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**DIVERSITY OF STRUCTURALLY CONTROLLED
GOLD THROUGH TIME AND SPACE OF THE
CENTRAL EASTERN GOLDFIELDS
SUPERTERRANE — A FIELD GUIDE**

by RS Blewett and K Czarnota



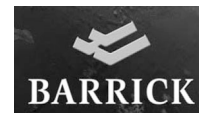
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DIVERSITY OF STRUCTURALLY CONTROLLED GOLD THROUGH TIME AND SPACE OF THE CENTRAL EASTERN GOLDFIELDS SUPERTERRANE — A FIELD GUIDE

**by
RS Blewett¹ and K Czarnota¹**

¹ pmd*^{CRC}, Onshore Energy and Minerals Division, Geoscience Australia,
GPO Box 378, Canberra, ACT, 2601

Perth 2007

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Hon. Francis Logan MLA

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The book 'Diversity of structurally controlled gold through time and space of the central Eastern Goldfields Superterrane — a field guide' is published by the Geological Survey of Western Australia (GSWA) to accompany the field trip of the same name conducted as part of the Kalgoorlie '07: Old Ground. New Knowledge conference, held in Kalgoorlie from 25 to 27 September 2007. The text was edited to bring it into GSWA house style. The scientific content and initial drafting of the figures were the responsibility of the authors

REFERENCE

The recommended reference for this publication is:

Blewett, RS, and Czarnota, K, 2007, Diversity of structurally controlled gold through time and space of the central Eastern Goldfields Superterrane — a field guide: Geological Survey of Western Australia, Record 2007/19, 65p.

National Library of Australia Card Number and ISBN 978-1-74168-133-8 (PDF)

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 51.

Cover image modified from Landsat data, courtesy of ACRES

Published 2007 by Geological Survey of Western Australia

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Contents

Introduction	1
Regional geology terranes	1
Regional geology greenstones	3
Kalgoorlie Terrane	3
Kurnalpi Terrane	6
Burtville Terrane	6
Greenstones: tectonic implications and isotopes	6
Late basins	6
Late basins: tectonic implications	7
Regional geology granites	7
Granites: tectonic implications and isotopes	7
Previous structural frameworks	9
D _E : early extension	9
D ₁ : north–south contraction	10
Late basins	10
D ₂ : east–west contraction	10
Local extension	10
D ₃ : ongoing east–west contraction	14
D ₄ : late contraction	14
Granite studies	15
Metamorphic patterns	15
Late extension (collapse)	15
New structural framework	15
A new integrated tectonic framework	18
D ₁ : long-lived extension and granite–greenstone formation	18
D ₂ : termination of an arc and east–northeast–west–southwest contraction	18
D ₃ : extensional granite doming, mafic granites, and late basin formation	19
D ₄ : sinistral transpression	19
D ₅ : dextral transtension and crustal melting	20
D ₆ : low-strain systemic collapse	20
D ₇ : Proterozoic contractional events	20
Timing constraints of deformation	20
D ₁ constraints	21
D ₂ constraints	21
D ₃ constraints	21
D ₄ constraints	21
D ₅ constraints	21
Post-D ₅ and younger event age constraints	21
Implications for predictive gold discovery	22
Excursion localities — Menzies to Leonora	23
Day 1	23
Locality 1: Yunndaga — a sinistral shear-hosted gold deposit	23
Locality 2: Tarmoola — contractional gold with an extensional overprint	23
Locality 2a: Mineralized greenstone with steep contact with trondhjemite	29
Locality 2b: Extensional overprint of contractional gold	29
Locality 2c: Late thrust overprinting extension	31
Locality 3: Sons of Gwalia mine — gold in extension during formation of the late basins	31
Locality 3a: View north of the Sons of Gwalia openpit	34
Locality 3b: Extensional kinematics of the Sons of Gwalia shear zone	35
Day 2	36
Excursion localities — Lawlers area	36
Locality 4: Sunrise Birthday — extensional gold in gabbro on a regional dome nose	36
Locality 4a: Regional north–northwesterly striking foliation	36
Locality 4b: Gold in an extensional shear zone	38
Locality 5: New Holland — low-displacement contractional gold in competent late basin sandstones	38
Locality 6: Poison Creek complex granites with multiple phases of intrusion and structure	42
Locality 7: Victor Well — dextral shear and gold	44
Excursion localities — Leonora to Laverton	45
Day 3	45
Locality 8: Mertondale — gold in sinistral transpression	45
Locality 9: Jupiter — syenite-hosted gold (a Wallaby analogue)	50
Locality 9a: View southeast of the Jupiter pit	50
Locality 9b: Syenite dykes, faults, and alteration up close and personal	50
Excursion localities — Laverton area	51

Day 4	51
Locality 10: King of Creation—transpressional, dextral shear-zone gold.....	51
Locality 11: Lancefield—extensional gold with a dextral strike-slip overprint.....	53
Locality 11a: View north over the openpit.....	59
Locality 11b: Extensional shear zone via the northern access ramp of openpit	59
Locality 12: Hanns Camp Syenite	59
Acknowledgements	59
References	62

