinolite alteration in chlorite schist

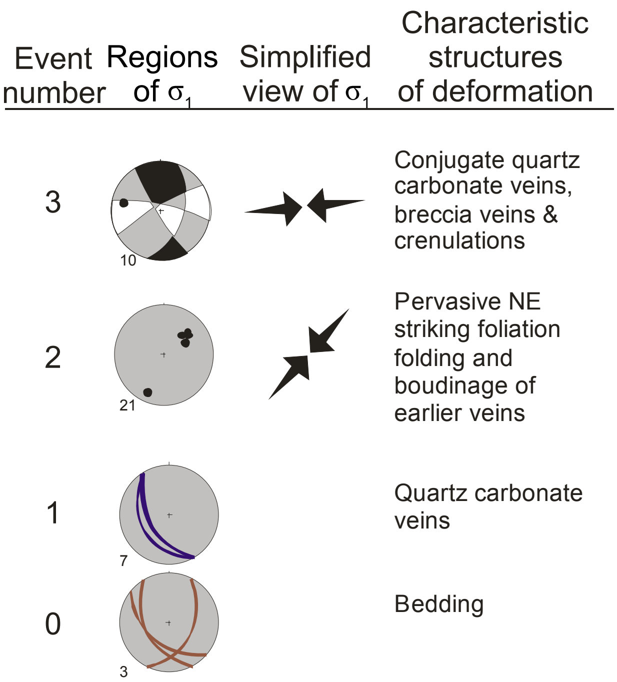
Key Point:
Complex successive overprinting relationships suggest that despite episodic deformation, the regional stress field was relatively constant during the ENE-WSW contraction.

Mt Owen

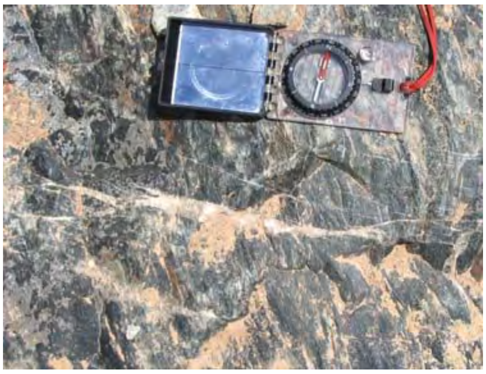
Mt Owen is a small pit located on the NW outskirts of the township of Menzies. It is an unremarkable pit developed in basalts, sediments, and talc-rich mafic/ultramafic rocks. Actinolite is a common mineral that is both aligned as a lineation or random as laths on the main foliation plane. The pit is near the Bardoc Fault System, which dips to the west.

The first stage of deformation is the emplacement of a set quartz-carbonate veins that dip moderately to steeply to the SW. These are overprinted by the main Stage 2 penetrative foliation, which was associated with flattening and boudinage. The main fabric dips moderately to steeply to the SW. The Stage 2 fabric likely developed during NE-SW contraction, and was overprinted by sets of conjugate quartz-carbonate veins and associated faults and crenulations. These more brittle to semi-ductile Stage 3 structures resolve a palaeostress to be approximately E-W oriented (Fig. 42).

Figure 42: Summary structural stratigraphy of Mt Owen



View west of fine crenulations associated with Stage 3



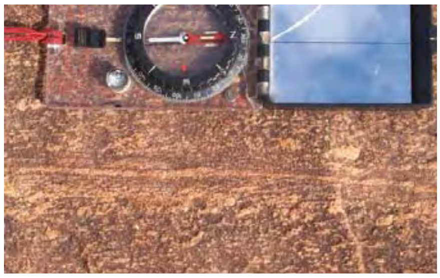
E-W contraction inferred for conjugate veins during Stage 3 contraction

Key Point:
The Bardoc Fault System dips to the west and records contraction from the northeast and east.

Pink Well

The Pink Well granite is a High-Ca type granite, located close to the Bardoc Fault System about 50 km SE of Lawlers. It has a young age of 2652±5 Ma (Lance Black unpublished GA data) for this type of granite.

The site is dominated by N-S oriented dextral shearing, with Stage 1 mylonite zones overprinted by leucogranite dykes, that themselves host a NNW-trending foliation. Ongoing E-W contraction is recorded by semi-ductile conjugate NE-trending dextral and NW-trending sinistral shears (Blewett et al., 2004a). The final stage of deformation is recorded by N-S dextral shears (see photograph right).



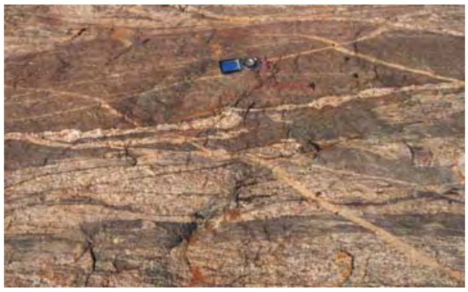
Poison Creek

The Poison Creek granite is a very complex multiphase site. No age constraints exist for the site, which is located close to the Old Agnew Road around 25 km SE of Lawlers.

The first five stages of deformation to be observed (Blewett et al., 2004a) could be interpreted to have developed during approximately E-W contraction. Evidence for extensional events within this was not found, but unravelling the high degree of complexity at this site is an immense challenge (see photograph). Throughout this period of deformation, at least 8 different phases of granite or pegmatite were emplaced into the deforming host High-Ca type granite protolith.

This period of inferred E-W shortening was terminated by a Stage of N-S sinistral shear zones with associated fine-grained granite dykes emplaced within the shears. More wide-spread NNW-trending sinistral shear zones overprint these earlier dykes and shears, both suggest a period of switch to NW-SE contraction.

This stage of possible NW-SE contraction was terminated by the emplacement of further granite dykes, which host a strong foliation, perhaps related to the widespread folding about NW-SE axes of favourably oriented (NE-trending) dykes, and flattening of unfavourable oriented (NW-trending) fabric elements.



At least three more phase of granite, aplite, and pegmatite intrude the site and some are associated with NNW-trending dextral brittle faulting.

Key Point:
Granites were emplaced episodically in a complex series of events that are commonly co-axial. Many of these subtleties may be 'lost' or unrecordable in the pits

Fairyland

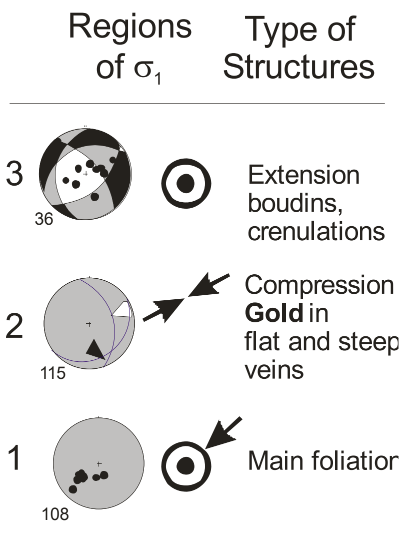
The Fairyland deposit is located 12 km east of Lawlers on the eastern limb of the Lawlers Anticline. Au is localised along a NE striking corridor associated with biotite alteration of the predominantly basalt and dolerite stratigraphy. Black shale also occurs, with unusual geometrical relationships to the basalt and dolerite. These relationships suggest that the shale has been utilised as zones of shearing. Ore grade gold is localised along shallow S- to SE- dipping veins which cut the major fabric.

The main penetrative foliation at Fairyland dips on average moderately to the NE parallel to bedding. The kinematics of this fabric is uncertain. It could have developed during extension or oblique flattening, or developed during NE-SW contraction as a shear foliation or have been rotated by later extensional events. Since the foliation is parallel to bedding with a down dip foliation which regionally radiates away from the Lawlers Anticline (Beardsmore, 2002) it is most likely that the foliation is an originally extensional foliation however may have been reactivated during vein emplacement associated with the D2 event.

With regards to the veins all but the steep veins could have formed in the same stress field during ‘D2’. Other ‘D2’ structures include conjugate veins, sinistral and dextral faults. The steep Au veins are either ‘D2’ veins re-oriented during ‘D3’ by folding/normal folding or may be earlier or later extensional veins like the early extension Au veins at Sunrise Birthday.

The stress inversion using P-T dihedral for ‘D2’ fabric elements has tightly constrained compression to a NE-SW orientation (Fig. 43) illustrating how apparent disparate structures can be related to the one statural event. Sigma 3 is resolved to plunge gently to the SSE, perhaps reflecting a transpressional component to the shortening (*cf.* Beardsmore, 2002).

Figure 43: Summary structural stratigraphy of Fairyland



Boudinage of D2 quartz vein and normal shearing along the limb of larger crenulations. View SE of an inclined surface, vein dips shallowly to the NE

Key Point:
Despite quite seemingly disparate fabric elements, many can be correlated into a single ‘D2’ event with NE-SW contraction.

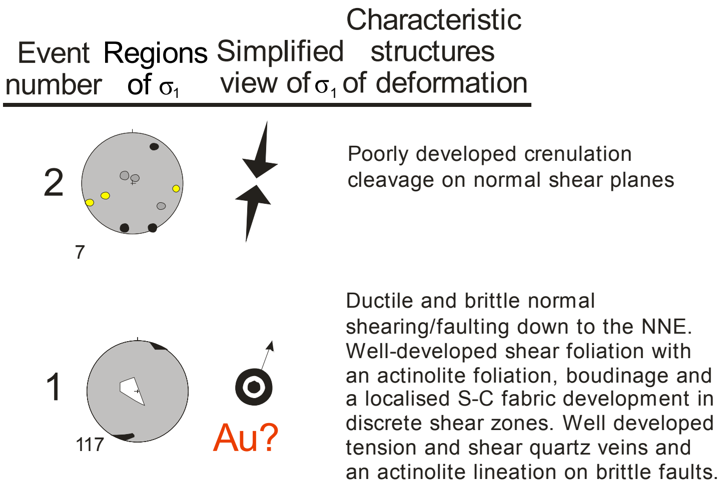
Sunrise-Birthday

The Sunrise-Birthday pit is located 7 km NNE of Lawlers, and was the site of some of the original discoveries in the district. The open cut pit produced around 30,000 oz, grading 3.76 g/t. (Beardsmore, 2002 and references therein). Sunrise-Birthday lies on the Cascade Shear which strikes WNW across the NE limb of the Lawlers anticline, with moderately to steeply NE-dipping gabbro (Wildcat Gabbro) and talc-chlorite schist.

Relationships in the pit are crucial for understanding the structural evolution of the region. At the surface and immediate environs, the gabbro is sheared into discrete high-strain zones of spaced foliation that dip moderately to the NE. These foliations are superficially similar to the classical 'S2'. However, these fabrics are demonstrably extensional (see photograph), raising serious questions about correlating between sites on the basis of a penetrative NNW-trending foliation (as traditionally done).

The event history at Sunrise-Birthday is resolved into two simple events (Fig. 44). Stage 1 is the development of high-strain extensional shear zones. Gold is hosted in these shear zones that pinches and swell, with the largest areas up to 2 m wide being mined out. In the lower strain domains, the gabbro is cut by apparently more brittle normal faults. The stress inversion on these faults gives consistent resolution of a vertical σ1, and σ3 oriented NNE-SSW (in the movement direction). The shallow west plunge of the lodes probably reflects the boudinage that developed during down to the NNE extension, or S-C intersections on a meso- to macro-scale. Similar geometries are still preserved at Fairyland and at Genesis. The Stage 2 event involved a switch in palaeostress to NNE-SSW oriented contraction. These structures are mainly minor crenulations developed on the Stage 1 shear planes.

Figure 44: Summary structural stratigraphy of Sunrise-Birthday



Extensional Stage 1 S-C fabrics

Key Point:
Classic example of extensional gold and lack of development or preservation of contractional 'D2'

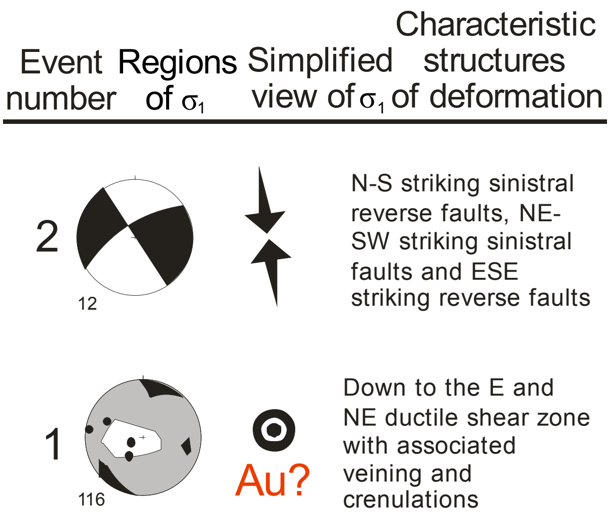
Lawlers East

The Lawlers East pit lies within the 2666±3 Ma Lawlers Tonalite (Fletcher et al. 2003) near the hinge of the broad N-trending Lawlers Anticline. The gold was hosted on the broadly E-W striking brittle-ductile splay of the Caroline Shear (Beardsmore, 2002). This shear was not observed in this study due to access with slope stability and flooding of the pit. Displacement was inferred to have been dip slip (Beardsmore, 2002).

The structural stratigraphy of the pit is relatively simple, with a Stage 1 extensional event responsible for most of penetrative fabric elements, overprinted by a Stage 2 N-S contractional phase. The Stage 1 extension resulted in down to the east and NE movements (similar to Sunrise Birthday). Stage 2 deformation is recorded by sinistral reverse faults that strike mostly NNW-SSE, N-S and NE-SW.

The eastern rim of the pit comprises talc-schist with strong penetrative S-C and flattening fabrics indicative of the Stage 1 extension (see photograph). The tonalite-schist contact is a normal ductile shear zone with a movement down to the NE. If gold was related to this extensional event, then continuation of the mineralisation may occur in the down-thrown hangingwall further east. However, Beardsmore (2002) reported that mineralisation was late-stage related to dip-slip movements on the 'central shear' (normal or reverse sense was not stated). If this is the case, then gold is likely to be Stage 2 and related to reverse movements (Fig. 45). More work is needed to resolve this.

Figure 45: Summary structural stratigraphy of Lawlers East



View SSE of down to the NE Stage 1 extension

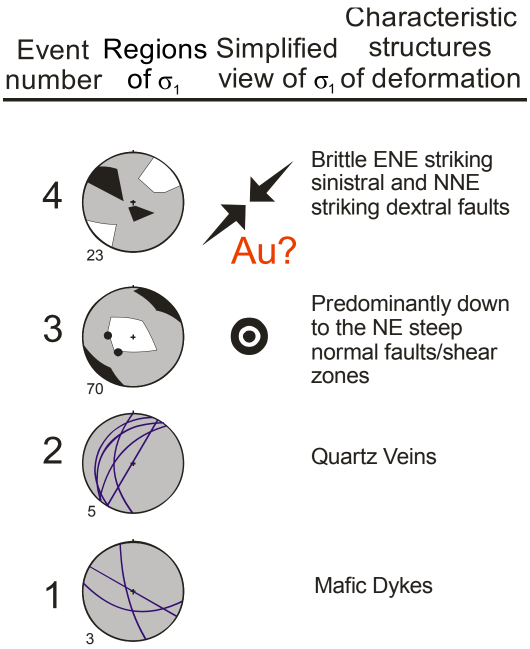
Key Point:
Example of extensional deformation in the centre of the Lawlers Anticline, and lack of development or preservation of contractional 'D2'

Daisy Queen

The Daisy Queen pit lies within the 2666±3 Ma Lawlers Tonalite (Fletcher et al., 2001) near the hinge of the broad N-trending Lawlers Anticline. Beardsmore (2002) reported that the biotite composition varies, with up to 20% in the most melanocratic phases. The intensity of foliation varies too, with a well-developed NE-trending vertical fabric in the centre of the pit associated with the central Caroline Shear. The foliation in the shear is defined by fine-grained biotite (Beardsmore, 2002). The central shear was not visited due to limited access. Sheared pods of leucogranite and metagabbro xenoliths are also present in the pit.

In this study the access available in the pit was dominated by NW-striking extensional faults and shear zones cutting a gently NE-dipping foliation. Many of the quartz veins dip moderately to the NW. Beardsmore (2002) described these NW-trending faults as being cut by the main NE-trending shear zone. Gold deposition is inferred to be related to the last stage of deformation (although it was not directly observed in this study). The extensional foliation (S-C fabrics), shear zones and brittle faults record mostly down to the NE sense of shear (Fig. 46). These extensional fabric elements are overprinted by the final stage of brittle ENE-striking sinistral and NNE-striking dextral faults. These faults and their lineations resolve a contractional palaeostress oriented ~NE-SW.

Figure 46: Summary structural stratigraphy of Daisy Queen.



Low-angle fabric in a dyke with extensional overprint

Down to the NE extensional fault

Key Point:
The dominant fabric elements in the pit are extensional, and do not preserve the previously inferred (classical D2) contraction for the formation of Lawlers Anticline.

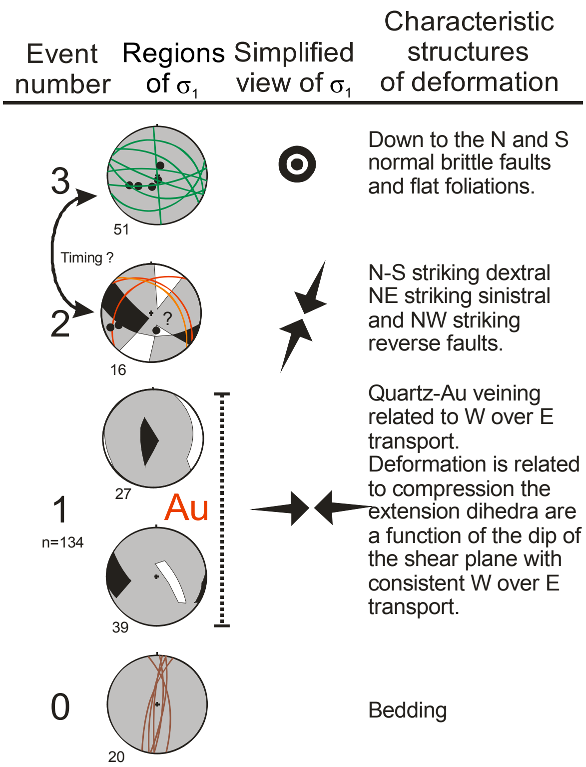
Genesis-New Holland

The Genesis-New Holland pits are located around 12 km NNW of Lawlers and hosted by steeply W-dipping metasediments of the Scotty Creek Conglomerate. The Scotty Creek Basin is a late basin sequence with a maximum depositional age of 2662±5 Ma (Dunphy et al., 2003). Gold veins are restricted to a silicified competent coarse sandstone unit.

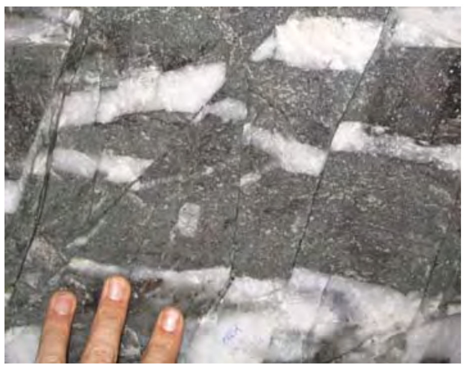
Bedding is vertical N-S striking and W-younging. Tilting of the basin occurred during the tightening of the Lawlers Anticline during regional D5 under E-W compression perpendicular to the present strike of the stratigraphy. Palaeostress inversion from mineralised quartz-carbonate en-echelon sigmoid veins resolved a predominantly W over E transport direction with reverse and normal shear sense. The presence of extensional and thrust kinematics is a function of an eastward roll of the shear plane with a consistent W over E transport direction (Fig. 47). Palaeostress inversions were carried out separately for reverse and extensional P-T dihedra since the case of cutting thrusts into their footwalls is anomalous. Further work would need to be conducted in the deposit to identify the cause of this trend. It should be noted that the thrust and extensional planes are dilational zones with preserved kinematics but with little to no displacements.