Figures

1. Tectonic division of the Yilgarn Craton, showing subdivision into terranes and domains.....	2
2. Map of the Eastern Goldfields Superterrane and sites of specific structural studies described	3
3. Greenstone stratigraphy of the Eastern Goldfields Superterrane	4
4. Map of the five granite types of the Yilgarn Craton	8
5. Histogram of granite and greenstone ages for the Yilgarn Craton	8
6. Integrated time–space synthesis of greenstone stratigraphy, granite ages by type, structure, tectonic mode, and Au mineralization for the Eastern Goldfields Superterrane (A3 fold out)	11
7. Fundamental architecture of the Eastern Goldfields Superterrane is revealed in the crustal residence ages.....	13
8. Comparative deformation chronology of various workers in the Eastern Goldfields Superterrane.....	13
9. Schematic diagram illustrating the geometry of the extensional architecture of the system	14
10. Synthesis structural-event chart of the localities visited in this field guide	16
11. Simplified geological map of the Yunndaga pit near Menzies	24
12. Stereographic compilation of structural elements into discrete events at the Yunndaga deposit	25
13. Compilation of photographs from the Yunndaga pit	26
14. Compilation of photographs from the Yunndaga pit	27
15. Simplified geological map of the Leonora district with the Tarmoola (Locality 2), Sons of Gwalia (Locality 3), and Victor Well (Locality 7) sites shown.....	28
16. Stereographic compilation of structural elements into discrete events at the Tarmoola deposit.....	29
17. Compilation of photographs from Tarmoola.....	30
18. Location of field sites in the Tarmoola pit.....	31
19. Schematic diagram illustrating how the geometry of faults influences the structures observed at each location.....	31
20. a) Orthophotograph of the Leonora area showing the location of the Gwalia mine and the ‘deeps’ to the southeast of the openpit and parallel to the stretching lineation b) Geometry of the Gwalia openpit and associated Gwalia deeps	32
21. Compilation of photographs from Gwalia openpit	33
22. Compilation of extension recorded on a range of scales in the Leonora area.....	34
23. Compilation of photographs from Gwalia openpit	35
24. Stereographic compilation of structural elements in the Gwalia pit	36
25. Simplified geological map of the Lawlers area with the location of Sunrise Birthday and New Holland	37
26. Compilation of photographs from the Sunrise Birthday pit.....	39
27. Compilation of structural elements from the Sunrise Birthday pit	40
28. Cross section from New Holland mine showing the development of stacked ore zones restricted to a steeply west-dipping sandstone horizon.....	40
29. Compilation of photographs from the New Holland mine and region	41
30. Compilation of structural elements from the New Holland mine.....	42
31. Details of the dextral shear at a sandstone–siltstone interface (Crucifix Fault)	43
32. Compilation of structures from a typical granite pavement (Poison Creek) in the EGST	44
33. Detailed pavement map of Poison Creek, showing the various phases of dykes and faults/shears	45
34. Schematic diagram of Victor Well pit illustrating the rotation of S_3 into the D_3 dextral shear zone and the development of C’ planes in the central part of the shear zone.....	46
35. Location map and geology of the Mertondale line of deposits	47
36. Compilation of structural elements from Mertondale.....	48
37. Compilation of photographs from Mertondale	49
38. Geological map, cross section and photograph of the Jupiter deposit	50
39. Compilation of structural events and features at the Jupiter pit.....	52
40. Stereographic compilation of structural elements into discrete events at the Jupiter deposit.....	53
41. Strain partitioning across the King of Creation shear zone under dextral transpression	54
42. Collage of folds and associated foliation at King of Creation	55
43. Compilation of photos of extension-related ore zones at the Lancefield mine	56
44. Compilation of photographs from post- D_3 extensional events in the Lancefield pit.....	57
45. Compilation of structural elements at the Lancefield pit	58
46. Simplified geological map of the Lancefield deposit and region	58
47. Panorama of the Lancefield deposit highlighting the convex nature of the pit and the Lancefield shear zone.....	58
48. Compilation of structural events of the c. 2665 Ma Hanns Camp Syenite	60

Diversity of structurally controlled gold through time and space of the central Eastern Goldfields Superterrane — a field guide

by

RS Blewett¹ and K Czarnota¹

Introduction

This field guide accompanies a pre-conference excursion of the Australian Institute of Geoscientists (AIG) conference entitled 'Kalgoorlie '07: Old Ground, New Knowledge'. This meeting is the third in a series of international conferences that bring into focus the recent advances in the understanding of the geology and mineral deposits of the Yilgarn Craton and its margins. It builds on the highly successful Kalgoorlie '93 and Kalgoorlie '97 conferences.

*Most of the trip localities are in active tenements and permission from the respective tenement holders is required **before** the reader attempts to revisit the sites. Personal Protective Equipment (PPE) and inductions will also be a requirement and these may vary from site to site.*

The purpose of this excursion is to examine the diversity in the structural setting of gold deposits across the Eastern Goldfields Superterrane (EGST; Cassidy et al., 2006), and establish a regional deformation framework for the EGST (Fig. 1). The excursion will demonstrate that gold is hosted in a wide range of structures including reverse faults, both sinistral and dextral strike-slip faults, and extensional shear zones. The excursion will also highlight the range of host lithologies for gold, including sedimentary rocks, intrusive and extrusive ultramafic and mafic rocks, together with granitoids (syenite and porphyry). The excursion will traverse the Kalgoorlie and Kurnalpi Terranes of the EGST, with localities in the far west at Lawlers through to the far east around Laverton (Fig. 2). The excursion will attempt to place these gold deposits, and their host lithologies and controlling structures, in an integrated geodynamic framework.