Stage 2 deformation is recorded by N-S striking dextral NE-striking sinistral and NW-striking reverse faults. Evidence for this being a separate stage is weak, and it may be progressive from Stage 1 deformation. The Stage 3 deformation resulted in the development of mostly E-W striking normal faults and some low-angle foliations (Fig. 47).

Figure 47: Summary structural stratigraphy of Genesis-New Holland



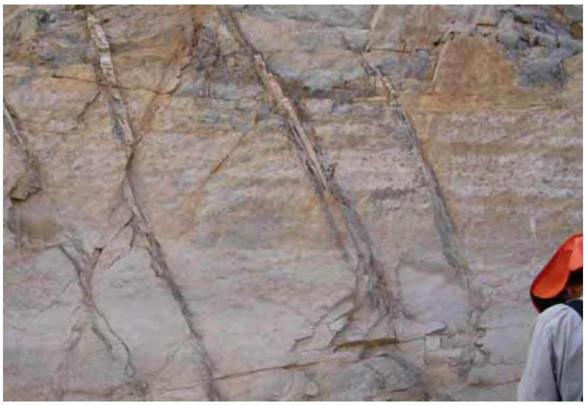
Sigmoidal en-echelon extension veins (view north)



Stage 3 normal faults (view west)

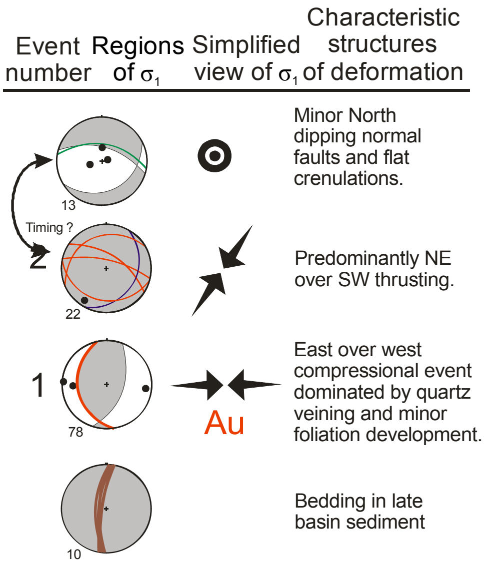
Glasgow Lass-Hidden Secret

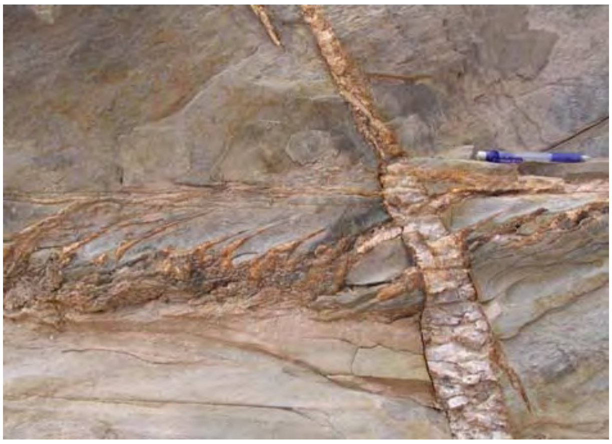
The Glasgow Lass and Hidden Secret deposits are located 10 km NNW of Lawlers, and are hosted in steeply W-dipping and W-younging conglomerate, sandstone and siltstone of the Scotty Creek Basin. Quartz veins are best developed in the competent sandstone units.



Three stages of deformation have been recorded to overprint the steeply tilted bedding. The tilting maybe a function of tightening of the Lawlers Anticline. The first stage of deformation overprinting the tilted sequence occurred during progressive E-W contraction. This resulted in reverse faults and quartz veins, with west over east displacement (see also Beardsmore, 2002), and the development of steep N-S trending foliation (see photograph). This was the mineralisation stage, with veins being subhorizontal extension type at a high angle to bedding, and shear veins parallel to bedding. Stage 2 deformation resulted in NE over SW thrusting and associated extension veins. Rare NW-SE striking crenulations overprint the 'S1' foliation. The final stage was extensional, with the development of minor N-dipping normal faults and subhorizontal crenulations (Fig. 48).

Figure 48: Summary structural stratigraphy of Glasgow Lass





View east of sigmoidal Stage 1 shear veins cut by S-dipping extension vein

Key Point:
Tilting of the sequence under E-W compression is associated with vein hosted Au mineralisation. Once the sequence had been tilted to vertical the competent sandstone unit resolved strain by brittle vertical extension expressed as horizontal veining.

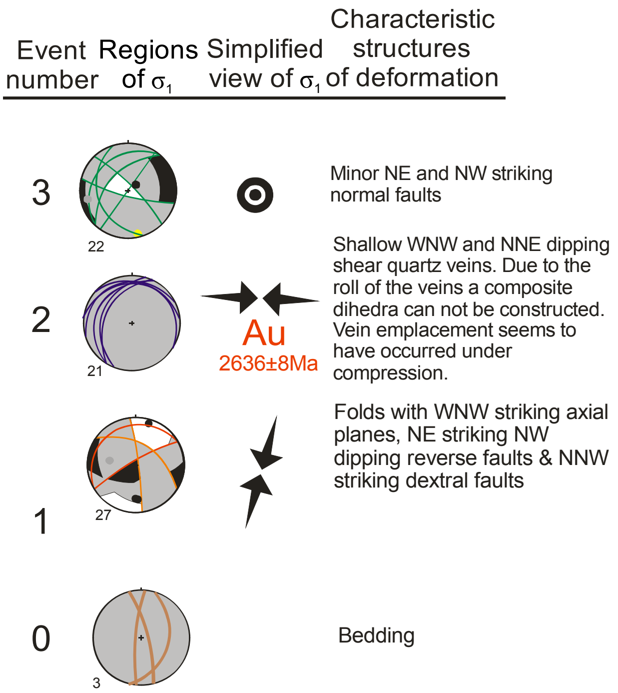
Redeemer

The Redeemer deposit is located 5 km WNW of Lawlers and lies within the Emu shear on the western limb of the Lawlers Anticline. The shear marks the contact between the west-facing Scotty Creek Conglomerate and ultramafic rocks of the Lawlers greenstone sequence (which is steeply E-dipping and overturned). The Scotty Creek Conglomerate is a late basin sequence with a maximum depositional age of 2662±5 Ma (Dunphy et al., 2003).

The structural evolution of the pit has been resolved into three main stages (Fig. 49). The first stage of deformation occurred during NNE-SSW contraction and resulted in the development of folds with WNW-striking axial planes, NE-striking NW-dipping reverse faults and NNW-striking dextral faults. The second stage occurred during E-W contraction and developed shallow WNW- and NNE-dipping quartz shear veins. The veins are curviplanar by their nature, making construction of an accurate composite dihedra difficult (see poster in Appendix 3). However, a general observation of E-W contraction for their genesis can be made. The Stage 3 deformation is general extension with the development of normal faults. Most throw appears to be down to the NE or SW (Fig. 49).

The age of mineralisation (2636±8 Ma: Phung Nugyen pers. comm., 2005) provides a temporal constraint of the Stage 2 contractional deformation. The mineralisation was high temperature with amphibole-plagioclase geothermometry reporting 520±30ºC (de Vitry-Smith, 1994).

Figure 49: Summary structural stratigraphy of Redeemer.



Mullion-like extension veins

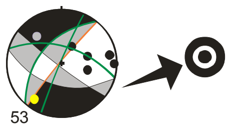
Key Point:
Example of late gold within error of Low-Ca granites, and associated with E-W contraction

North Cox

The North Cox pit (Crusader being the underground operations) is located around 9 km SSW of Agnew on the sheared contact between moderately to steeply W-dipping komatiite (footwall) and tholeiitic basalt (hangingwall) on the western limb of the Lawlers Anticline. The mineralisation plunges 20-30º N, parallel to the main lineation in the area. Gold is hosted in three parallel shear lodes, as well as orthogonal extension veins.

The pit is poorly preserved, and only limited access was possible. The preserved structural history, presumably post tilting and initiation of the Lawlers Anticline, is dominated by extension (Fig. 50). The structures include predominantly NNE- and WNW-striking faults with down to the NW or N movement and associated crenulations. The main foliation is phacoidal locally and preserves extensional kinematics (see photograph right). A large range of crenulation orientations occur in the incompetent ultramafic rocks. Details of the observations are available in Appendix 3 as worked up dihedra (poster) and raw data (Excel spreadsheet).

Figure 50: Summary structural stratigraphy of North Cox.

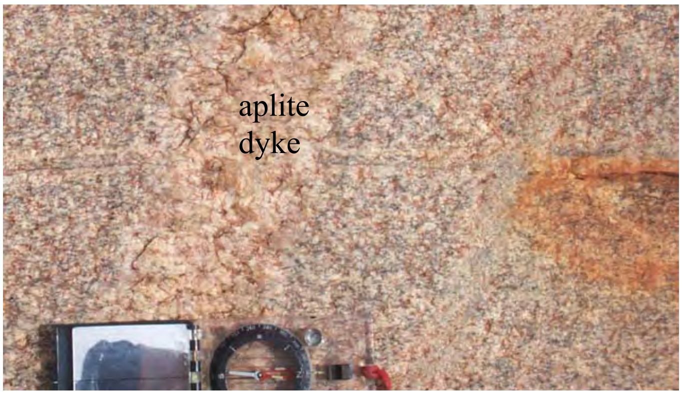
Event number	Regions of σ_1	Simplified view of σ_1	Characteristic structures of deformation
1	 Au?		Predominantly NNE and WNW striking faults with down to the NW movement and associated crenulations. Large variety of orientations in ultramafics

Complex refolded foliation in talc schist (20 cm across)

Key Point:
Despite a complex and apparently chaotic event history, the extensional stage of deformation is ubiquitous, repeatable, and consistent deformation style and sense of shear.

Pepperil Hill

The Pepperil Hill monzogranite is a High-Ca type granite with a crystallisation age of 2678±7 Ma (Lance Black unpublished GA data). The site is to the west of the Bardoc Fault System and appears to mostly record dextral shear and flattening during E-W to NE-SW contraction. The host rock is cut by pegmatite and aplite dykes, all of which are overprinted by a strong steeply dipping NNW-trending mylonitic fabric. Most kinematic indicators favour a dextral shear at this time, however associated folds plunge shallowly to the NNW (Blewett et al., 2004a). The main blastomylonitic fabric is overprinted by E-W trending aplite dykes (see photograph right), that also hosts a NNW-trending fabric (weaker than the main foliation). These aplite dykes are crosscut by brittle-ductile N- to NNW-trending dextral faults and biotite-rich shears. The final stage recorded is brittle low-displacement E-W trending sinistral faults.

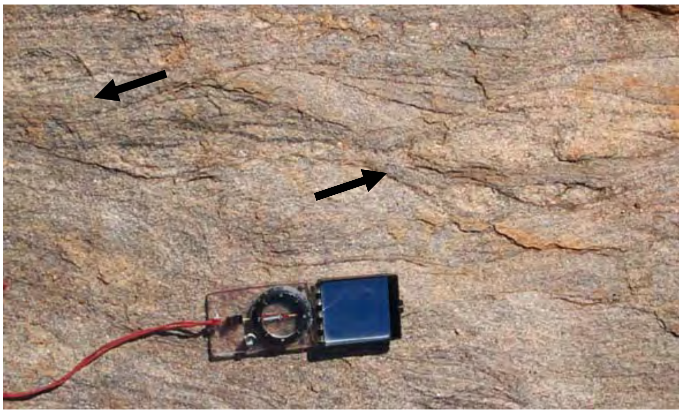


Wilbah

The Wilbah Gneiss is a site close to the Bardoc Fault System, and is a complex site with at least six phases of granite intruding a High-Ca host with an age of ~2675 Ma. The earliest stage of deformation is recorded as foliations in leucosome of the gneiss. Stage 2 resulted in isoclinal folding of dykes (sills?), followed by intense NE-SW sinistral mylonites with a shallow SW-plunging lineation. These are overprinted by intense NNE-trending dextral mylonites. This site was chosen at a field stop in the Kalgoorlie '93 field excursion, and participates could not agree on the kinematics of the main mylonitic fabrics (Dave Champion personal communication, 2002). E-W sinistral faults with pegmatite injection along the fault plane occur next in the sequence. These are likely to be the result of ENE-WSW contraction. A change in stress field to more N-S oriented contraction is inferred from the overprinting NNW-trending dextral shear zones (these shears also host pegmatite dykes). Overprinting all previous fabric elements, and providing a minimum age constraint are a series of Low-Ca granite dykes (see photograph) dated at Mars Bore at 2647±3 Ma (Lance Black unpublished GA data). These dykes are associated with a further palaeostress switch back to NE-SW oriented contraction. The last stages of deformation include weak fabrics in the Low-Ca granite and small offset faults (Blewett et al., 2004a).

Mars Bore

The Mars Bore site is close to the Wilbah Gneiss site, and is hosted by a ~2810 Ma High-Ca granite protolith which was metamorphosed to gneiss at around 2675 Ma (Black et al., in press). The gneissic fabric is folded into isoclinal and transposed folds and these are overprinted by NNW-trending sinistral C' shear bands (see photograph right), together with coeval dykes/sills. The original orientation of these fabric elements is unknown, and they are interpreted as being extensional. The main transposing fabric element is intense dextral mylonites that trend N to NNE, and are likely the function of ~ENE-oriented contraction. Low-Ca aplite dykes strike E-W and overprint these intense dextral shears, and are dated at 2647±3 Ma (Black et al., in press). Ongoing dextral shearing overprinted the Low-Ca granite dykes, which preserve a weak N-S trending foliation. The last stage of deformation was brittle E-W striking sinistral faulting (Blewett et al., 2004a).



Turkey Well

The Turkey Well Gneiss site is close to the Mars Bore and Wilbah Gneiss. The host is a High-Ca granite with extensive melanosome-leucosome layering that is overprinted by two phases of granite/pegmatite and both are deformed into long-limbed isoclinal folds and shallow S-plunging rods. The pavements are overprinted by NNW-trending dextral S-C mylonites (a common fabric element in the region of the Bardoc Fault System). N-trending granite dykes cut across the dextral mylonites, and these are themselves deformed by NNW-trending sinistral mylonites. This stage reflects a rotation of the stress field from NE-SW (E-W?) to NW-SE. The final two stages of deformation record a return to E-W contraction with the development of E-W sinistral faults and associated granite dykes along the shear planes, together with open folding and a weak fabric in these youngest dykes (Blewett et al., 2004a).

Riverina

The Riverina Gneiss site is hosted within the high-grade gneisses in the western region of the Kalgoorlie Terrane adjacent to the Ida Fault System. The main penetrative fabric (like elsewhere along the western Kalgoorlie Terrane) is a NNW- to N-trending dextral blastomylonite. The mylonites overprint dykes/sills that overprint a subtle foliation in the melanosome-leucosome of the host gneiss. The main dextral mylonites are overprinted by E-W trending aplite dykes that are themselves tightly to isoclinally folded about N-trending upright folds. These folded dykes are overprinted by further dextral shears, represented by narrow high-strain ultramylonite bands. All these dextral ductile fabric elements are interpreted to have formed during prolonged ~NE-SW contraction (Blewett et al., 2004a). The final stage of deformation at this site was the development of brittle sinistral faults and quartz veins, probably during WNW-oriented contraction (see photograph above).

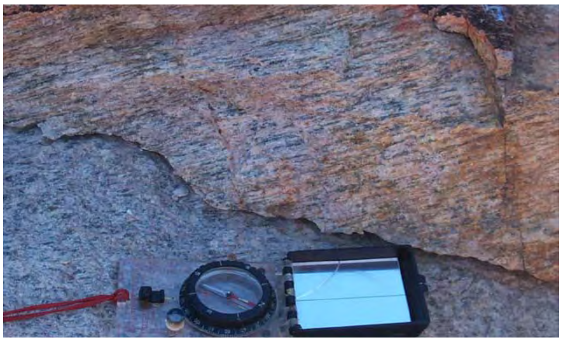
Key Point:
The gneissic sites along the western margin of the Kalgoorlie Terrane following extensional deformation was dominated by dextral shear.

Top Well (Peter's Bore)

The Top Well granite site is located in the western region of the Kalgoorlie Terrane, to the west of the Bardoc Fault System. The main host granite is a High-Ca type which has been dated at 2678±7 Ma (Black et al., in press). The granite has a strong N-trending sinistral mylonitic fabric (see photograph right) that is interpreted to be due to NW-SE contraction (see Beardsmore, 2002: who recognised a late-stage WNW-oriented contraction in the Lawlers region). This main fabric is overprinted by Low-Ca granite dykes that strike E-W. Open N-S trending upright folds overprint these dykes (E-W contraction?). These fabric elements are in turn deformed by NNW-trending dextral shear bands, with subsequent NE-trending sinistral faults and open folds and extension veins. The late-stage contraction is interpreted to be NNE-SSW oriented (Blewett et al., 2004a).

Oberwyl

The Oberwyl granite is an undated Low-Ca type granite close to the Copperfield mine at the western margin of the Kalgoorlie Terrane. The site is located at the southern end of a pluton between the Ida and Bardoc Fault Systems. Nearby Low-Ca granite sites have ages of around 2647 Ma (see Wilbah and Mars Bore), so it is likely that the events described below are younger than this time.



The main fabric element at the Oberwyl granite site is an intense L-S tectonite, with a lineation plunging gently to the SSE (see photograph above). Kinematic indicators are vague and there has been extensive recrystallisation in thin section. Preferred shape orientations suggest a component of dextral shear for this fabric. Aplite dykes that trend NE-SW cross cut the intense L-S tectonite fabric and are themselves overprinted by a weak NNW-trending foliation (that is parallel to the main fabric). Later stage minor ductile NE-trending shears (parallel to the aplite dykes) suggest that contraction at this time was NNE-SSW oriented. Brittle late-stage NW-SE sinistral faults imply ENE-WSW contractional strains (Blewett et al., 2004a).

Waroonga

The Waroonga granite site is located west of the Scotty Creek Basin in the Waroonga Fault System. The structural geology is relatively simple and records dextral shearing and reworking along this western margin of the Kalgoorlie Terrane. The foliation is an intense S-C mylonite with asymmetric tails consistent with dextral shear (see photograph right). The lineations plunge gently north on the steeply W-dipping fabric. The main fabric is overprinted by C' shear bands developed during further dextral shearing. The final stage of deformation is the development of NW-trending upright crenulations, consistent with a prolonged stage of NE-SW oriented contraction (Blewett et al., 2004a). The age of these deformation events is unknown, but the Waroonga Fault System cuts the Scotty Creek Conglomerate, which constrains the dextral shearing to be younger than 2660 Ma.

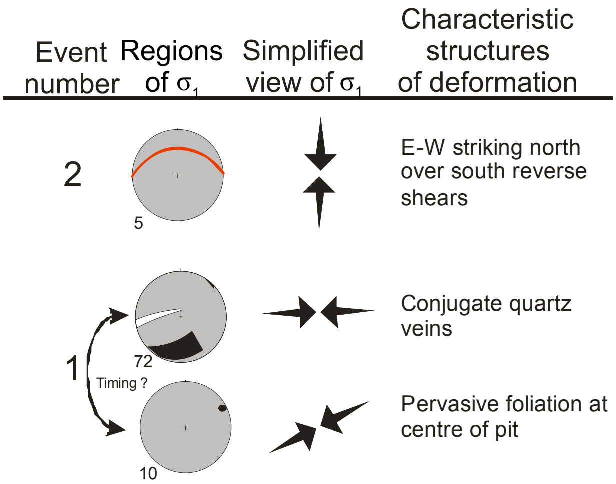
Key Point:
The granite sites along the western margin of the Kalgoorlie Terrane were dominated by dextral shear.

Bottle Tree Creek

The Bottle Tree Creek deposit is located 10 km south of the Copperfield Mining Centre, and is located on the Ida Fault System at the western boundary of the Kalgoorlie Terrane. The deposit is hosted by carbonaceous shales close to a contact between a lower sequence of BIF, mafic volcanic rocks, conglomerate and quartzite, and an upper sequence of mafic and ultramafic rocks with minor interflow sediments intruded by porphyry. Both sequences dip steeply to the east. The mineralisation is hosted by the sheared sulphidic and graphitic 'Emu formation' black shale (Robertson, 2003).

The pit is deeply weathered and access was limited to a couple of ramps. The observed shear in the centre north wall dipped steeply west not east as reported (cf. Robertson, 2003). Most of the structures that were able to be measured were conjugate veins in the east and west walls. These conjugate quartz veins overprint a steeply ENE-dipping penetrative foliation, interpreted to be a flattening foliation during ENE-oriented contraction. The flattening of pillows (see photograph above) becomes progressively more intense into the centre of the pit (together with foliation intensity). These pillows face west. The palaeostress resolved from the Stage 2 veins is approximately E-W and the timing in relation to the penetrative fabric is uncertain. The last stage of deformation is the development of S-directed reverse faults of low displacement (Fig. 51).

Figure 51: Summary structural stratigraphy of Bottle Tree Creek



View north of steeply W-dipping fabrics and shears

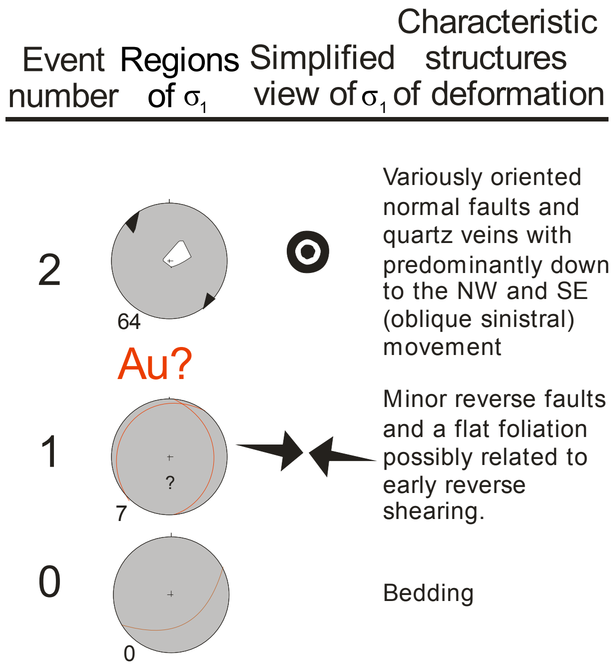
Key Point:
Well constrained flattening during ENE to E-oriented contraction associated with gold on the Ida Fault System.

Bellevue

The Bellevue group of gold mines are located 40 km north of Leinster on the northern edge of Lake Miranda. The mines are hosted by greenstones of the Yakabindie belt, which comprise the Mt Goode Basalt (upper) and the 2736±3 Ma (Lance Black, GA unpublished data) Kathleen Valley Gabbro (lower). The open pits visited include Paris and Westralia. The rock type in both pits is the Mt Goode Basalt, which is fine- to coarse-grained basalt (locally pillowed).

Gold is reported on N- to NNW-trending shear zones and associated thin quartz veins (Liu et al., 2002). The Bellevue shear zone is the main mineralised structure, and it is interpreted as a reverse fault (Fig. 52). The most obvious structural elements in the pit are the late-stage normal faults of variable orientation. These overprint Stage 1 reverse faults that record ~E-W contraction and have down throws mostly to the NW and the SE. The main fabrics in the pits are associated with this Stage 2 extension, with well-developed flattening of pillows and S-C fabrics recorded. The kinematics of the pits are dominantly sinistral normal on these structural elements (see Appendix of Bellevue poster for details).

Figure 52: Summary structural stratigraphy of Bellevue.



Dolerite intruding pillow basalt with normal fault at contact

S-C fabrics with extensional shear

Key Point:
Despite being an old sequence (~2730 Ma) the structural history is relatively simple

Key Learnings and Synthesis

Introduction

The principal question being asked of this study is: what is the difference between the structural history of one terrane versus another? The approach throughout this study (as detailed in the Introduction section) has been to treat each site alone and to build up a structural stratigraphy for the site. The next step was to correlate from site to site within a pit and establish a synthesis of the structural stratigraphy of that pit. The next step was to correlate between pits and granite sites across a terrane, with reference to the regional geological map patterns, geochronological knowledge, geochemical type of granite (cf. Champion and Sheraton, 1997), potential field geophysical images (especially magnetics), and seismic data. The final stage has been to assess how similar or different the three terranes, Burtville, Kurnalpi and Kalgoorlie (Fig. 1), are. The essential conclusion from this work is that there the terranes have experienced a similar structural history, and that events can be matched across time and space for the entire transect of this study. The synthesis banner (Appendix 3.1.1) provides immediate visual comparison of the terranes of the Eastern Yilgarn Craton. The implication of these observations is that the 'Terranes' of the Eastern Yilgarn are not separate crustal block that have been accreted.

One of the major problems with the terrane accretion hypotheses is the recognition that the main terrane boundary (Ockerburry Fault System) between the Kalgoorlie and Kurnalpi Terranes has mostly extensional kinematics (see also Blewett et al., 2002). The boundary between the Kurnalpi and Burtville Terranes (Hootanui Fault System) does have contraction and transpression, and may represent accretion of disparate blocks as evidenced by the variation in basalt geochemistry north of the Turnback Fault System. However even in this case the structural histories of the Kurnalpi and Burtville Terranes are similar.

The following section is a temporal progression from the oldest events to the youngest events.

Deformation event history through time

The D1 event of Swager (1997) was established in the Kalgoorlie and Kambalda area on the basis of stratigraphic repetitions across E-W striking thrusts that were thought to pre-date D2. There has been debate as to the polarity of this event, with both top to the north and top to the south movements inferred. In the central and northern Eastern Yilgarn, many workers have 'failed' to find this D1 event (e.g., Beardsmore, 2000; 2002; Wyche and Farrell, 2000; McIntyre and Martyn, 2005). Furthermore, Blewett et al. (2004) re-examined the map patterns used as the basis for the interpretations in the southern Eastern Yilgarn Craton and were able to show that the structures mapped as 'D1' thrusts cut F2 folds and were therefore younger not older. Similar map patterns occur around Kanowna Belle and the Fitzroy Fault.

In this report, unequivocal evidence for **early** major contraction in a N-S direction is not described. However, a post D3 contraction that was N-S to NW-SE is described. D1 in this report refers to extension, or the De of Swager (1997).

D1: long-lived extension and basin formation

One of the immediate impressions when viewing a geological or geophysical map of the Eastern Yilgarn Craton is the prominent NNW-trending grain. Many workers have interpreted this grain to be a function of the regional contractional 'D2' event, that was thought to be oriented ENE-WSW (e.g., Gee, 1979, Swager et al., 1989, Swager, 1997, Myers, 1997).

The grain is more fundamental than simply a contractional event. The grain is reflected in the broad distribution of the greenstone stratigraphy (Swager et al., 1992; Swager, 1997), the granite types (Champion and Sheraton, 1997), and the Sm-Nd isotopes of the granites (Fig. 53). Figure 53 shows the pronounced NNW-trending grain (Cassidy and Champion, 2004). A 'corridor' of youngest ages corresponds approximately to the western Kurnalpi terrane or Gindalbi Domain (Fig. 1). The isotope map could be interpreted in terms of an ENE-facing extensional rift. This rift and the youngest TDM ages correspond to the youngest arc material (see Module 1). Figure 54 show the general age progression of arcs from ~2715 to ~2680 Ma from east to west in the Kurnalpi Terrane. The oldest sequences are located in the east of the Eastern Yilgarn Craton, possibly representing basement fragments, the rifted shoulders from an older western nucleus (Youanmi Terrane?). These older sequences are exposed in the Burtville Terrane (see Module 1).

The geodynamic setting envisaged is one dominated by ENE-facing extension, with a W-dipping slab (located to the east) driving extension via a roll-back mechanism. Adjustments (shallowing) of the slab likely controlled the location of the active arc (younging to the west), and may have controlled the position of back-arc depocentres (around Kalgoorlie) and their rates of subsidence and accommodation (Fig. 54).

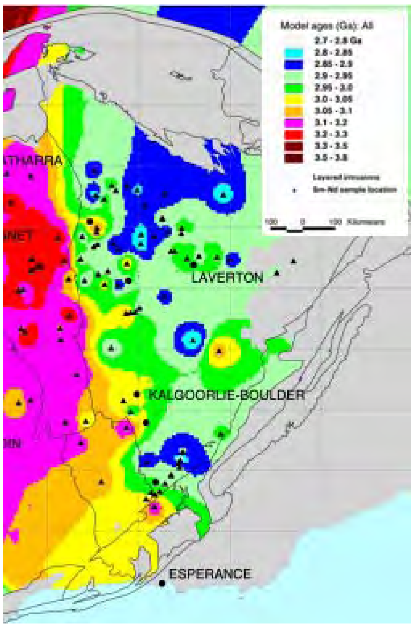


Figure 53: Fundamental architecture of the Eastern Yilgarn is revealed in the crustal residence ages (TDM). Note the NNW-oriented grain marked by the Ida Fault System located around the orange-green colour change. 'Cooler' colours are younger TDM ages. After Cassidy and Champion, 2004).

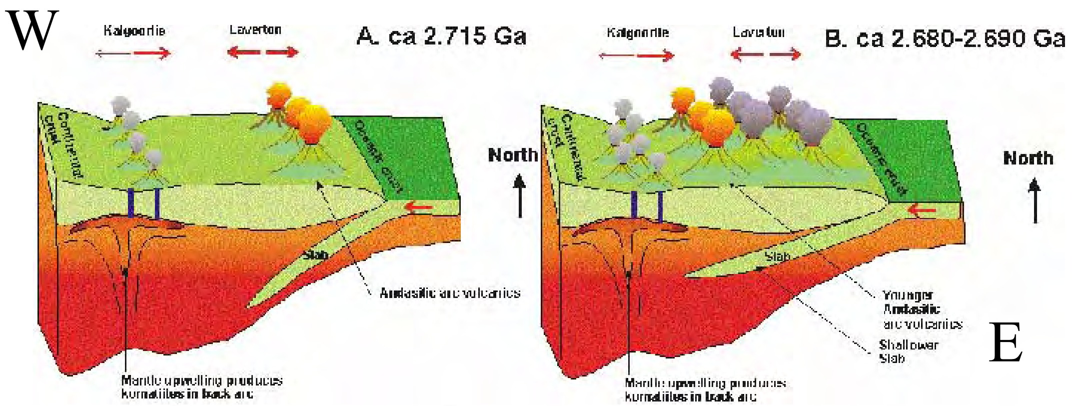


Figure 54: Schematic diagram illustrating NNW-trending tectonic grain controlled by the distribution of arc/backarc rocks. Migration of arcs to west through shallowing of subduction slab (after Cassidy and Champion, 2004)

The distribution of ultramafic rocks (komatiite) in the Kambalda area change markedly across NNW-trending faults (Fig. 55). The inference is that the architecture was extensional, and controlled the emplacement and deposition of the lower parts of the Kambalda sequence at around 2700 Ma (Karen Conners, written communication, 2004).

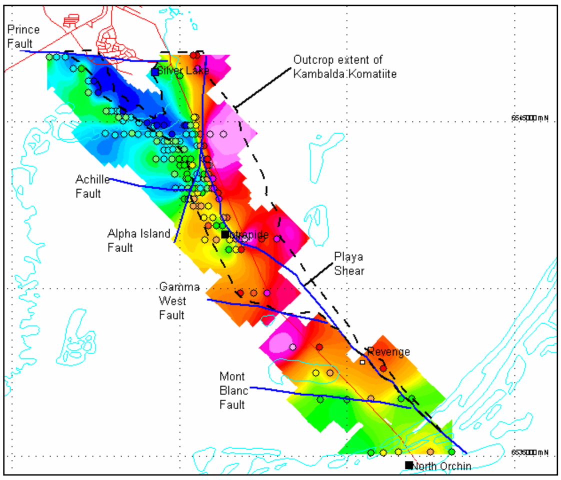


Figure 55: Colour contour map of komatiite thickness variations around the St Ives area (Kambalda), cool colours are thin (200-300 m), warm colours are thick (>1000 m). Note the NNW-grain to the image, reflecting the original extension architecture. Acknowledgements to Karen Conners (St Ives Goldfields).

Swager and Griffin (1990) noted a similar difference in the distribution of the so-called Upper Basalt above the Kambalda Komatiite. For example, across the NNW-trending Lefroy Fault System (Champion, 2004) in the Borrara Domain the Upper Basalt is absent, with the Kalgoorlie Sequence (Black Flags) lying directly upon komatiite. A similar relationship occurs with the distribution of mafic sills, with thick sills present in the Kambalda and Ora Banda Domains, and almost totally absent in the Boorara Domain. Many of these mafic sills intrude the Kalgoorlie Sequence, suggesting that extensional control was exerted with an E-W polarity through the entire greenstone up to (and probably including – see later) the Late Basin Sequences.

Krapěz et al. (2000) described a number of unconformities in Kalgoorlie Sequence, with a prominent angular discordance at around 2675 Ma (Fig. 56). Tilting during extension may account for the development of the topography and therefore high points for erosion and preservation as angular unconformities (as opposed to contractional folding events).

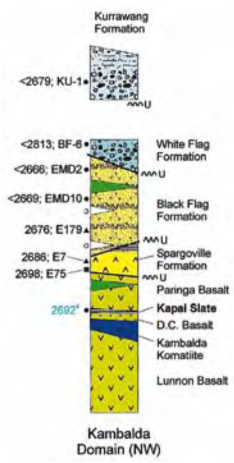


Figure 56: Schematic stratigraphic column of the NW Kambalda Domain (after Krapěz et al., 2000). Note the unconformities in the sequence indicating ongoing deformation (tilting).

Alternatively, the differences in stratigraphic thickness between domains reflect excision by detachments, especially near the base of the Kalgoorlie Sequence or Black Flag Formation (Blewett, et al., 2004a).

The external granites record a major melting and exhumation event at around 2675-2672 Ma (Cassidy et al., 2002). The development of significant gneissic fabric elements have been dated across the entire Eastern Yilgarn, irrespective of terrane or domain. Summaries of the granite events are found in Appendix 3.3, with brief descriptions outlined above. The fabric elements developed at this time include melanosome-leucosome differentiated layering, which are commonly isoclinally folded and transposed. When unfolded of the effects of later upright folding, these isoclinal folds were likely recumbent and have the geometry of lower-plate folds developed during vertical flattening and extension (Fig. 57). See Appendices 3.1.1 and 3.1.2 for the temporal and spatial maps of their distribution.

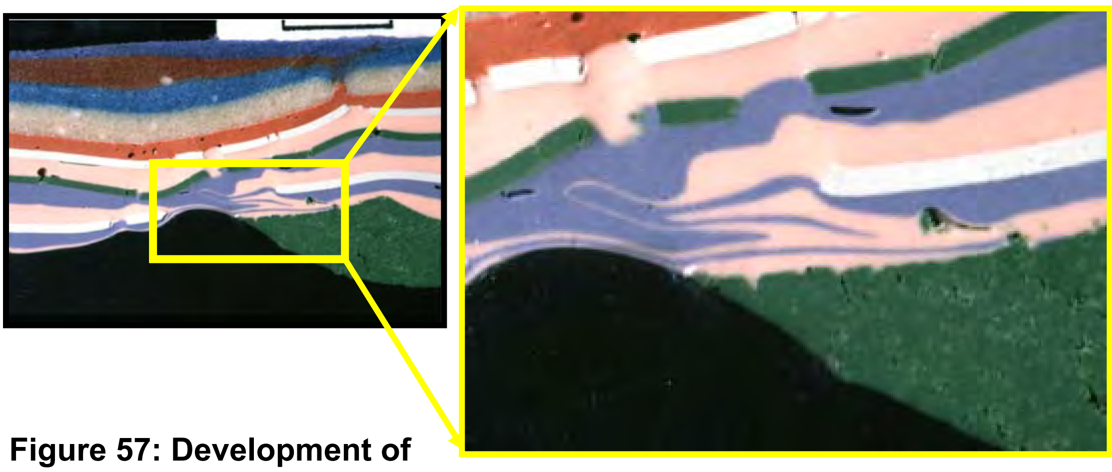


Figure 57: Development of recumbent folds in ductile lower plate (after Harris et al., 2002).

The widespread nature of this thermal event suggests that it reflects a fundamental stage in the extensional evolution of the orogen. Granites and their overlying detachments had not become emergent for the purposes of providing detritus until Late Basin times (see Module 2), indicating the extensional unroofing had further to develop after 2665 Ma (see later).

In summary, the D1 event was extensional with a dominantly ENE-directed polarity (Fig. 58). The timing of the event likely includes the earliest greenstone rock record (2800 Ma) through to the onset of the first significant contraction at around 2665 Ma. A map of the 'intensity' and location of the D1 event (as identified in this study) is shown in Appendix 3.1.2. A CorelDraw (v.12) file layered by event is also available in Appendix 3, and this allows comparison and contrast of D1 with other events.