The science underpinning this excursion was developed during the Y1-P763 project of the Predictive Mineral

Discovery Cooperative Research Centre (*pmd**CRC) and AMIRA International. The project was executed as three modules between 2002 and 2005, with the structural evolution being the third. The aim of Module 3 (being described here) was to determine the structural evolution of the various terranes of the EGST as well as the nature and significance of their boundaries. Module 3 was a comprehensive structural study of 42 mines and was integrated with earlier structural work on 32 granite sites (Blewett et al., 2004a) and 3D regional map patterns (Henson et al., 2004a; Henson, 2006). A comprehensive database, atlas, series of posters and a report were delivered to sponsors in November 2005. A public domain release of this document has now been prepared (Blewett and Czarnota, 2007b).

The science driver behind the Y1-P763 project was to try to resolve the geodynamic evolution of the EGST. A range of competing models have been proposed, including:

- ensialic extensional rifts or basins (Archibald et al., 1978; Hallberg, 1985; Hammond and Nisbet, 1992; Williams and Whitaker, 1993; Passchier, 1994);
- convergent margin settings (Barley et al., 1989; Eisenlohr et al., 1989; Swager et al., 1992; Witt, 1994);
- accretionary models (Myers, 1995);
- strike-slip tectonics (Krapěž et al., 2000); and
- mantle plumes (Campbell and Hill, 1988).

This field guide is an extract of the final report delivered to sponsors of the Y1-P763 project. The regional geology sections below are extracted from the *pmd**CRC Y2 project report (see Cassidy, 2006). The sponsors of Y1-P763 and Y2 are acknowledged for permission to publish this guide.

Regional geology terranes

The Yilgarn Craton has been recently subdivided by Cassidy et al. (2006) into six terranes, three of which

¹ *pmd**CRC, Onshore Energy and Minerals Division, Geoscience Australia, GPO Box 378, Canberra, ACT, 2601

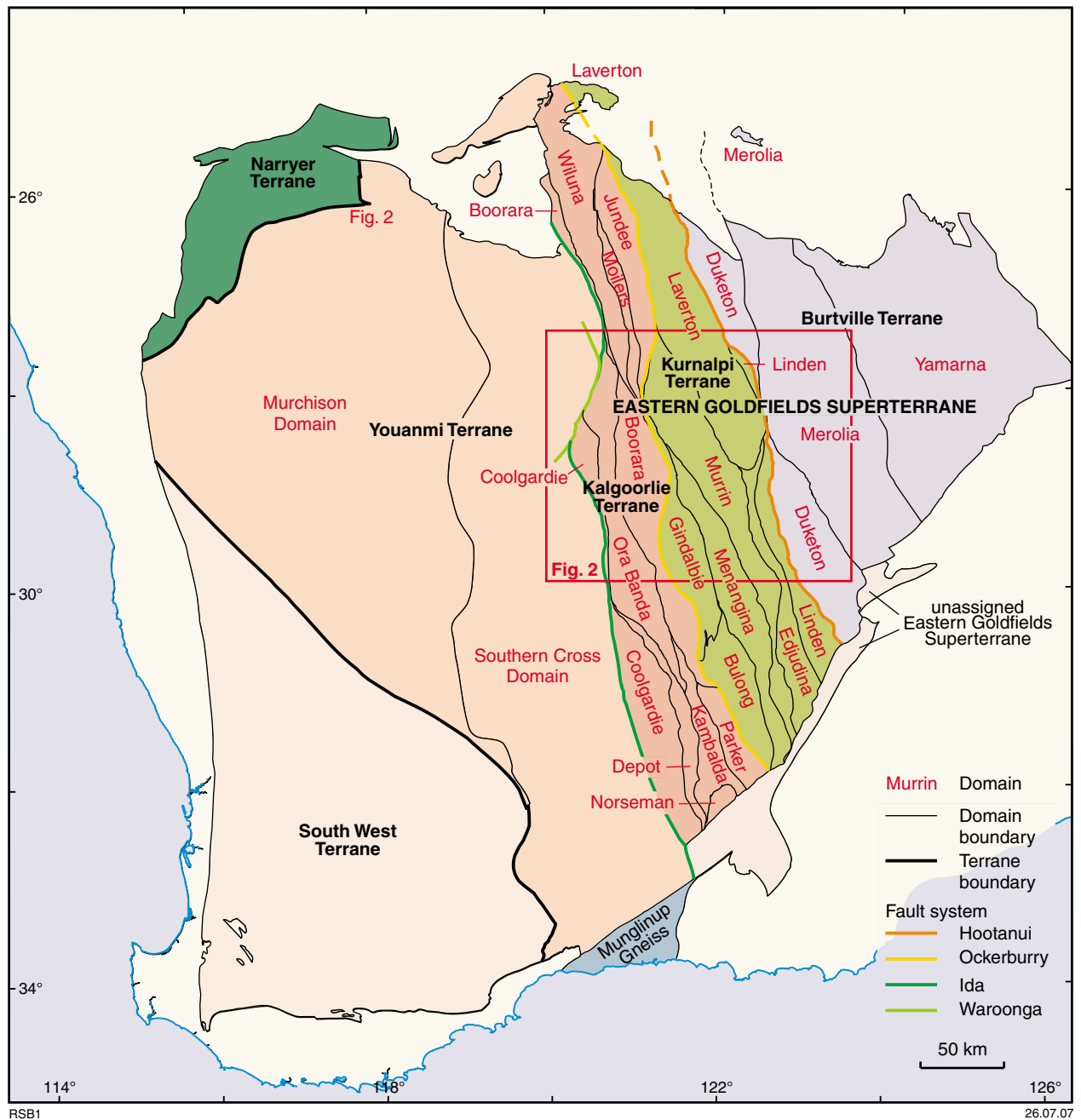


Figure 1. Tectonic division of the Yilgarn Craton, showing subdivision into terranes and domains (after Cassidy et al., 2006). Note the north-northwesterly trending grain of the fault-bounded terranes and domains of the Eastern Goldfields Superterrane. The red box shows the location of Figure 2