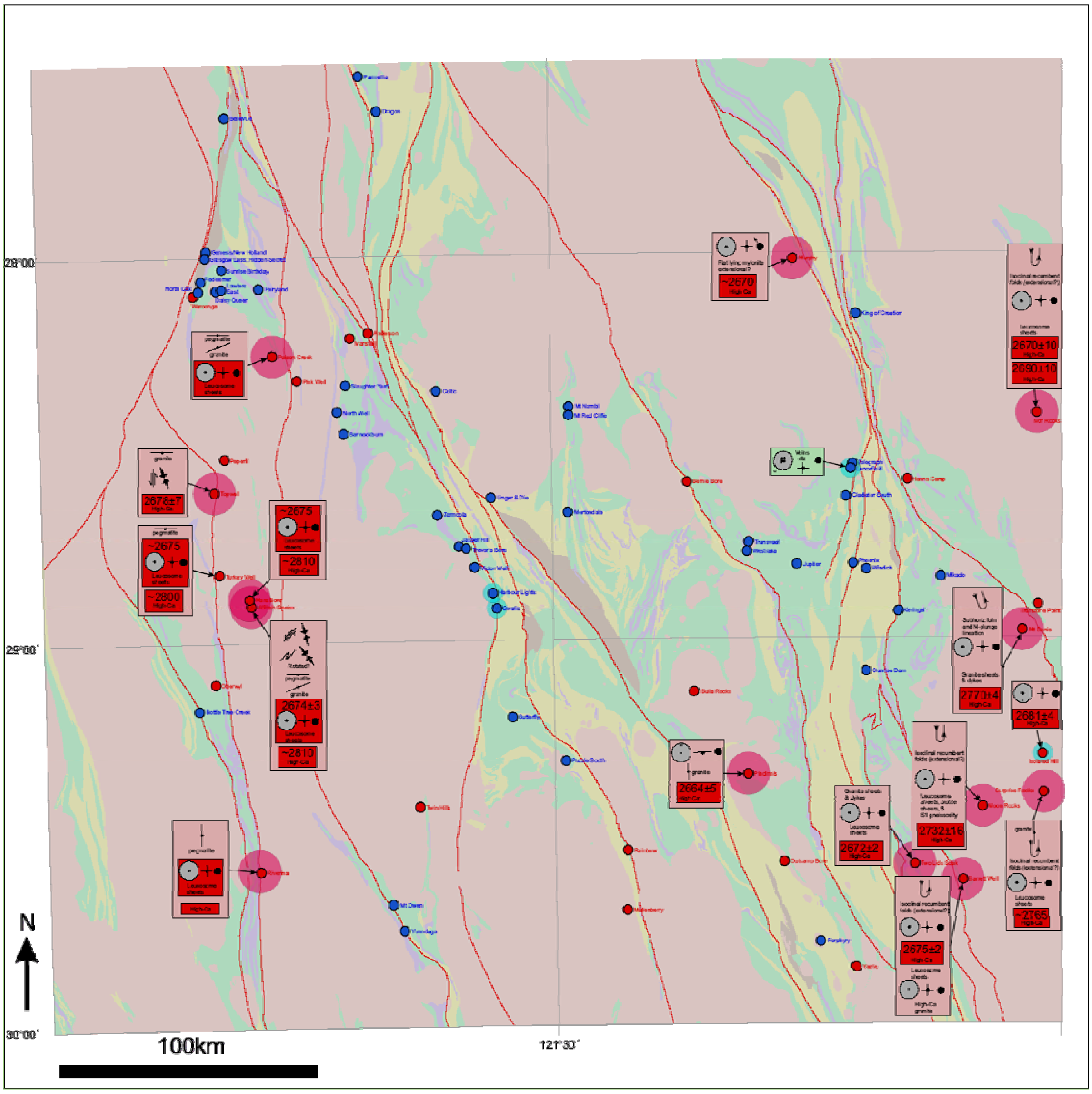


Figure 58: Map of D1 structures and their intensity across the study area at individual locations. Pink - granites, Yellow – sediments and felsic volcanics, Green – mafic-ultramafics, and Brown – late basins.
Intensity shown as size and colour of circles, with red (high strain), yellow (medium strain), and blue (low strain). See Appendix 3.1.10 for interactive maps

D2/D3: competing contraction and extension

One of the major difficulties in understanding the D1 extension is when it ended and when D2 contraction began. Part of the problem has been the general assumption that many of the upright broad folds that are cored by granites were developed solely by

‘D2’ contraction. A further problem is that the D3 event following this contraction was also extensional with an essentially E-W polarity. One of the consequences of the large amount of extension in the orogen is the impact on crustal thickening – or lack of it. If correct, then lack of crustal thickening has implications for understanding the geodynamics of the Yilgarn.

In areas where D2 is absent, the D1 and D3 events have become indistinguishable (see Appendix 3.1.1). In the majority of cases D2 and D3 display an inverse spatial distribution hence establishing timing between these two events is very difficult.

D2 contractional examples

Clear examples of D2 contraction are recorded around the Laverton area, and the include Windich and Phoenix deposits (Appendix 3.1.1) which are hosted by the Granny Smith Stage 1 Late Basin. Other examples include Telegraph, Transvaal, and further west, Porphyry (probably), Mertondale and Butterfly, which are hosted in older sequences. The fabric elements include a penetrative S2 foliation that strikes NNW and generally dips steeply east, N-S dextral shears, conjugate quartz vein arrays (from which ~E-W $\sigma 1$ can be inferred), and folds.

At many of the granite sites, D2 is represented by upright asymmetrical (Z-shaped) folds, and N-S dextral shear zone transposition of, D1 extensional fabric elements (Appendix 3.1.1). There appears to be a general change from folding to shearing in the ‘external’ granites. These fabric elements were observed across the entire Eastern Yilgarn (Blewett et al., 2004a). The overwhelming kinematics of overprinting shear zones, together with the asymmetry of the earlier F2 folds dextral (Blewett et al., 2004a), suggest that far-field kinematic framework was one of dextral transpression onto an NNW-trending architecture.

In regions away from the influence of granite domes, in general the D2 contraction involved predominantly N-S dextral reworking of a NNW-oriented grain. Exceptions are localised sinistral shearing at Mt Owen and Yunndaga near Menzies and Mertondale east of Leonora. The former two localities are dominated by a NW-trending grain (rather than N-S as elsewhere), and influenced by a NW-trending limb of a regional S-plunging anticline (Appendix 3.1.3).

The general dextral transpressional sense of shear during D2 is in contrast to previous interpretations. Swager (1997), Chen et al. (2001) interpreted D2 to be associated with <u>sinistral</u> shear. Their general proposition has been that during ~E-W contraction a NNW-trending fabric, when steepened following folding and thrusting, will fail in a sinistral mode with ongoing contraction.

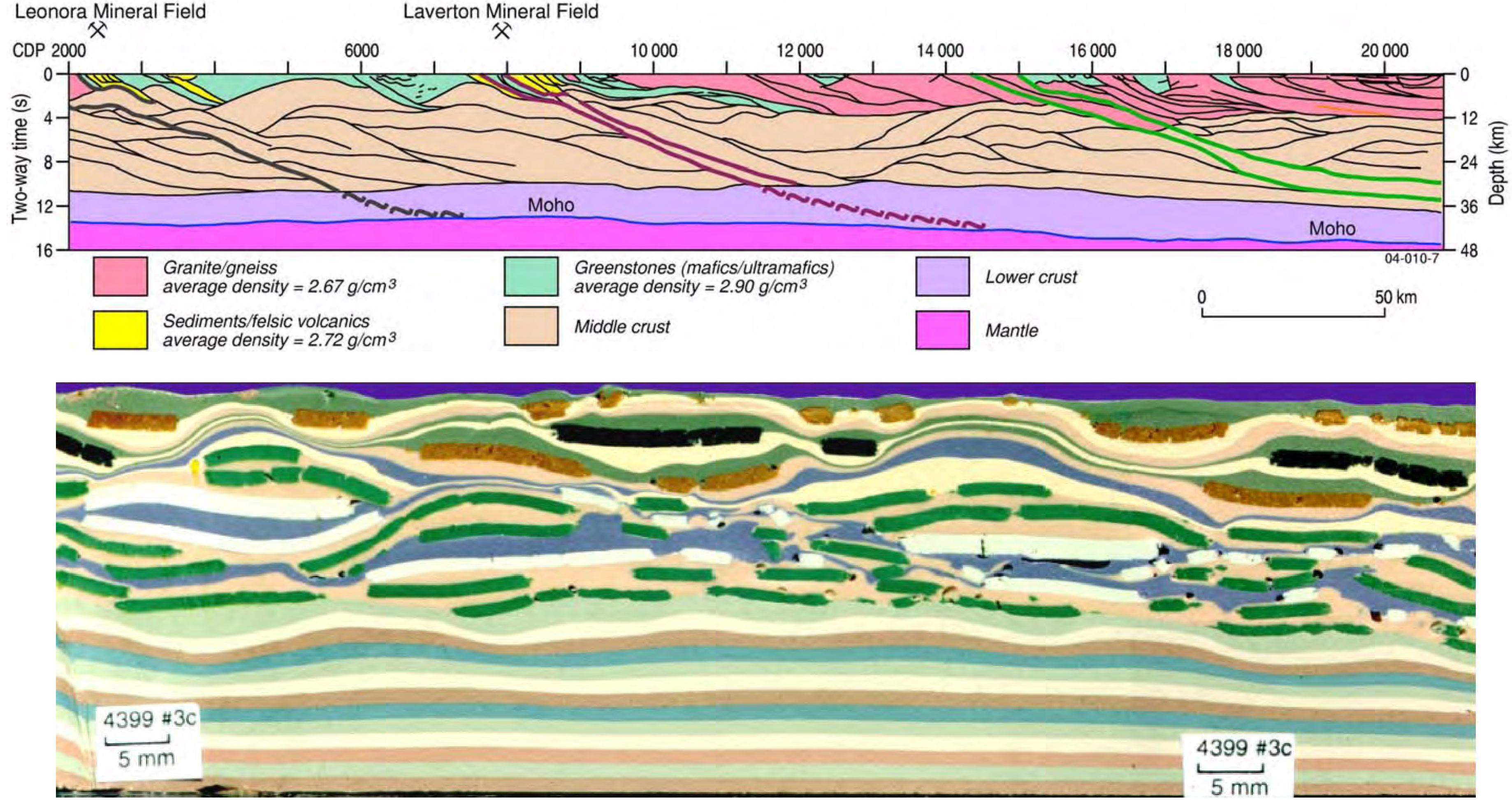


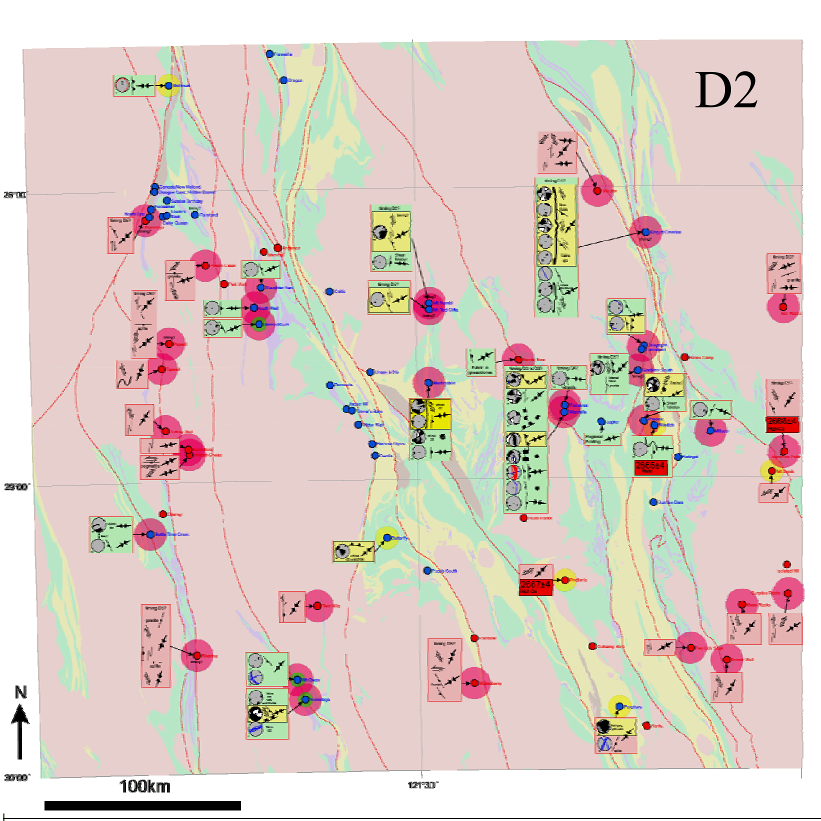
Figure 59: Simplified interpretation of seismic line 01AGSNY1 from Leonora to Lake Yeo. Note the similarity of seismic geometry to the extensional analogue model from Harris et al. (2002).

Another common view has been that D2 contraction involved folding and thrusting. This view has been influenced by the observation that most of the large regional folds (many are granite cored) plunge gently to the NNW or SSE (see later about development of granite-cored folds during extension). This 'D2-thrust' view has also been influenced by the interpretation that the architecture imaged in the seismic reflection data (Fig. 59) represent a fold and thrust belt (Goleby et al., 1993, Drummond et al., 2000; Blewett et al., 2002, 2003). Later it will be shown that much of the architecture imaged by the seismic reflection surveys is extensional. For thrust-dominated systems, the orientation of σ3 will be steep to vertical allowing the vertical stacking of thrust sheets. Associated fold plunges will be subhorizontal, parallel to σ2 and 90º from σ1. The accurate mapping of σ1 and σ3 by the PT-dihedra method (Czarnota and Blewett, 2005) has shown that many of the stress axes reveal that D2 involved both dextral strike- to oblique-slip and reverse faulting or thrusting (Appendix 3.1.3). The overall kinematic régime during D2 was likely to be transpressional with development of both strike-slip and dip-slip movements. Transpressional systems partition strain into strike- and dip-slip panels, and lineations developed in this framework are both down dip and along strike.

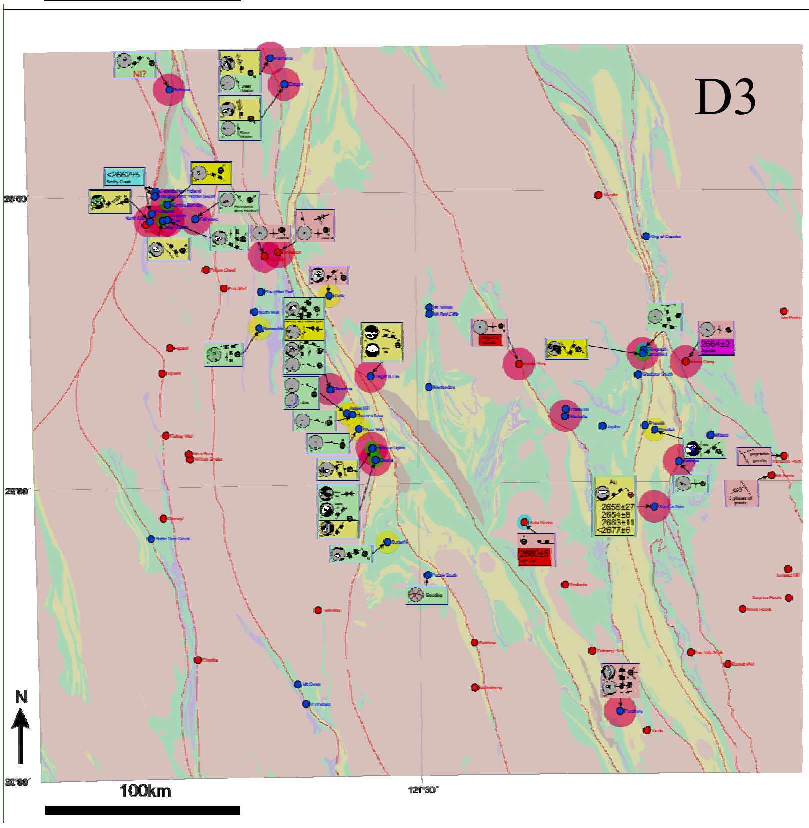
D2/D3 intensity and outline of the problem

The enigma regarding the relationship between D2 and D3 is particularly apparent when one contrasts the location and intensity of the respective events in a transect from east to west across the Kalgoorlie Terrane (Fig. 60). Around the Leonora area in the east, the prominent fabric element is an intense L/S- and S-tectonite developed under down-to-the-east extension (Williams et al., 1989; Williams and Whitaker, 1993). This area of greenstones (basalts and ultramafic rocks) is adjacent to a moderately E-dipping margin of the Raeside Batholith (Fig. 9). Logically one would expect this to be favourably oriented to intense E-W shortening, with folding and thrusting of the greenstones against and over the large granite batholith. The simplest interpretation is that D2 contraction occurred, and was essentially obliterated by a later (D3) and very intense extensional event. Contrast this with further west (see Slaughter Yard to Mt Owen in Appendix 3.1.1), where the main fabric appears to be caused by flattening and contraction during a classical Swager (1997) D2 event. In this location, there is limited evidence for extensional fabric elements (D3 or other), apart from limited switching at Bannockburn. Further west around the Lawlers Anticline (see Fairyland to North Cox in Appendix 3.1.1), the prominent fabric element is again extensional.

For the purposes of this report, the hypothesis forwarded is that large-scale (basin forming) extensional events are D3 and related to a return to the geodynamics present during pre-D2 times. Intra-contractional extensional switching (e.g., Mertondale and Westralia pits) is considered within the D2 event. The constraints on this interpretation are: a few sites localities at which compression pre dates major extension; for example: at the Porphyry deposit, the lack of regional D2 along the eastern flank of the Raeside Batholith, and the observation that late basins unconformably overlay a pre-folded sequence (Blewett et al., 2004b). The majority of these folds have been linked to extension (see discussion below) however folds north of Pig Well seem to be too tight to have developed purely due to extension. The core of the Mt Margaret anticline has a tighter fold in the greenstones than the adjacent batholith.



Intensity shown as size and colour of circles, with red (high strain), yellow (medium strain), and blue (low strain). See Appendix 3.1.10 for interactive maps



Intensity shown as size and colour of circles, with red (high strain), yellow (medium strain), and blue (low strain). See Appendix 3.1.10 for interactive maps

Figure 60: Map of D2 (upper) and D3 (lower) structures and their intensity across the study area at individual locations. Pink - granites, Yellow – sediments and felsic volcanics, Green – mafic-ultramafics, and Brown – late basins.

Alternatively, both contraction and extension are coeval (cf. Lin, 2005) and are developed in different places depending on the role of granites and their perturbation of a regional contractional stress field (see Figures 61, 62). Lin (2005) has recently described synchronous vertical and horizontal tectonics in the development of a single set of structures in the NW Superior Craton of Canada. Lin (2005) suggests vertical tectonics (extension) was important in setting up fluid pathways for the Late Archaean gold mineral system.

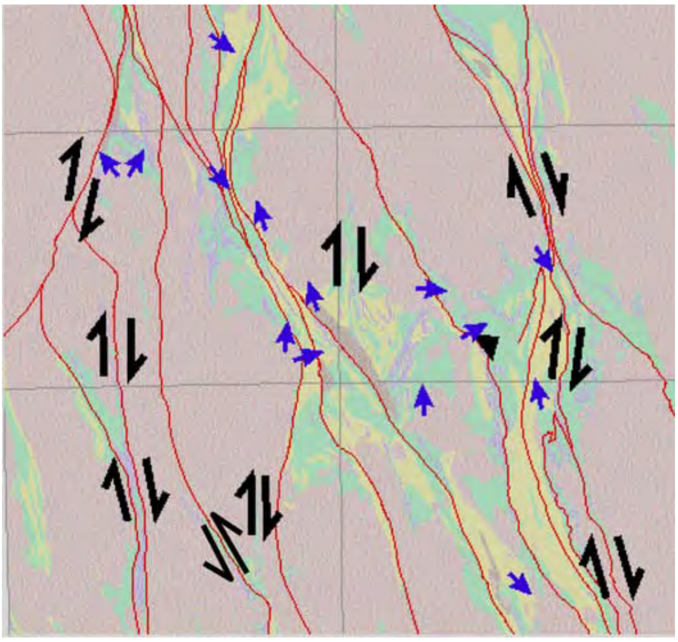


Figure 61: Major D2 and D3 kinematics. Black shear sense arrows indicate major D2 transpression kinematics. Blue arrows indicate D3 extension vectors.

Role of granites in D3 extension

Both the Leonora and Lawlers areas are dominated by large granite batholiths in the cores of regional N-plunging anticlines. Both areas appear to lack unequivocal evidence (at the mesoscale for contractional deformation (see Appendix 3.1.1, 3.1.3). These regional upright folds appear to have developed at the same time as contraction elsewhere (especially in the centres of the terranes). The role of granites during D2 contraction in localising extensional deformation can not be underestimated. Figure 63 is from Harris et al. (2002) and shows the development of upright (gently plunging) folds adjacent to extensional shear zones. The models of Harris *op cit.* are obviously developed in plasticine, but the resultant geometries bear an uncanny resemblance to the deep crustal seismic reflection profiles (Goleby et al., 1993; 2003; Blewett et al., 2003). The broad antiforms in these models (Fig. 63) may be analogous to the broad antiforms such as the Mt Margaret, Raeside, and Lawlers Anticlines (Fig. 9). In the analogue modelling, these antiforms are cored by more ductile material (the more competent layers such as the brown and black markers) boudinage. This inference may suggest that magmatism at the time of extension may be required to reduce the lower-plate viscosity to facilitate this doming.

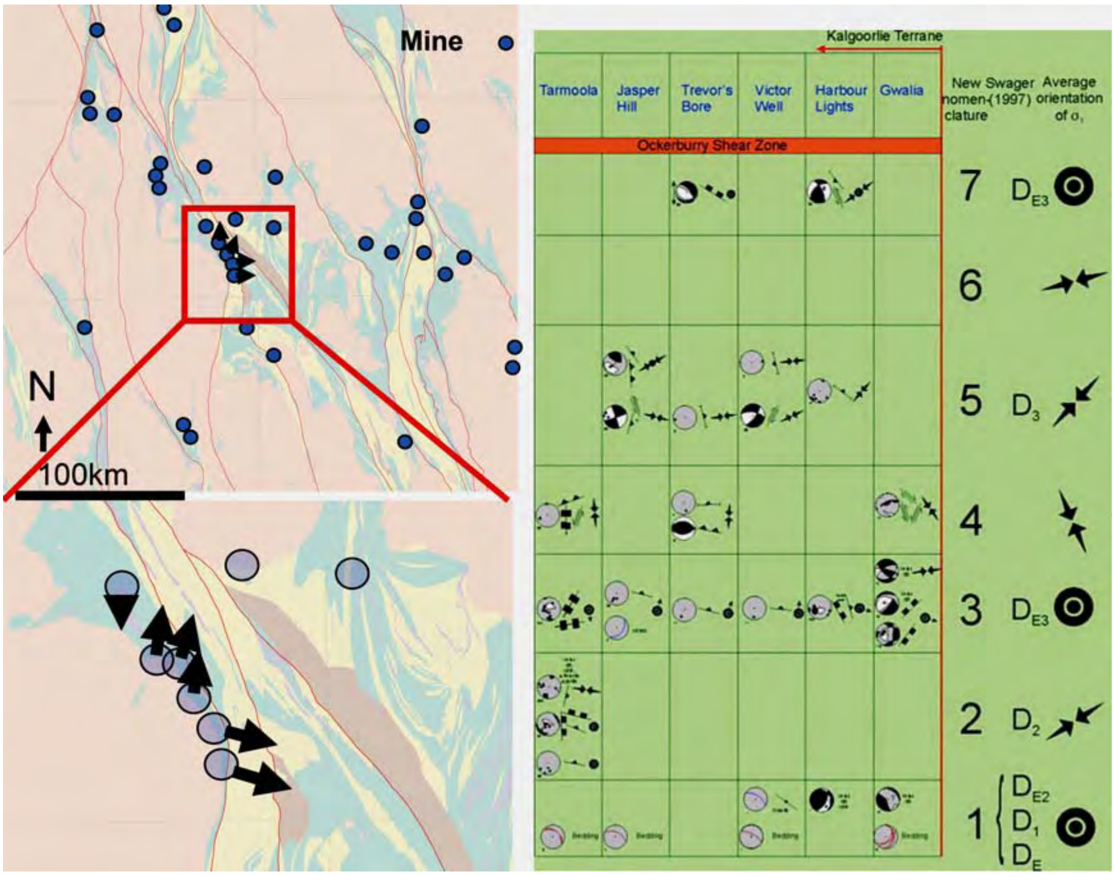


Figure 62: Lack of D2 compression on Ockerburry Fault System around Leonora. Notice switching between compression and extension at Tarmoola.

Figure 63: Illustration of centrifuge modelling of upright antiforms (domes) developed during extension. These may be viewed as analogues for the development of the granite-cored such as Mt Margaret, Raeside, and Lawlers. The development of the folding is not diapirism, but gravitational instability facilitated rising batholiths in an extensional environment.

D2/D3 Extension and formation of Late Basins

The traditional paradigm has been that the Late Basins are pre-'D2' as they are deformed by a 'D2' event (Swager and Griffin, 1990; Swager et al., 1992; Swager, 1997, Krapěz et al., 2000; Weinberg et al., 2003). D2 in these workers definition was the first ~E-W contraction.

Blewett et al. (2004b) demonstrated that the Late Basins lay unconformably on a prefolded sequence deformed by the first ~E-W contraction. They labelled this early event D2a, and gave two regional examples. The first example in the Kalgoorlie Terrane was the N-plunging regional syncline-anticline pair at Ora Banda and its relationship with the overlying Kurrawang Basin (Fig. 64a). The second example in the western Kurnalpi Terrane was the S-plunging upright Corkscrew Anticline at Welcome Well, and its relationship to the Pig Well Basin (Fig. 64b).

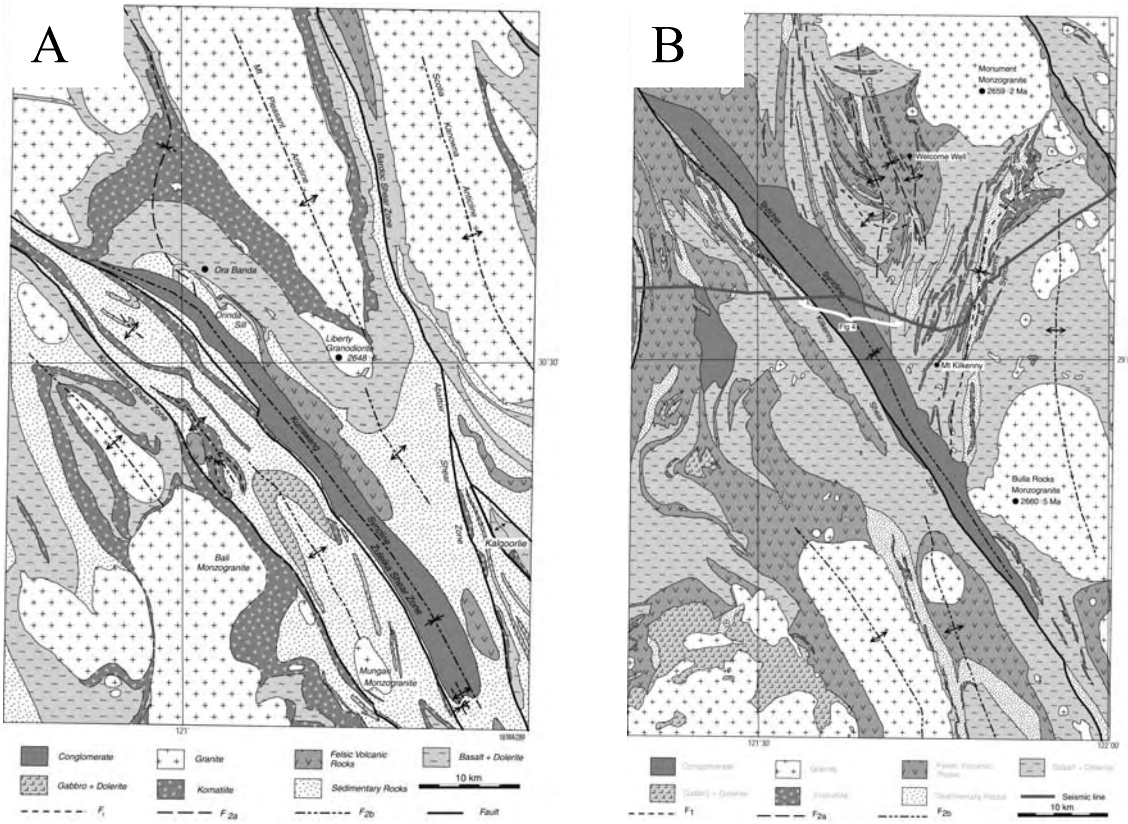


Figure 64 a, b: Simplified Geological Maps of the Late Basins (A–Kurrawang and B–Pig Well) overprinting the Ora Banda Anticline and Corkscrew Anticline respectively (after Blewett et al., 2004b).

Blewett et al.'s *op cit.* observations were important in that they showed that D2-style folds were developed in the basement to the Late Basins, and not necessarily D1 contraction (*cf.* Swager, 1997). One question not addressed by Blewett et al. was the mode of formation of these D2a folds, the assumption being that they were developed solely in contraction.

A study of structures around the Lawlers Anticline and adjacent Scotty Creek Late Basin has raised the question whether the NNW-SSE trending upright folds cut by

Late Basins are developed under contraction or extension. The same geometric relationship as described for the Kurrawang and Pig Well basins seem to hold true at Lawlers. That is a Late Basin unconformably overlies a pre-folded (NNW-SSE trending) mafic-dominated sequence, and the basin itself is deformed by a E-W contraction.

However the question has been raised by this study as to the mode of formation of the Lawlers Anticline itself. Could it be that the Lawlers anticline is related to extension as opposed to compression? It is difficult to unequivocally identify early E-W contraction around the Lawlers region. The region is dominated by down-to-the-E, -NE, and -N extensional fabric elements (see Appendix 3.1.1 from Fairyland to North Cox). The Lawlers Anticline is cored by a coarse-grained granite, which raises the question as to the role of the granite in the development of the fold. Similar questions could be asked with respect to the Mt Margaret Anticline and the development of the Stage 2 Wallaby Basin and possibly the Stage 1 Granny Smith Basin. McIntyre and Martin (2005) suggested that the Late Basins in the Laverton area were developed as upper-plate rift basins above a detachment related to 'extrusion' of the Mt Margaret Batholith to the north.

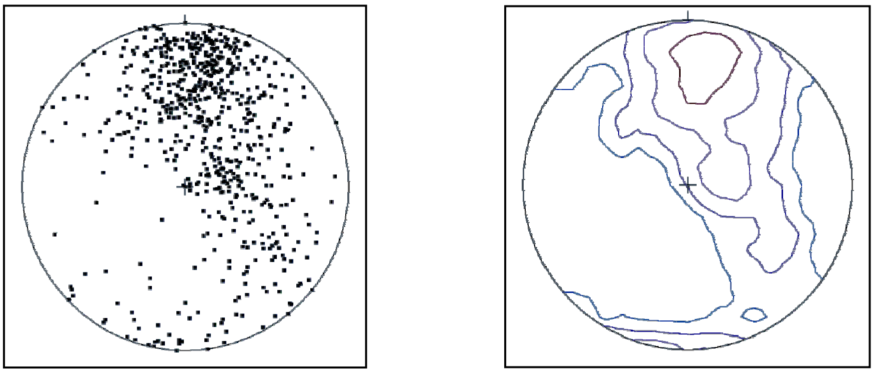


Figure 65: Stereonet of lineations in granites and greenstones around the Lawlers Anticline (generated from data in Beardsmore, 2002). Note that the main population plunges gently north, this is parallel to the hinge of the regional fold (and the shape of granite at depth). A second sub-population plunges steeply ENE. Note the lack of W- and SW-plunging lineations.

Beardsmore (2002) showed in a very comprehensive mapping study of the Lawlers region that the main foliation transects the axis of the regional fold (Fig. 66a). Also revealing in this study was the pattern of lineations (Fig. 65b). They plunge gently to the N in the north, becoming progressively steeper NE and finally steeply E-plunging along the eastern limb of the fold (Fig. 66b). In contrast, the western limb of the fold does not have down-dip lineations like its eastern counterpart. Rather, the lineations plunge gently S and are more akin to strike-slip (Beardsmore, 2002).

This pattern of foliations and lineations is not consistent with diapirism. The lineations are not radial as there are few if any down-dip lineations on the western limbs across the Eastern Yilgarn. This is not simply a sampling problem as Beardsmore (2002) has systematically encircled the Lawlers Anticline (Fig. 66b).

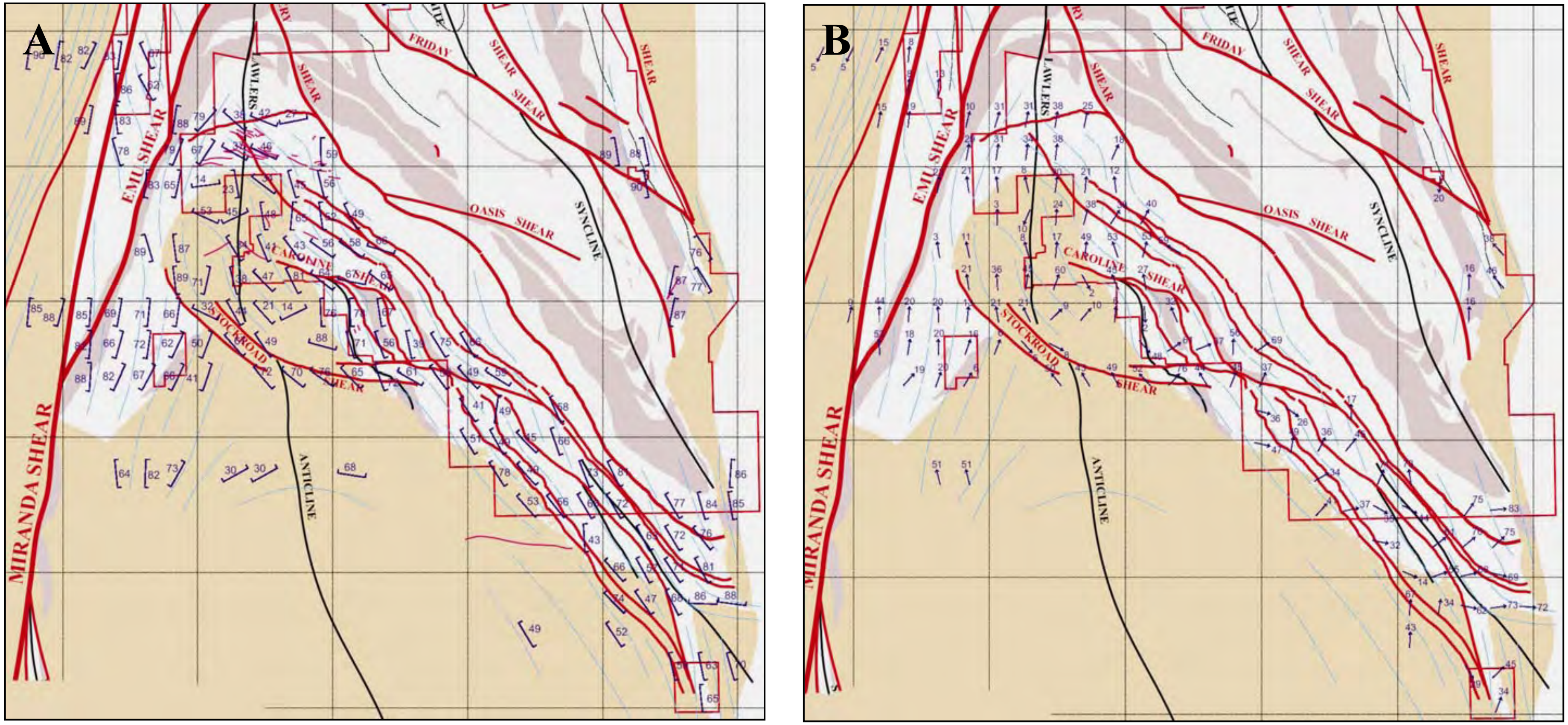


Figure 66a, b: A-Map of the main foliation and the main lineation in the Lawlers region (after Beardsmore, 2002). The red lines are major faults, and many were observed to have normal or extensional kinematics on them in this study. Note that the foliation transects the fold axial trace (black line). The foliation is therefore overprinting (is later than) the development of the fold. B-Map of lineation trajectories showing the gentle (hinge parallel) plunge in the centre and north, and the steepening and rotation of the plunge to east on the SE limb of the fold (see Fig. 65).

Figure 67: Photographs of the core of the Lawlers Anticline showing a gentle N-dipping penetrative foliation 'S1' and associated stretching lineation (rods), and folding about upright gentle N-plunging 'F2' folds.

In the Lawlers area, there is a question regarding whether there is only one foliation. Beardsmore (2002) suggested that there might be two populations, one shallow NE-dipping, and another steeper and striking NNW. He also plotted up the shallow fabrics in the granites and showed that they lay on girdle with a pole (fold axis) that plunged 23º to 359 (cf. Fig. 66b). Blewett noted similar relationships in the leucogranites in the innermost nose of the Lawlers Anticline (Fig. 67), where two stages of deformation are recorded. Beardsmore (2002) also noted dextral shearing on the steeper NNW-trending fabric (which we would interpret as D5 dextral – see later). The map patterns of the Lawlers Anticline (Fig. 66), especially the SW limb, show that the Lawlers Tonalite (~2665 Ma) intruded into an already domed sequence. This suggests that the magmatism was concentrated into incipient antiforms, and that the extension and doming was likely a long-lived process.

The Lawlers Anticline is therefore interpreted to record extensional uplift and exhumation, with doming and magmatism at ~2665 Ma. The overlying greenstones were domed and tilted and overprinted by extensional down to the N-, NE- and E-dipping extensional shear zones. Shear was accommodated on structures such as the Cascade Shear in the Sunrise Birthday pit (Fig. 66), and was associated with gold mineralisation. Similar extensional shear zones include the Stockyard and Caroline shears (Fig. 66). These faults have **apparent** sinistral offset in map patterns, which when resolved kinematically, is the result of normal offsets on NE-dipping markers. This extensional mode explains the paradox for Beardsmore (2002) of the steep down-dip lineations he recorded on these shears, and negates the need for an additional deformation event to explain the geometry and relationships.

Beardsmore (2002) also described the 'rolling' of the stratigraphy on the eastern limb of the Lawlers Anticline. He noted that the lowest units dipped on average 35º to the NE, while the upper units dipped more than 75º to the NE. This change in dip was interpreted to be a function of back rotation during NE-over-SW thrusting. An alternative interpretation presented here is that this change in dips reflects the position of the stratigraphy with respect to the C' shear planes, and the footwall uplift and doming common to extensional systems (see Fig. 68). Mesoscale examples are exposed at Sunrise Birthday and the distribution of ore shells at Fairyland follow this trend. This mineralisation trend at Fairyland suggests that the distribution of lithology caused by extension places is a strong control on the later contractional mineralisation.

The Lawlers Anticline and the Mt Margaret Anticline are located at the western and eastern margins of the Kalgoorlie and Kurnalpi Terranes respectively. Both folds are granite-cored and are associated with significant Late Basin preservation, and gold deposits. The initiation of the antiforms may have been during extension, with rising granite magma being emplaced into these incipient domes. The development of extensional shear zones and detachments within the granite and overlying greenstones tilted the country rocks so that when the Late Basins were deposited they 'found' a 'D2' pre-folded sequence. The intensity of this extensional event was sufficient to finally bring the lower-plate to the surface so that granitic detritus could be sourced and deposited both locally and afar. The presence of a layer parallel shear fabric along moderately dipping limbs of antiforms further support to the extension hypothesis since a steep axial-plane foliation which transects the layering would be expected in compression. Figure 61 shows that the partially radial pattern of extension away from granite dome cores during D3 observed at Lawlers is replicated on the regional scale.