constitute a superterrane (Fig. 1). In the west, the Narryer Terrane and the South West Terrane are dominated by granite and granitic gneiss, whereas the central Youanmi Terrane and the Eastern Goldfields Superterrane are composed of north-trending greenstone belts separated by extensive granite and granitic gneiss.

The Narryer Terrane in the northwest part of the craton consists of c. 3.73–2.6 Ga high-grade gneiss, and supracrustal and granitic rocks. It is host to metasedimentary rocks famous for their greater than 4.4 Ga detrital zircons (Wilde et al., 2001).

The South West Terrane in the southwest part of the craton consists of greater than 3.2–2.6 Ga high-grade gneiss, and supracrustal and granitic rocks. The Youanmi Terrane consists of c. 3.01–2.63 Ga greenstones and granitic rocks. It incorporates the ‘Southern Cross and Murchison Provinces’ of Gee et al. (1981), and includes the Cue Domain that may constitute a separate terrane.

The Eastern Goldfields Superterrane consists of three terranes. In the west, the Kalgoorlie Terrane is made up of a series of greater than 2.76–2.63 Ga granite–greenstone

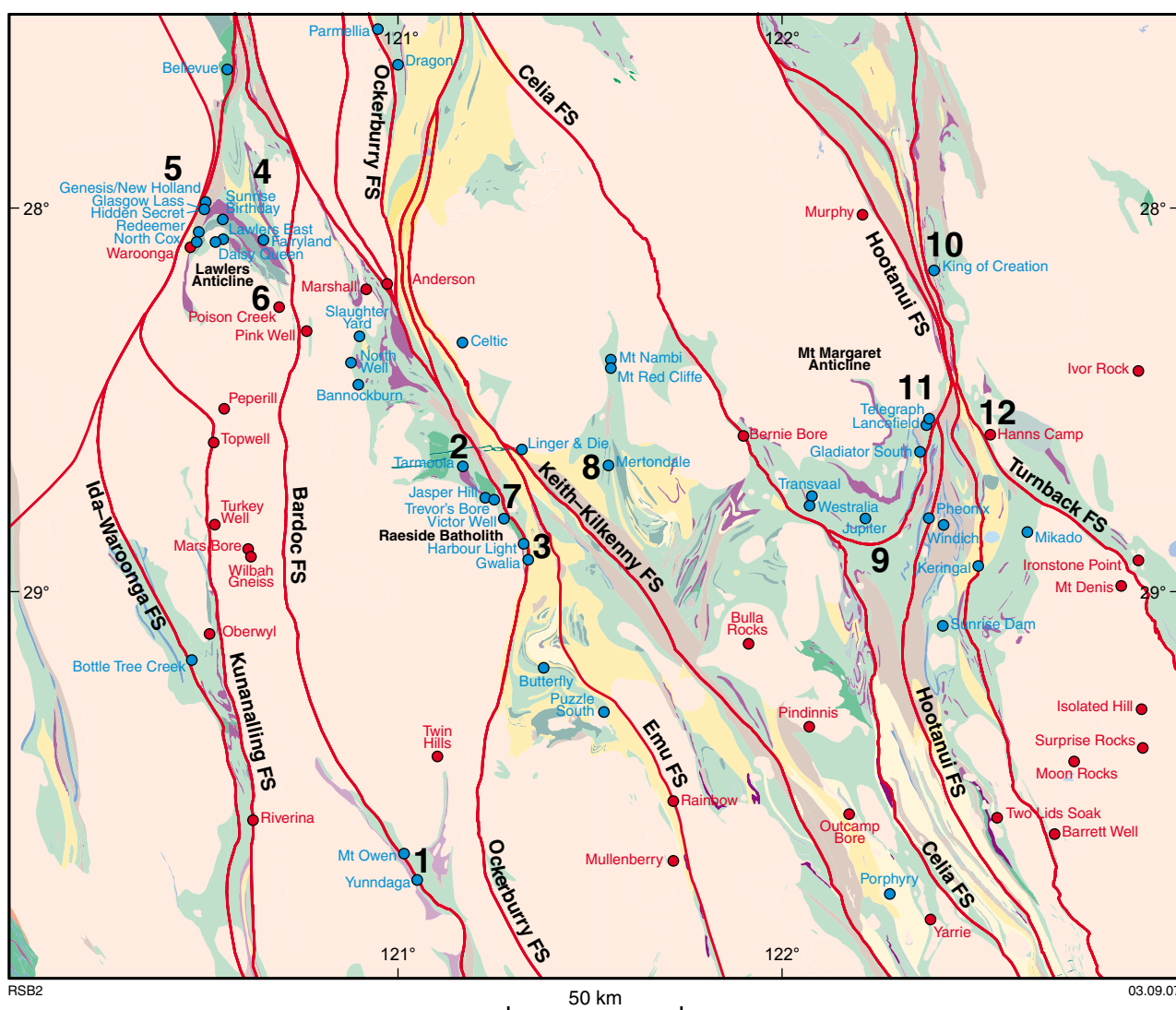


Figure 2. Map of the Eastern Goldfields Superterrane and sites of specific structural studies described (blue = mine sites; red = granite sites). The localities visited in this field guide are numbered. FS = fault system