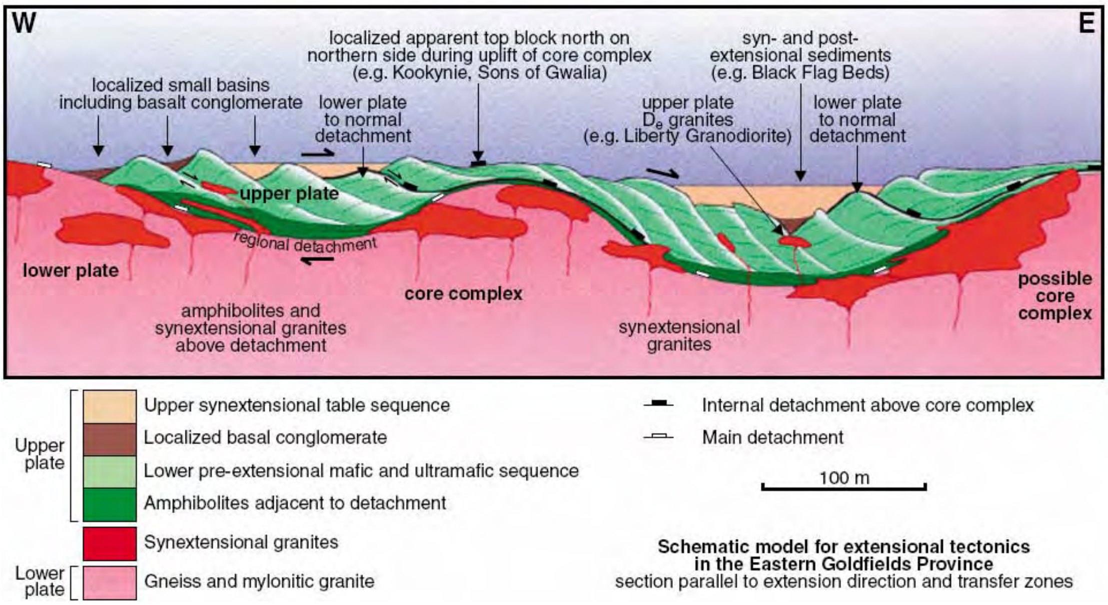


Figure 68: Schematic diagram from SRK (2000) illustrating the geometry of the extensional architecture of the system. The model has errors of fact such as assuming the Late Basins are the same age as the Kalgoorlie Sequence (Black Flags), but the overall picture is appealing. We have switched the view from on of ENE to one of north as we interpret that the fundamental polarity of extension to be E-W not NNW-SSE.

Seismic reflection at Leonora and Pig Well – extensional formation of a Late Basin

The project was fortunate to have access to publicly funded (GA-GSWA) seismic reflection data (01GASNY1) through the Leonora area (Fig. 59). These data were interpreted as part of the *pmd**CRC Y2 project (Blewett et al., 2004c), and results therefore made available to this project with end its confidentiality. Figure 69 shows the location of the seismic line in relation to the regional solid geology. The main faults, the Ockerburry and Keith-Kilkenny Fault Systems have normal (extensional) map patterns with the younger (Late Basin in brown) on older basement greenstone (green and yellow).

The 01GASNY1 seismic line is a high-quality dataset that was reprocessed by Dr. Leonie Jones at Geoscience Australia. The result was the resolution of macro-scale extensional shear zones (S-C-C' relationships) that can be traced from 5-6 km depth to the surface (Fig. 70).

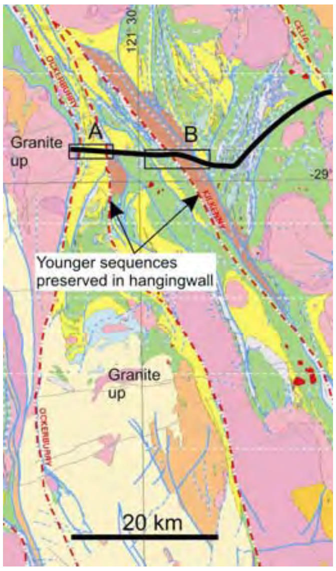


Figure 69: Location of the 01AGSNY1 seismic reflection line from Leonora across the Pig Well (Late) Basin (brown). The Ockerburry and Keith-Kilkenny Fault Systems have normal (extensional) map patterns with the younger (Late Basin in brown) on older basement greenstone (green and yellow). The relationship is also one of lower granites juxtaposed across E-dipping contacts (shears) against higher greenstones to the east. Location A and B are detailed views of the lines in Figures 69 and 70 respectively.

The re-processing of seismic line 01AGSNY1 across the SOG pit (Fig. 70) shows excellent S-C-C' relationships; consistent with the mesoscale observation in the pit and surrounding locality. Intense foliation (reflectivity up to 5 km wide) is imaged by the seismic line, and this soles out into a convex up detachment (analogous to core complex development). Geometries such as this are illustrated in the conceptual sketch of a core complex (Fig. 68).

To the east, the Keith Kilkenny Shear Zone displays a similar geometry of S-C' shear bands, consistent with a down to the east sense of shear (Fig. 71). The Pig Well Basin (Graben) appears to partly overprint (with an unconformity?) A foliation (extension?), and is dragged in a normal sense by further extensional movement along this zone. Shear bands within the basin are also extensional in geometry. Examination of map patterns along strike for the Ockerburry, Emu and Keith Kilkenny Shear Zones also show younger rocks preserved on the eastern (downthrown-hangingwall) side of the faults (Fig. 69).

What is most revealing about these seismic lines (Figs. 70, 71) is the spacing of the intensity of reflectivity (foliation development). Intense reflectivity can be correlated at the surface with high-strain zones. These appear to be zones up to 5 km wide both in surface mapping and in the seismic data. These can convincingly be regarded as extensional fabrics, with raises a very serious question about how NNW-trending foliations have been interpreted about the region in the past! This is the so-called 'S2' fabric and it has been used as the correlation foliation by most workers for their site to site correlations, and to construct event stratigraphies. As outlined earlier, the NNW-trending foliation, commonly called 'S2' can be a strike-slip, normal/extensional dip slip, axial planar flattening, and/or a combination of these in any one locality. This variation in its genesis makes it a poor marker fabric.

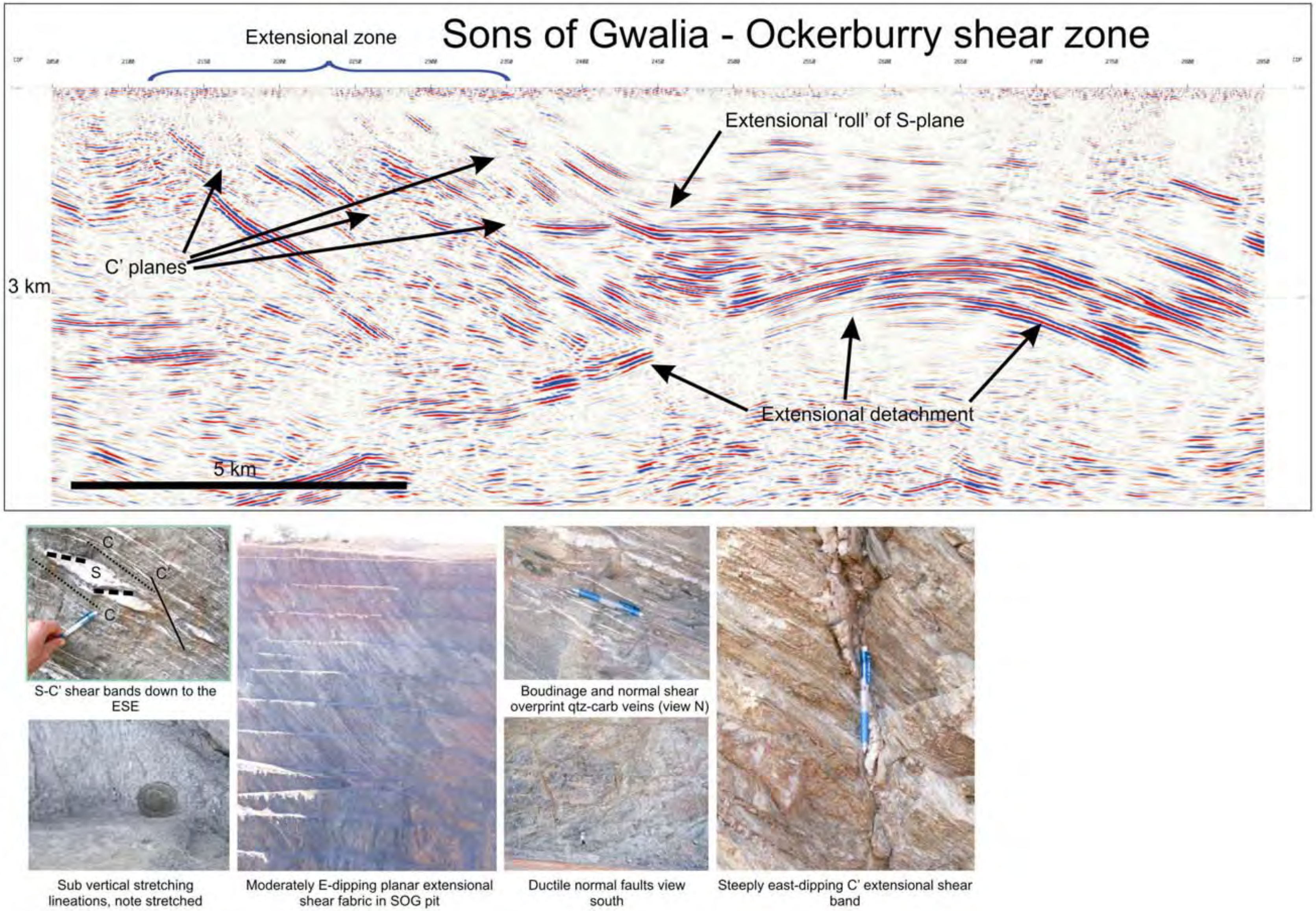


Figure 70: E-W Seismic line through the Sons of Gwalia pit (SOG) showing a broad zone of extensional shear. Compare this image with the conceptual sketch of a core complex (Fig. 68). These features mapped in the seismic are mirrored on the meso-scale in the pit (see inserts).

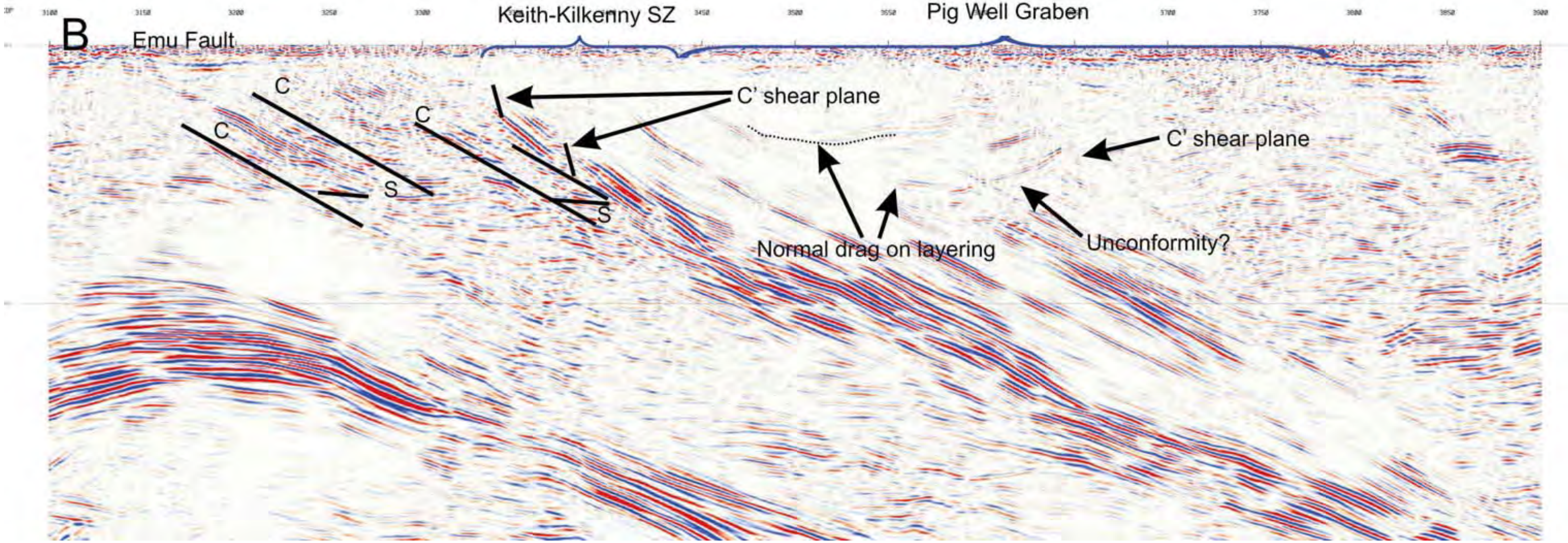


Figure 71: E-W seismic line showing intense foliation development along a ~3 km wide zone of the Keith-Kilkenny is considered to be a result of extension. The Pig Well Basin (graben) appears to overprint (unconformity) some of the foliation and is also overprinted by a sub-parallel foliation defined by shear bands (C planes). Localised higher angle C' (prime) extensional shear bands overprint the fabrics. The layering of the basin is also dragged into a synformal geometry, consistent with extension down to the east. This suggests that the basin was both formed and deformed by the extensional D3 event.

Metamorphism across extensional shear zones

Figure 68 shows that low-angle extension is an effective mechanism for juxtaposing low-grade upper-plate rocks against high-grade lower-plate rocks. Williams et al. (1989), and later in Williams and Whitaker (1993), related the juxtaposition of high-grade greenstones (immediately adjacent to the Raeside and Mt Margaret Batholiths) against low-grade greenstones across batholith-away dipping shear zones, as a function of extension. Williams and Currie (1992) noted at least 5 km of excision from this extensional event (Fig. 72). In these papers, Williams suggested that the extension was the DE event described by many workers. They may have been right, as these areas have been dominated by extension for much of their history and it is likely that this was a long-lived event.

Dr Ben Goscombe (NTGS and ex-GSWA) has compiled the existing metamorphic database and also analysed all available pelitic assemblages with a probe. His unpublished results show that the general field gradient is one of not only steadily increasing temperature towards the granites from the greenstone synforms (as Binns et al., 1976 showed), but of increasing pressure (Fig. 73). In fact, Goscombe's results show that pressure increases dramatically close the granites, confirming the extensional excision of stratigraphy inferred by Williams and Currie (1992).

In terms of the general field gradients, a question remains regarding the pressure estimates of the granites. Goscombe's work ended at the granite margins and there was uncertainty as to whether pressure dropped in the granites (i.e., the narrow high-grade greenstone margins were channel flow material from the deep crust. However, barometry on granites around the Wilbah Gneiss and Mars Bore (see Fig. 9) showed them to have been exhumed from around 8 kbars or 20-24 kms (Morrie Duggan, unpublished GA data). If these pressure estimates represent the general case for the high-grade granite-gneiss regions, then the channel flow hypothesis is invalid and so a core-complex type model is favoured (*cf.* SRK, 2000).

Orogenic surge or episodic thrust behaviour during D2

In general, where D2 contraction is well established, the D3 extension is essentially absent. Similarly, where D3 extension is well established, the D2 contraction appears to be absent.

However, in other sites it was possible to determine that both extension and E-W contraction were switching repeatedly, but invariably one mode would be dominant over the other. Good examples of this switching occur at Tarmoola, Mertondale and Westralia (Fig. 60). Tarmoola appears to have a contractional gold event during dominantly extensional tectonic mode. In contrast, Mertondale and Westralia have extensional switches during a dominantly contractional tectonic mode.

So it is clear that contraction and extension can occur at the same time, and these ideas were explored by Blewett et al. (2004c) in terms of formation of the Late Basins and a tectonic surge. This hypothesis is not considered viable for the formation of large-scale inversions and basin formation (see later in D4 section below). However, the understanding of the mechanics of thrusting and observations of active thrust-convergent systems today indicate that contraction is episodic (surge) and interspersed with periods of relaxation which may led to localised extension. This maybe what is recorded as shock and after-shock sequences in the resolution of structural elements in the pits via the PT-dihedra method, and is likely a key to permeability creation and destruction. The switching between a sequence of coaxial contractional deformation and extensional events may indicate that, at a larger scale, both tectonic modes were active together (*cf.* Lin, 2005).

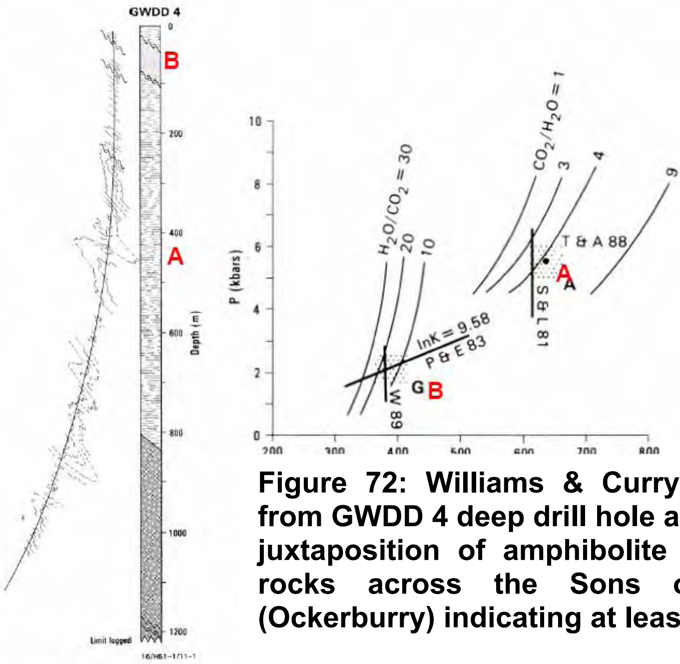


Figure 72: Williams & Curry (1992) P-T calculations from GWDD 4 deep drill hole at Sons of Gwalia showing juxtaposition of amphibolite (A) and greenschist (B) rocks across the Sons of Gwalia shear zone (Ockerburry) indicating at least 5km of excision.

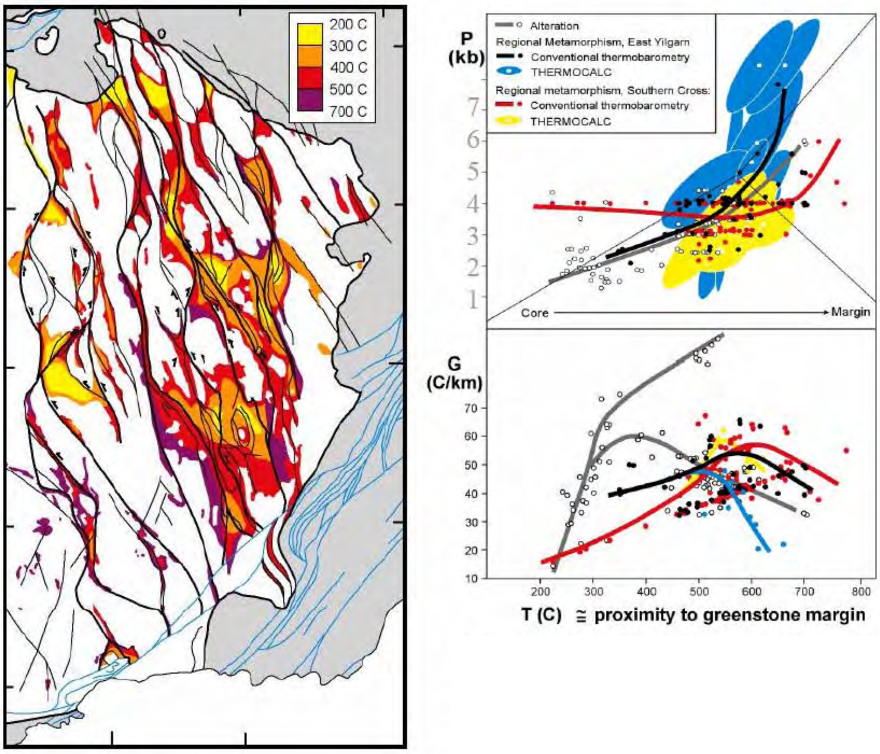


Figure 73: Unpublished metamorphic temperature map (a) and P-T diagrams (b) by Goscombe et al. (2005). NB kinematic indicators in temperature map are sourced from the literature and conflict with the observations in this study.

Polarity of D2-D3 deformation

As argued earlier, the long-lived D1 extensional event(s) established the NNW-oriented architecture of the Eastern Yilgarn Craton. Slab roll-back from the east may have favoured the development of an asymmetric system with a down to the ENE sense of shear. The polarity of the D2 contraction can be inferred from the numerous PT-dihedra calculations made in this study. In this study, like many before, D2 contraction was oriented ENE-WSW, and had a likely dextral transpressional couple across it. Much of the movement that was dextral strike-slip occurred along N-S trending structures.

The fundamental grain viewed in the seismic (Figs. 59, 70, 71) is down to the east (ENE), a ‘rebirth’ of the D1 extension(?). However, in detail the lineations plunge to the eastern hemisphere around the domes (e.g., at Lawlers Fig. 66a). It has been at Lawlers (and by Williams and Whitaker, 1993 at Leonora) that the granites rose upwards in the crust while under extension and the greenstones were shed off these rising bodies. The regional far-field ENE-directed extension from the rolling-back slab to the east was enhanced locally in the domal regions by magmatism. The fact that greenstones slide off to the north, east, and south (and all points in between), and that the granites were locally ‘extruded’ to the NNW, W, and SSE, imply that the orogen was not fixed at the sides. Davis and Maidens (2003) also described a late D2 extension in the Laverton area (described as D2e), and related this to collapse of the D2 orogen along its axis. In a slightly different model, SRK (2000) suggested that the polarity of extension was NNW-SSE, building on the early work of Hammond and Nesbit (1992; 1993). In these models, the NNW-trending architecture formed the transfer faults (localising Late Basins in narrow troughs in these transfers), while the main detachments were arcuate about the broad granite domes. In both cases, SRK (2000) and Davis and Maidens (2003) mapped the local effects of a larger system.

The SRK model (Fig. 68) is appealing in many ways, but does not explain the temporal relationships of the Late Basins, nor the fact that the primary architecture in a multitude of geophysical, geochronological, geochemical and geological datasets show that the fundamental compartments strike NNW (during D1 and D3). These all data point to an ENE-directed extension direction, and may reveal something about the orientation of the orogen’s margin (it was likely NNW-trending in today’s reference frame).

Implications for Gold

In terms of the spatial association of proximity of major gold deposits and Late Basins, it could be that the basins are a consequence of a process that is linked to both. This common process is extension which established deep-connected fluid pathways onto detachments at depth, and their domal focussing architecture. The fact that magmatism (a hot fluid) also favours the domes created by the extension may also point to a common process (or architecture) for magmatism and gold mineralisation. In this study gold localisation has been observed in both extensional and compressional structures. However the majority of gold deposits are localised in compressional structures indicating that compression is an important aspect in focusing fluid. The relationship of inferred and known gold mineralisation to mapped structures is presented in Appendix 3.1.1 & 3.1.10. Gold occurs in D2 through to D5 structures with the majority of the gold localised in: D2, D3 and D5 structures. Gold related to the D4 deformation appears to be confined to the Laverton region. There may be an over estimate of gold mineralisation at D2 and D5 time since at some sites it was not possible to distinguish between these events. When Au was localised in ductile shear zones it was always localised in the central high strain parts of the shear zone thereby indicating that in ductile shear zones permeability and fluid flow is a function of continued deformation.

Summary of D2/D3

In summary, the D2 event was contractional with a dominantly ENE-WSW polarity of convergence. The timing of the event marks the first significant contraction at < 2665 Ma. Maps of the 'intensity' and location of the D2 and D3 events (Fig. 60) are shown in more detail in Appendix 3.1.3 and Appendix 3.1.4 respectively. A CorelDraw (v.12) file, layered by event, is also available in Appendix 3.1.10. This file (pseudo-GIS) allows spatial comparison and contrast of the D2-D3 relationship (Fig. 60), and also these with other events, in the context of the geology and regional fault systems.

D4: low-strain ~N-S contraction

The D4 event is a low-strain contraction oriented N-S to NW-SE that overprints the D2/D2 fabric elements. It was first described by Ellis (1939) and remained in the literature up until the early 1970's. It was recognised as broad upright folds and E-W trending foliations overprinting NNW-trending folds and foliation. This event was identified in the granite study of Blewett et al. (2004a), and it was considered significant as it reflected a late palaeostress switch and possibly related to gold mineralisation. The D4 N-S contraction was recognised across all the terranes of the Eastern Yilgarn in the granite study. The style of the deformation event is dominated by N-S to NNW-SSE trending sinistral strike-slip shear zones and both S-over-N and N-over-S thrusts. Previous workers probably identified these sinistral structures as the classical D2 (as described above), rather than a separate event (*cf.* Swager, 1997; Chen et al., 2001).

The localities with well-developed or intense D4 deformation reported here include Jasper Hill, Puzzle, Jupiter, Poison Creek, Turkey Well, Two Lids Soak, Barrett Well and Isolated Hill (Fig. 9; Appendix 3.1.1).

The event is particularly strong in Jupiter and Wallaby (John Miller pers comm., 2005). Interestingly in both these pits syenites are associated with the NW-SE oriented contractional events. At Jupiter the resolved palaeostress changes from NW-SE contraction, to uniaxial (radial) extension associated with the emplacement of the syenite, and returns to NW-SE contraction. The interpretation of Jupiter is that the syenite was emplaced into a regional contractional setting and, at the time of emplacement, the magma pressure was greater than the far-field compression across the orogen.

In the Lawlers area, Beardsmore described a deformation event with WNW-ESE $\sigma1$, post his D2 (E-W $\sigma1$). These structures were dominantly sinistral strike-slip faults. In the granites study (Blewett et al., 2004a), the D4 event is characterised by sinistral strike-slip faults (Fig. 75) and NW-SE dextral faults (Fig. 74). Most structures are low-strain, both brittle and ductile.

Figure 74: NNW-trending dextral ductile shear zone with granite vein emplaced along the shear.

Figure 75: sinistral shear zones in Yarrie Monzogranite implying WNW-ESE contraction associated with gold.

The D4 event is expressed as the most intense deformation (Fig. 77) in the 'internal' granites of the central Kurnalpi Terrane (e.g., Outcamp Bore, Yarrie and Bernie Bore). Most of the associated structures are steeply dipping sinistral shear zones. At Yarrie, D4 was the gold event (Fig. 75). NW-SE contraction is also the gold event at Jupiter and at Wallaby (John Miller pers comm. 2005). Elsewhere in the granites, dykes of pegmatite and granite (not Low-Ca type) were intruded into the active shear zones (Figs. 74, 76), demonstrating that magmatism was active despite this being a low-strain event (Appendix 3.1.10). Jupiter and Wallaby are the best examples of magmatism during this event.

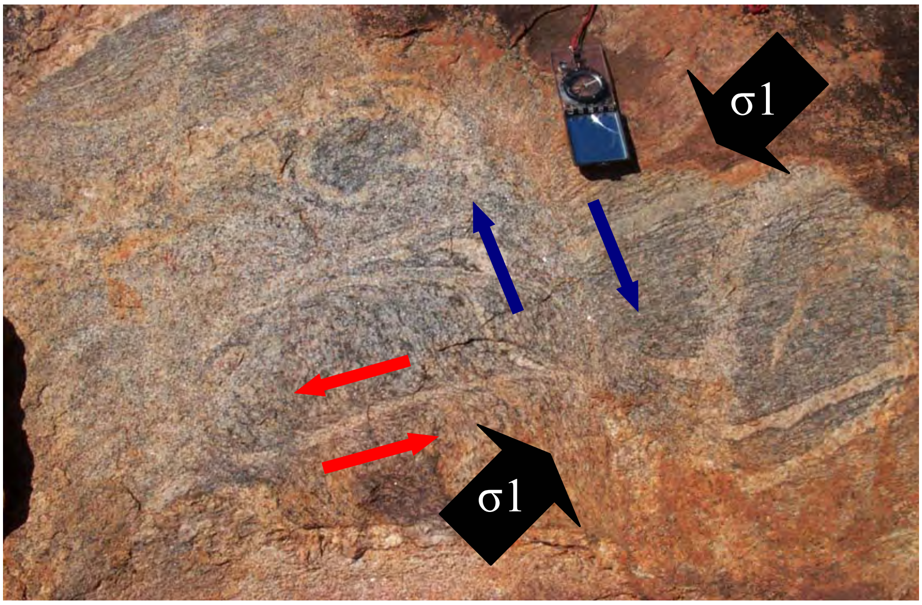


Figure 76: View east of a Moon Rocks pavement showing ductile (N-trending) sinistral (red) D4a shear zones. These D4a shears and dykes are overprinted by D4b WNW-trending (blue) dextral shears. Maximum compression was likely NW-SE during this event.

The D4 event is also important in that it 'separates' the D2/D3 deformation from the co-planar and co-kinematic D5 event. In some sites there appears to be only dextral transpression recorded (e.g., King of Creation) and without dating it is not possible to resolve whether the fabric elements are D2 or D5 or both (or a progression *cf.* Weinberg et al., 2003).

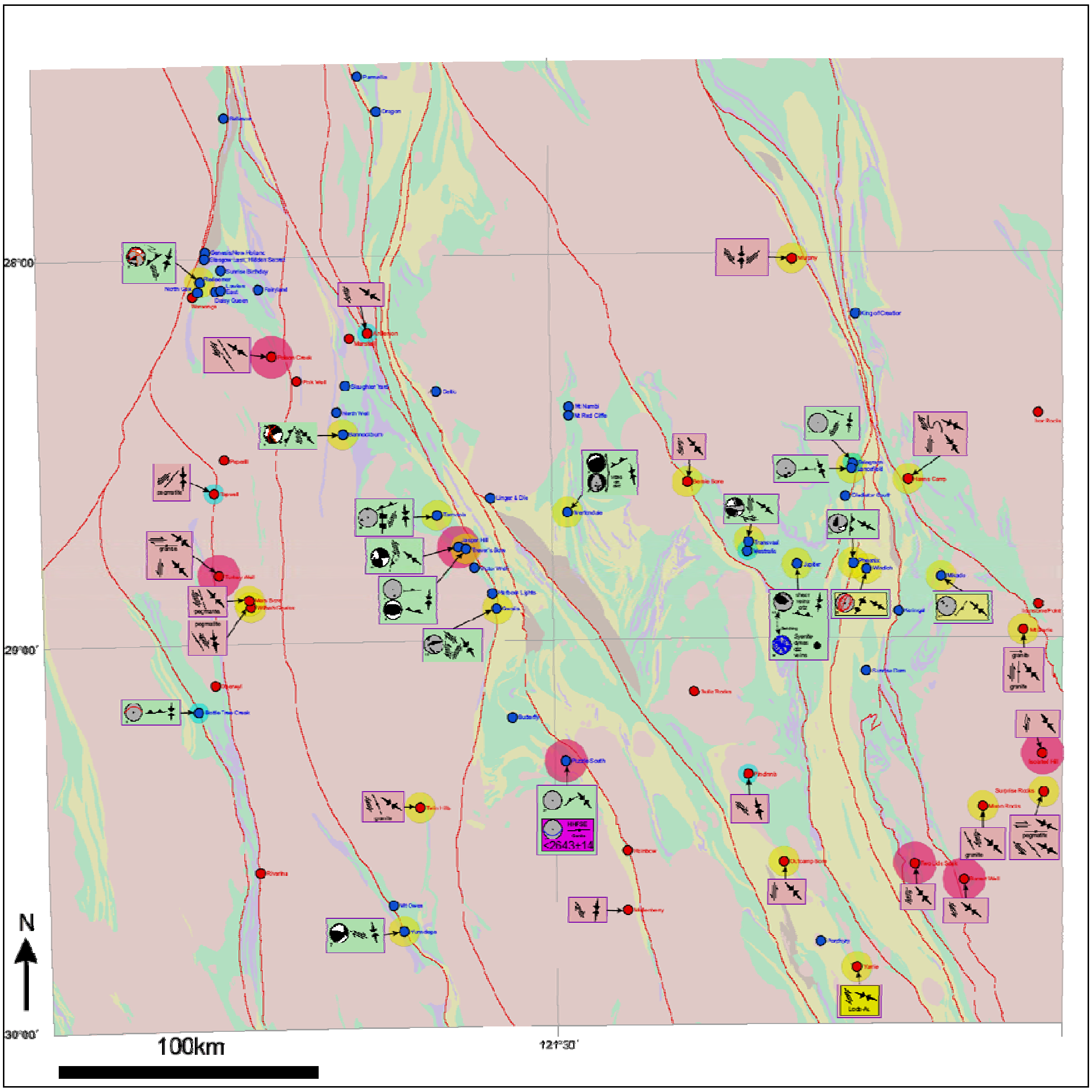


Figure 77: Map of D4 structures and their intensity across the study area at individual locations. Note the high degree of variability in the inferred maximum compression (σ1) orientation with this event.

Pink - granites, Yellow – sediments and felsic volcanics, Green – mafic-ultramafics, and Brown – late basins. Intensity shown as size and colour of circles, with red (high strain), yellow (medium strain), and blue (low strain). See Appendix 3.1.10 for interactive maps.

D5: dextral transpression

The D5 event is traditionally called D3 in the Swager (1997) nomenclature, and many workers have suggested that it was a progressive event from earlier D2 (e.g., Weinberg et al., 2003 and references therein). However, this study has shown that a significant extensional event and, although low-strain, a significant ~N-S contractional event separates them. Blewett et al. (2004b) defined the D5 event as their 'D2b', with D3 as their 'D2e' events. They, like many others did not account for the intervening D4 event (thinking it was younger than D5 as described here). It is because of this intervening D4 event that the surge hypothesis is rejected (*cf.* Blewett et al., 2004c).

The main feature of the D5 deformation is the re-establishment of the NE-SW contraction, under a dextral strike-slip régime (Fig. 78). In some localities along the eastern margin of the Kurnalpi Terrane the entire history recorded appears to be dextral shear (e.g., King of Creation). It could be that the D5 event was of sufficient intensity to 'obliterate' the pre-D5 history. The fundamental grain of this D5 dextral event was oriented N-S, similar to D2.

Characteristics of D5

One of the features of the D5 event was the steepening of layering, reworking of S2 foliations and the tightening of F2 folds. The fact that this was largely co-planar with the previous D2 event, that D3 was related and D4 of low strain; makes it particularly difficult to unravel the structural history through its various increments.

The D5 steepening on the western margin of the Kalgoorlie Terrane resulted in the Scotty Creek Basin being rotated into a vertical attitude. This basin was deposited onto a pre-folded sequence during D2 contraction or more likely D3 extensional doming (see above). With ongoing contraction onto the vertical layering failure was accomplished by thrusting at a high angle (orthogonal) to bedding. This late-stage failure is clearly demonstrated in the New Holland and Genesis pits as brittle-ductile conjugate vein arrays that host the gold. Overall tightening of the regional Lawlers Anticline occurred during this event.

Along the eastern margin of the Kurnalpi Terrane, dextral shear predominates, especially on the Hootanui Fault System (Fig. 78). Further west from the terrane boundary, D5 is partitioned into reverse faulting, with a NE-over-SE sense of movement. This thrust reworking of the earlier D2/D3 architecture gives the impression that this late event was the creator of the architecture. The amount of thrust movement is not known, but many appear to be relatively small scale and unlikely to cause significant crustal thickening. However, some crustal thickening may have been achieved by horizontal flattening and vertical extrusion of the crust.

D5 and the Low-Ca granite 'bloom'

A significant feature of the D5 event is that Low-Ca granites are either:

- overprinted by D5 structures (e.g., Mars Bore);
- overprint D5 structures (e.g., Ironstone Point); or,
- are emplaced into active D5 structures (e.g., Mt Denis).

These relationships are significant in that the Low-Ca granite type marks a fundamental change in the thermal régime of crust. These are high-temperature crustal melts and were emplaced over a short period of time (<2655-2630 Ma) relative to the higher-pressure High-Ca granite type (Champion and Sheraton, 1997; Cassidy and Champion, 2003). These granite types therefore provide temporal markers and provide maximum ages for the earlier events.

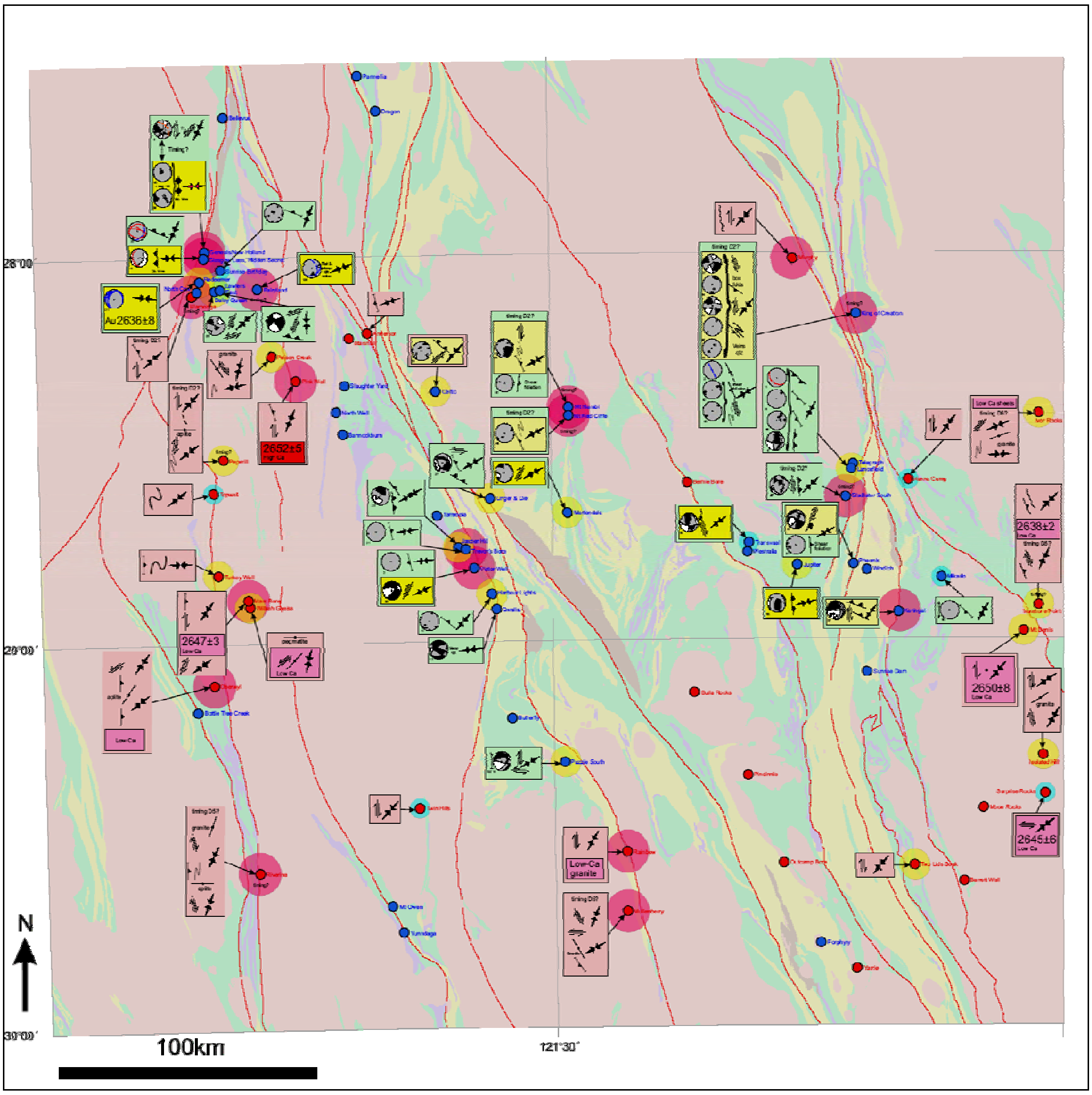


Figure 78: Map of D5 structures and their intensity across the study area at individual locations. Compare the location, intensity and direction of inferred σ1 for D5 and D2 (*cf.* Fig. 60)

Pink - granites, Yellow – sediments and felsic volcanics, Green – mafic-ultramafics, and Brown – late basins. Intensity shown as size and colour of circles, with red (high strain), yellow (medium strain), and blue (low strain). See Appendix 3.1.10 for interactive maps.