domains that form part of the 'Eastern Goldfields Province' of Gee et al. (1981), and approximates the 'Kalgoorlie Terrane' of Myers (1997). The central Kurnalpi Terrane is a complex series of c. 2.95–2.63 Ga granite–greenstone domains that form part of the 'Eastern Goldfields Province' of Gee et al. (1981), and incorporates the 'Gindalbie, Kurnalpi and Laverton Terranes' of Myers (1995, 1997). To the east is the Burtville Terrane, which is poorly defined by c. 2.95–2.63 Ga granite–greenstone domains, and forms part of the 'Eastern Goldfields Province' of Gee et al. (1981) and incorporates the 'Duketon Terrane' of Barley et al. (2002, 2003).

The terranes and domains in the EGST are bound by interconnected systems of faults (Swager et al., 1992, Swager, 1997; Liu et al., 2000) that have been defined as part of the *pmd**CRC Y2 project (see Champion, 2006). From west to east, these terrane-bounding fault systems are the Ida, Ockerburry and Hootanui Fault Systems (Figs 1 and 2).

Regional geology greenstones

Tholeiitic, komatiitic, and calc-alkaline volcanic and sedimentary rocks that developed dominantly between c. 2.72 and 2.66 Ga form the bulk of the successions in the EGST (Fig. 3). These sequences generally young towards the west, with the greenstone succession in the Kalgoorlie Terrane containing the youngest volcanoclastic units (Barley et al., 2002, 2003).

Kalgoorlie Terrane

The intensely mineralized Kalgoorlie Terrane is an amalgamation of young (<2.71 Ga) and fragments of old (>2.74 Ga) tectono-stratigraphic associations (Fig. 3). Enclaves or domains of older (>2.74 Ga) greenstone successions (Kambalda and Wiluna Domains, Leonora district in the Boorara Domain) are present in the

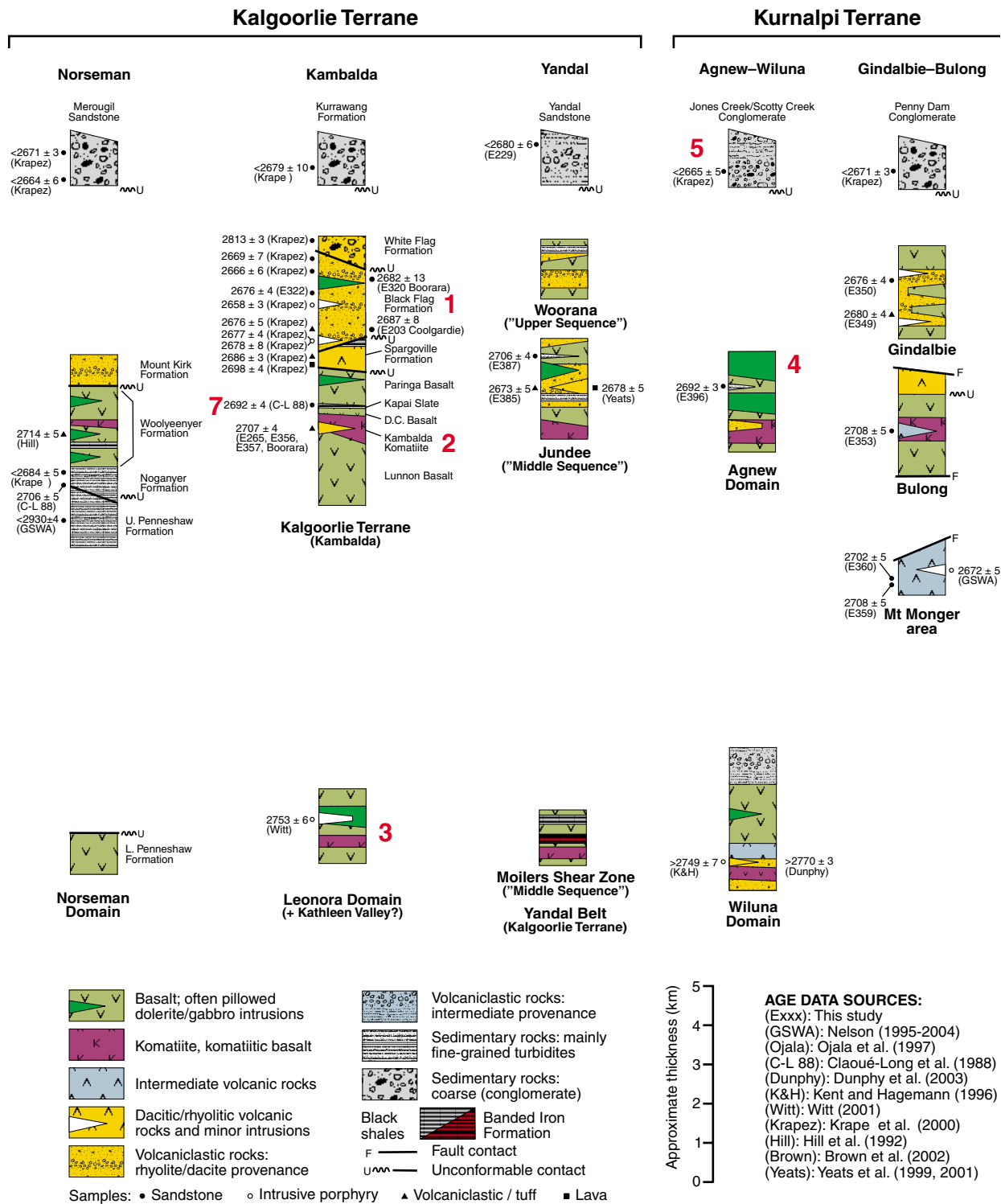
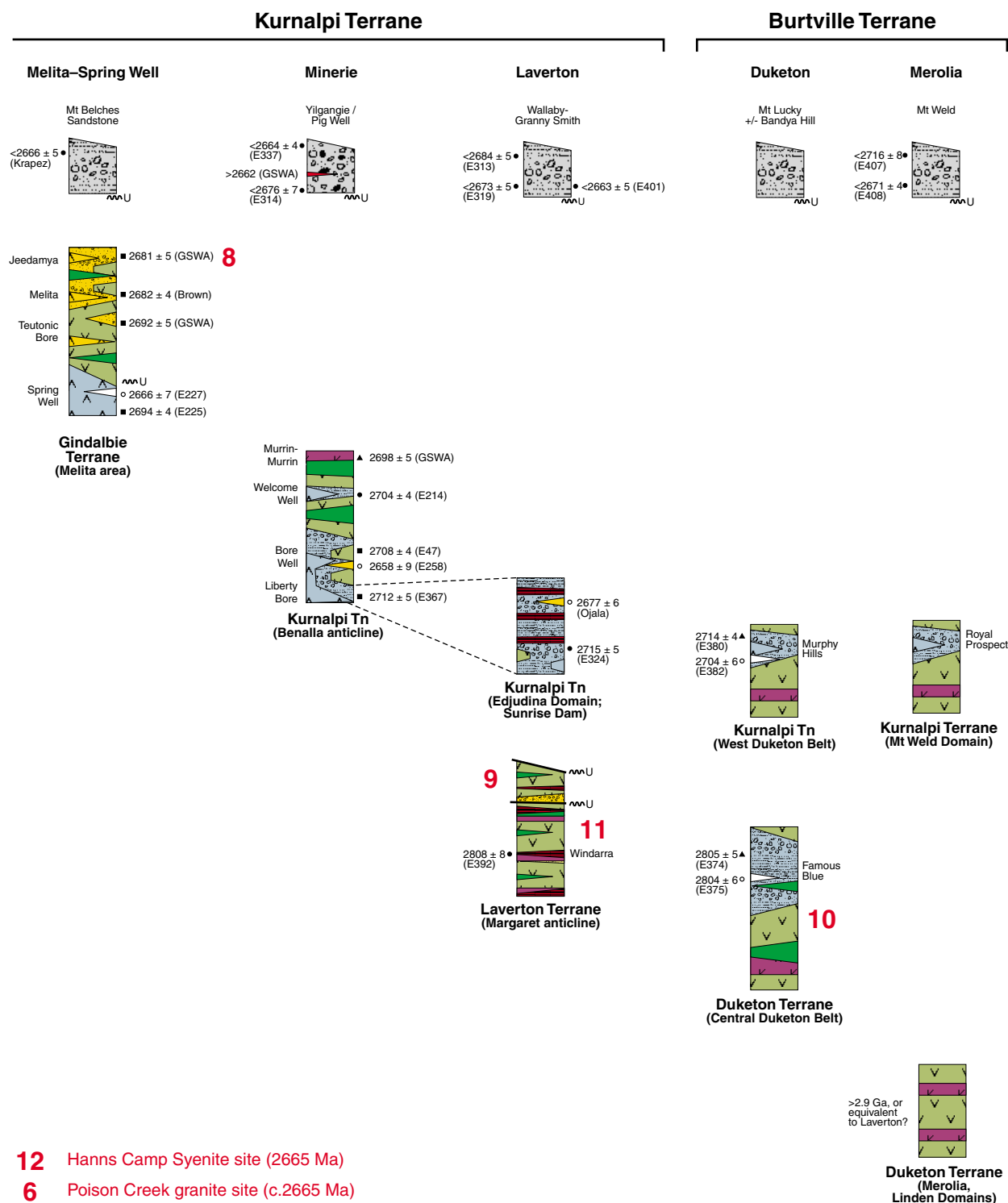


Figure 3. Greenstone stratigraphy of the Eastern Goldfields Superterrane (after Barley et al., 2002). Red numbers are the stratigraphic position of the locality stops in the field guide (except the two granite sites)



Kalgoorlie Terrane (Barley et al., 2002). It is possible that these older enclaves represent autochthonous fragments of Youanmi Terrane basement to the EGST younger rock units.