Significance of D5 to terrane boundaries

The event is most intensely developed on the western margin of the Kalgoorlie Terrane (Ida-Waroonga Fault System) and the eastern margin of the Kurnalpi Terrane (Hootanui Fault System). The D5 event is mostly weakly developed on the Ockerburry Fault Zone (except at Trevor's Bore and Victor Well), the terrane boundary between Kalgoorlie and Kurnalpi (see Appendix 3.1.10).

It is interesting to note that the boundaries with greatest difference across (Ida-Waroonga and Hootanui Fault Systems) recorded the greatest strain. It may indicate this D5 dextral transpressional event reorganised the Eastern Yilgarn sufficiently for differences in chemistry and age to be recorded across them.

D6: embrittlement of a dextral system

The D6 stage is likely a progression from the D5 dextral transpressional stage. It is separated from D5 because the style is brittle (as opposed to ductile) and the intensity and degree of reworking is minor. The D6 event is still present across the Eastern Yilgarn and there does not appear to be any diagnostic spatial significance to its distribution (Appendix 3.1.10). No gold is known from this event, it is traditionally described as D4 in the Swager (1997) framework.

At the largest scale, the consistent E-W sinistral faults offsetting the main NNW-oriented structures with 1-2 km displacements that are visible in aeromagnetic images are interpreted as D6.

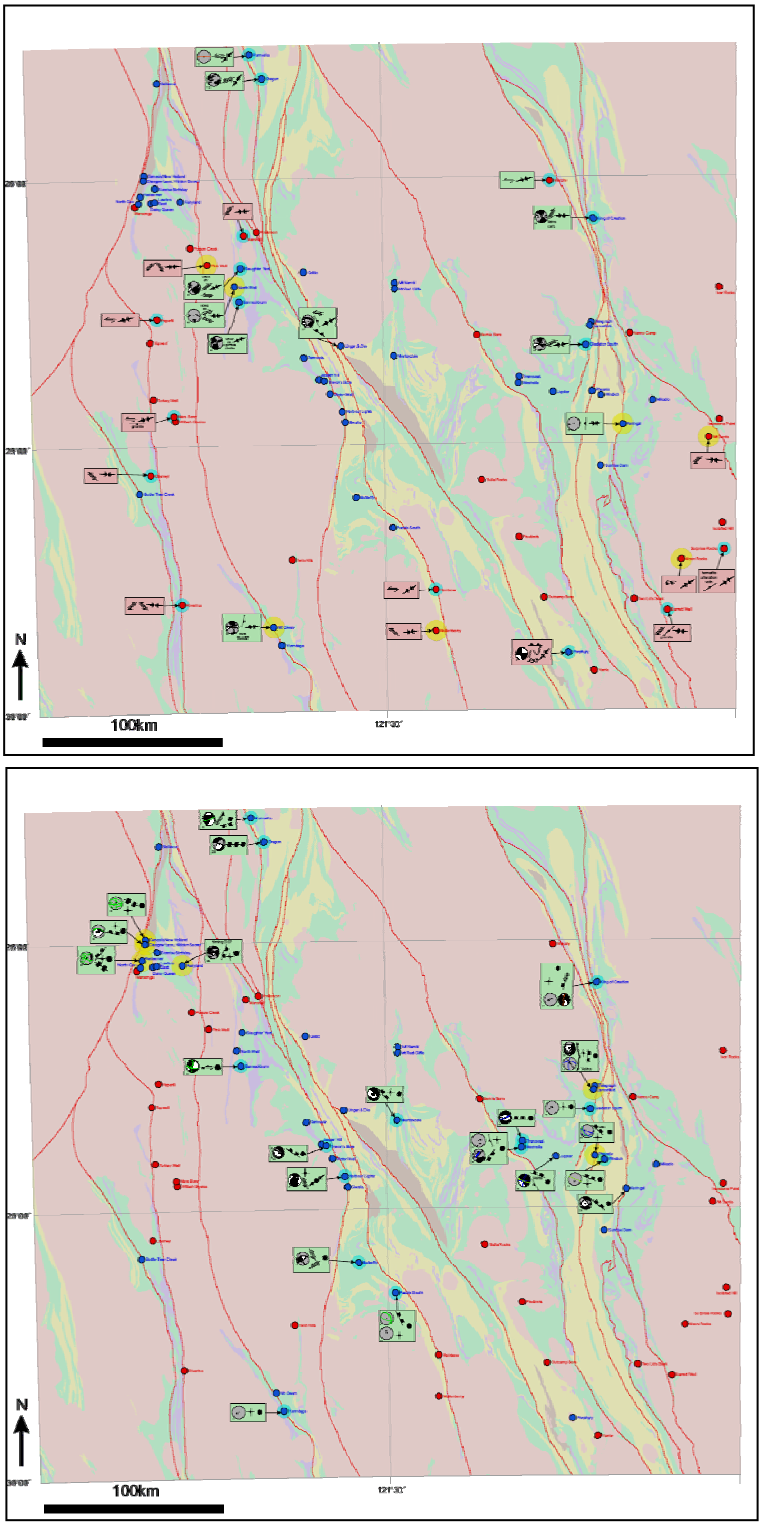
On the scale of the pits and granites sites, the D6 structures include E-over-W thrusts, open folds and strike-slip faults of varying geometry and kinematics. All these structures resolve their PT-dihedra into an ~E-W contractional régime.

D7: Low-strain systemic collapse

The last event of significance is the late orogenic collapse of the system. This event has been described previously by Swager (1997), Davis and Maidens (2003) and Weinberg et al. (2003). Swager (1997) suggested that this event was responsible for the present day juxtaposition of the high-grade Youanmi Terrane against the Kalgoorlie Terrane across the Ida-Waroonga Fault System. If the Ida-Waroonga Fault System collapse is related to the D7 event described here, then a constraint of older than 2640±8 Ma is provided by the stitching pluton of this deformation (i.e., Clarke Well Monzogranite – age from Nelson, 1997).

The D7 event occurs across the Eastern Yilgarn and is represented by the development of crenulations, with sub-horizontal axial planes at a range of amplitudes from millimetres to metres. The fold hinges plunge variably. The structural style is brittle to locally brittle-ductile normal faulting (Fig. 79).

The D7 event is most intensely developed (Appendix 3.1.10) on the western margin of the Kalgoorlie Terrane (Ida-Waroonga Fault System) and the eastern margin of the Kurnalpi Terrane (Hootanui Fault System) (Fig.79). The spatial co-incidence in intensity of D5 flattening and transpression and subsequent collapse in D7 may be significant and reflect re-adjustment of the crust to the previously partitioned D5 event.



Pink - granites, Yellow – sediments and felsic volcanics, Green – mafic-ultramafics, and Brown – late basins. Intensity shown as size and colour of circles, with red (high strain), yellow (medium strain), and blue (low strain). See Appendix 3.1.10 for interactive maps.

Figure 79: Map of D6 (upper) and D7 (lower) structures and their intensity across the study area at individual locations. These are both very low strain events.

Timing constraints of deformation

The best dataset available for constraining the ages of the deformation stratigraphy is in the granites (Blewett et al., 2004a). This work was based on the geochronological framework established by many workers, but in particular Nelson (1996, 1997), Fletcher et al., (2001), Cassidy et al. (2002), Dunphy et al. (2004), and Black (unpublished GA data).

The Eastern Yilgarn Craton was deformed by a series of what appears to be long–lived extensional stages associated with granite emplacement, interspersed with short–lived contractional stages. A graphical representation of the timing constraints on deformation is presented in Figures 80 and 81. A comparison to the deformation framework of Swager (1997) is presented in Figure 80 (see also the Forward section in this report). The classical 'D1' N–S contractional event of Swager (1997) appears absent. In this study, D1 is interpreted as a long-lived extensional event with time recorded in the rock record itself. A question remains whether the extension was episodic or continuous.

The Kambalda Komatiite is dated around 2705 Ma (Nelson, 1997), and the Upper Basalt is younger than the Kapai Slate which is dated around 2692±4 Ma (Claoue-Long, et al., 1989). The Kalgoorlie Sequence (Black Flag Formation) has age ranges from 2690 to 2665 Ma (Krapěz et al., 2000). The Kalgoorlie Sequence has a number of unconformities, with one at around 2675 Ma (Fig. 56). At the same time in the 'external' granites, a major melting and exhumation event occurred. The age of the gneissic fabrics are in the range of: 2672±2 (Two Lids Soak); 2675±2 (Barrett Well); 2670±10 (Ivor Rocks); 2681±4 Ma (Isolated Hill), and 2674±3 Ma (Wilbah). Such consistent data, across regionally separate sites (similar ages are reported from Duketon: Dave Champion pers comm. 2005), indicate a maximum age for metamorphism and D1 extension of around 2672 Ma.

The first contractional event is D2, which has a maximum age range constrained by the dates of deformed granites and a minimum age range from cross-cutting granites. In this study the available ages are found in the Burtville and Kurnalpi Terranes. In the Burtville Terrane D2 occurred in the range <2668±4 Ma (Ironstone Point) and inferred to be >2664±2 (Hanns Camp Syenite) based on a relative timing correlation (see appendix 3.1.1). In the Kurnalpi Terrane D2 occurred at <2667±4 Ma (Pindinnis), <2665±4 Ma (Granny Smith Granodiorite), <2667±5 Ma (Porphyry), <2657±8 Ma (Porphyry), and is inferred to be >2660±5 Ma (Bulla Rocks) based on a relative timing correlation (see appendix 3.1.1).

The D3 event is a strong extensional event associated with the development of Late Basins and the emplacement of the Syenite type granites. This D3 extensional event occurred between a major switch in palaeostress from D2 ENE–WSW contraction to D4 NNW–SSE contraction. The Syenite and Mafic granite types are generally regarded as reflecting regional extension, as these rock have 'seen' the mantle (Champion and Sheraton, 1997). A maximum age for D3 can be inferred from the overprint of extensional fabric on granites such as the 2664±2 Ma Hanns Camp Syenite and 2660±5 Ma Bulla Rocks Monzogranite. If the mineralisation at Sunrise Dam is related to the D3 extension then the overlap in Au mineralisation ages at Sunrise can be used to constrain the timing of D3 to 2658±4. This age is consistent with the maximum deposition age of the Scotty Creek late basin of 2662±5 Ma.

The D4 NNW–SSE contractional stage occurred prior to any Low-Ca granite type magmatism which is present across all terranes (and the Yilgarn Craton as a whole).

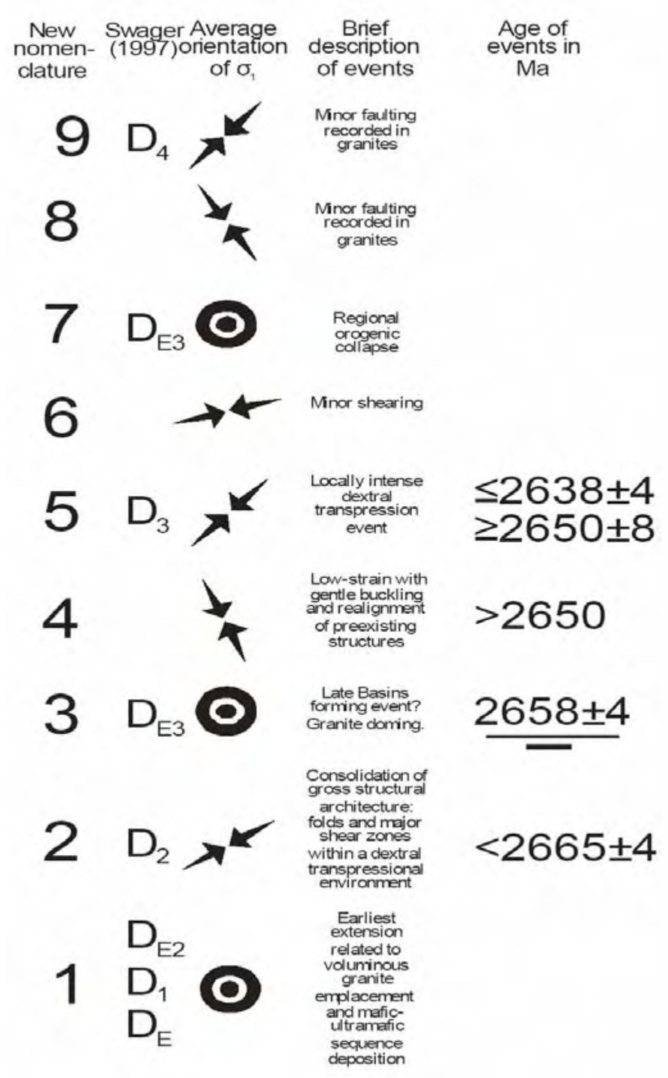


Figure 80. A synthesis of the timing and deformation history presented here in as compared to Swager (1997).

The Low-Ca granite type granites were emplaced following a switch in palaeostress back to NE–SW contraction (D5). These granites provide a maximum age for D5 as <2652±5 Ma (Pink Well), <2650±8 Ma (Mount Denis), and <2645±6 Ma (Surprise Rocks). At Mars Bore a dyke of Low-Ca type granite with an age of 2647±3 Ma overprints D5 dextral shear zones and is overprinted by D5 dextral shear zones. A minimum age for D5 is obtained from Low–Ca granite type dykes that overprint D5 fabric elements of 2638±2 (Ironstone Point).

SHRIMP dates of the youngest phases of the Low–Ca granite types of the Burtville Terrane provide temporal constraints on the D7 extensional collapse, which occurred between contractional D6 and D8. At Ironstone Point, 2638±2 Ma Low–Ca granite dykes are overprinted by D6 ENE–WSW contraction. At Moon Rocks, 2637±7 Ma Low–Ca granite dykes are syndeformational and were emplaced into dextral faults during the D8 NW–SE contraction. Despite both the Moon Rocks and Ironstone Point ages being within error, and considering the larger errors bars at Moon Rocks, it is suggested that the D7 extensional collapse occurred at about 2635 Ma. The regional orogenic collapse event on the Ida Fault System described by Swager (1997) has a minimum age of 2640 ±8 Ma (Clarke Well Monzogranite: not in this study area), and is consistent with this estimate.

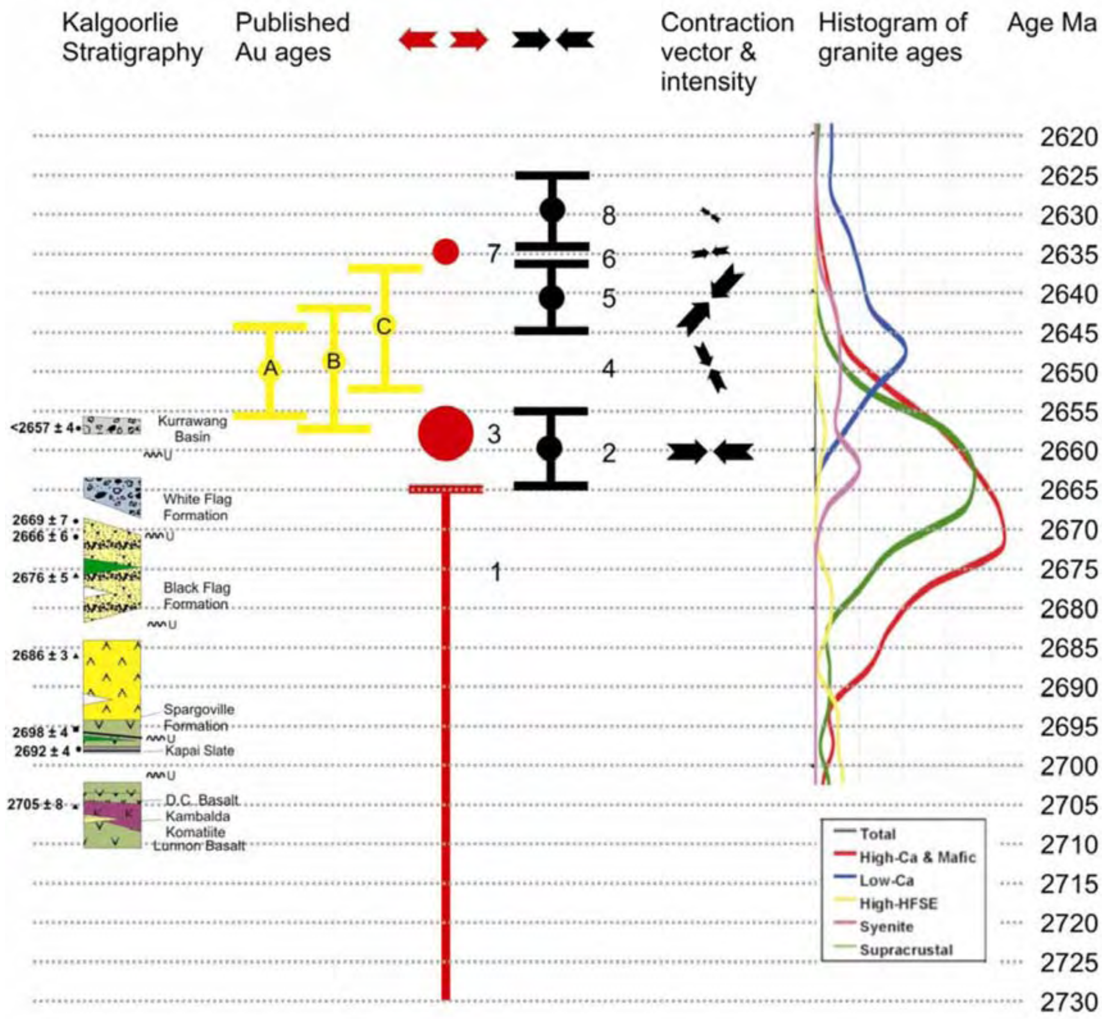


Figure 81: Time event intensity history chart for the Eastern Yilgarn Craton. The chart compares granite ages (from Cassidy and Champion, 2002) and the Kalgoorlie stratigraphy (from Krapěz et al., 2000). Note the peak High-Ca type granite age of ~2673 Ma and the unconformity at the top of the Black Flag Formation followed by the onset of coarse clastic sedimentation (White Flag Formation). Vectors of contraction and stylised intensity are shown in black arrows. Error bars for the ages of the contractional events are shown (see text for details). Extensional events are dominantly ENE-directed, with local perturbations around individual domes. Published direct-dating of gold deposits (A-Wallaby: Salier et al., 2004; B-Sunrise Dam: Brown et al., 2002; C- Chalice: Bucci et al., 2004) are around 2650 Ma. All occur within error at the switch from High-Ca type to Low-Ca type granites and during a switch in contractional palaeostress from dominantly E-W (NE-SW) to NNW-SSE vectors (during D4).

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