The less than 2.71 Ga greenstone successions in the southern Kalgoorlie Terrane (especially the Kambalda Domain) are divided into the 2.71–2.69 Ga tholeiitic and komatiitic mafic–ultramafic (Kambalda sequence) and 2.69–2.66 Ga felsic volcanoclastic (Kalgoorlie sequence) sequences (Barley et al., 2002, 2003). The Kalgoorlie sequence (incorporating the Black Flag Group) is a tonalite–trondhjemite–granodiorite (TTG) volcanoclastic association restricted to the Kalgoorlie Terrane and was deposited in an extensional, deep-marine, intra-arc basin between 2.69 and 2.66 Ga. The Kalgoorlie Terrane includes similar greenstone successions in the Boorara and Yandal Domains (Fig. 3).

Kurnalpi Terrane

The Kurnalpi Terrane includes 2.715–2.705 Ga mafic volcanic rocks, intermediate calc-alkaline complexes, feldspathic sedimentary rocks, and mafic intrusive rocks, and 2.695–2.675 Ga bimodal high field strength element (HFSE)-enriched rhyolite–basalt and intermediate–felsic calc-alkaline complexes that extend along a linear belt (principally in the Gindalbie Domain) at the eastern edge of the Kalgoorlie Terrane (Fig. 3). The 2.71–2.715 Ga andesite-derived volcanoclastic rocks, and fine-grained sandstone–shale units ('BIF') in the eastern part of the Kurnalpi Terrane are separated out as the Edjudina Domain (Barley et al., 2002).

Despite now being juxtaposed, the felsic rocks in both the Kalgoorlie and Kurnalpi Terranes have distinct geochemistry at 2.715–2.66 Ga. Rocks of the c. 2.72–2.68 Ga Edjudina, Murrin and Menangina Domains in the east Kurnalpi Terrane are interpreted as representing an arc basin. In contrast, the 2.69–2.68 Ga rocks of the Gindalbie Domain to the west are interpreted as a rifting phase of this Kurnalpi Terrane (or similar) arc (Barley et al., 2002, 2003).

The c. 2.81 Ga Laverton Domain includes less than 2.8 Ga mafic and ultramafic volcanic rocks, BIF, fine-grained tuffaceous sediments, and possibly less than 2.87 Ga mafic and ultramafic volcanic rocks and BIF of the Dingo Range greenstone belt (Barley et al., 2003). The Edjudina and Linden Domains may form subdomains above an unconformity-bound not fault-bound Laverton Domain basement to the younger rock units (Cassidy et al., 2006).

Burtville Terrane

The Duketon Domain in the Burtville Terrane (Fig. 1) includes c. 2805 Ma intermediate and felsic volcanic rocks and associated mafic (–ultramafic) rocks in the central and eastern part of the Duketon greenstone belt, as well as greenstone assemblages dominated by mafic and ultramafic volcanic and fine-grained sedimentary rocks

east of Laverton. The Merolia and Yamarna Domains contain poorly understood, variably deformed and metamorphosed mafic and felsic volcanic and sedimentary sequences.

Greenstones: tectonic implications and isotopes

Sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon data show three main peaks in age of the volcano-sedimentary sequences: 2.65–2.72, 2.81, and 2.95–3.05 Ga. Nd data suggest marginal arcs rather than purely oceanic arc systems, and recycling of crust (≥ 2.8 Ga) along a complex convergent margin, with the youngest crust represented by rocks of the Gindalbie Domain and some intermediate volcanic rocks from the Menangina and Murrin Domains of the Kurnalpi Terrane. Hf data suggest there were periods of addition of newly generated crust–lithosphere (+ve ϵHf) and that these episodes also reworked crust that originally formed at c. 3.05 Ga or earlier (Barley et al., 2003). Overall, there is a dominance of continental margin signatures as well as evidence of magmatic recycling of older arc-related crust. The terranes were possibly part of the same arc–back-arc system dismembered and then reassembled by accretionary tectonics.

Late basins

Late basins are coarse siliciclastic sequences that unconformably overlie, or are in fault contact with, the volcano-sedimentary successions. Based on intrusions by younger porphyries and syenites, or detrital zircon maximum-depositional ages, they were deposited after 2.665 Ga (Krapčez et al., 2000; Barley et al., 2003; Rick Squire, unpublished data). Two facies types are recorded in the late basins—fluvial deposits and turbidites. Krapčez et al. (2000) suggested that the fluvial facies are older than the turbidite facies, as the former have restricted provenance and the latter have a more diverse zircon population reflecting a larger source area evolving through time.

SHRIMP dating of detrital zircons indicates multiple older sources corresponding to the ages of the greenstones and granites of the EGST (Barley et al., 2002, 2003). Some old populations however have no recognized source in the EGST. With the exception of some zircons from the Kurrawang and Jones Creek Conglomerates, the age and isotopic characteristics of these sources reflect major magmatic and crustal recycling.

The late basins lie with an angular unconformity on the older volcanic-dominated greenstone sequences (or granite basement), indicating that regional orogeny pre-dated the commencement of their deposition at c. 2.665 Ga (Blewett et al., 2004c). Their deposition was followed by the emplacement of low-Ca granites, syenites, lamprophyres and porphyries between c. 2.65 and 2.63 Ga, and various stages of the deformation cycle (see **Granites: tectonic implications and isotopes**).

Late basins: tectonic implications

The importance of the late basins is that they mark a fundamental change in geodynamics from volcanic-dominated sedimentation (the arcs shut off and mantle magmas appear) to clastic-dominated sedimentation with extensive recycling.

Presently, the late basins are preserved in structural basins mostly in the hangingwall of major terrane and domain-boundary faults. In a general pattern, these late basins fine upwards (conglomerates at the base and turbidites at the top). Although they are synorogenic, the late basins do not have the characteristic stacking pattern (coarsening upwards) of foreland or piggyback basins (DeCelles and Giles, 1996). Blewett et al. (2004c) interpreted these basins as 'surge basins' (a form of piggyback basins) and suggested that the fining-up record was a preservation anomaly and that the complete sediment cycle was missing. In contrast, Krapěž et al. (2000) suggested that the late basins were developed in a strike-slip tectonic mode; however, most faults that are closely associated with these basins are rectilinear, with few localities for suitable releasing jogs and step-overs comparable to the dimensions of these basins.

Geometrically there are two types of late basins. The oldest (Stage 1) are arcuate and are preserved in the noses of major extensional granite domes (e.g. Wallaby and Kanowna Belle). The youngest (Stage 2) are elongate and linear, parallel to the main north-northwest–south-southeast tectonic grain. The arcuate Stage 1 late basins developed in the hangingwall of outward-facing extensional shear zones within the greenstone pile as these were shed off and away from rising and extruding granite domes. The Stage 2 late basins occur in the hangingwall of major north-northwesterly trending faults and are likely to have developed by down-to-the-east-northeast extension, reflecting the influence of the regional extensional-stress field.

Regional geology granites

Champion and Sheraton (1997) divided the granites of the Yilgarn Craton into five main classes or types (Fig. 4). These are in order of volumetric contribution: high-Ca (~60%), low-Ca (~25%), high-HFSE (~5%), mafic (~5%), and syenite (~1%). The evolution of granite magmatism, with the exception of the high-HFSE granites, is broadly similar across the EGST (Champion and Sheraton, 1997; Cassidy et al., 2002b; Champion, 2006). High-Ca, mafic and high-HFSE granites have equivalent timing and chemistry to specific volcanic associations in the greenstone belts. In contrast, the youngest magmatic rocks (low-Ca and syenitic granites) have no (preserved) extrusive equivalents in the EGST. All granite groups are present across the EGST (Fig. 4), with high-HFSE and syenitic granites mostly restricted to the western Kurnalpi Terrane (Champion, 2006).

Most magmatism occurred between c. 2.72 and 2.63 Ga (Figs 5 and 6). Remnants of older (>2.74 Ga) granites and older inherited zircons are most prevalent

within the Kalgoorlie Terrane, and the Laverton, Linden and Duketon Domains. These are consistent with the Sm–Nd isotopic data (Fig. 7), which are indicative of older crust (Cassidy and Champion, 2004).

Although each granite/volcanic group was long lived (Fig. 5), there are distinct periods where particular groups are most common:

- 2.72 to 2.68 Ga was variably dominated by high-HFSE, high-Al TTG-type high-Ca and mafic magmatism;
- 2.675 to 2.655 Ga was dominated by transitional TTG-type high-Ca, with lesser mafic (sanukitoids) and syenitic magmatism; and
- post c. 2.655 Ga was dominated by low-Ca with lesser syenitic and minor mafic magmatism (Champion and Sheraton, 1997; Champion, 2006).

High-HFSE (and associated mafic) granites exhibit a broad decrease (diachroneity) in ages from east to west (Cassidy et al., 2002a). A similar decrease is evident in the geochronological data for felsic and intermediate volcanism in the Kurnalpi Terrane (Fig. 6).

The period c. 2.675–2.66 Ga is characterized by high-Ca and lesser mafic and syenitic magmatism across all the terranes within the EGST. High-Al TTG-type high-Ca and mafic granites that are geochemically similar to TTG-related volcanoclastic rocks that are confined to the Kalgoorlie sequence in the Kalgoorlie Terrane are present throughout the EGST, including intrusive dykes and plutons into older intermediate volcanic-dominated sequences in the Kurnalpi Terrane.

The switch in granite style from high-Ca and mafic granites to low-Ca-dominated magmatism at c. 2.655 Ga was preceded, and partly accompanied by, 'late' (2.66 to 2.65 Ga) high-Ca and mafic magmatism (Champion, 2006; Blewett et al., 2004b). This appears to be concentrated within the Kalgoorlie Terrane, suggesting that this region was the main locus of magmatism at this time (Fig. 6). Since these melts are associated with extension (Fig. 6) then it might suggest that the Kalgoorlie Terrane has seen more extension than the Kurnalpi Terrane. In support of this hypothesis is the greater preservation of younger and thicker stratigraphy in the Kalgoorlie Terrane. Furthermore, there are also large deposits associated with the extension in the Kalgoorlie Terrane (see **D₃: extensional granite doming, mafic granites and late basin formation**). Many of these 'late' granites are transitional TTG-type high-Ca and 'sanukitoid'-like mafic granites. This suggests that the switch in granite type from high-Ca mafic to low-Ca granites subsequent to c. 2.655 Ga accompanied availability of a metasomatized mantle source for the high-Ca mafic granites, at least in the Kalgoorlie Terrane, as well as a tectonic trigger to promote derivation of low-Ca granites through melting of older granitoid material within the crust.

Granites: tectonic implications and isotopes

The high-Ca, low-Ca, and high-HFSE granites have a clear crustal component involved partly or solely within

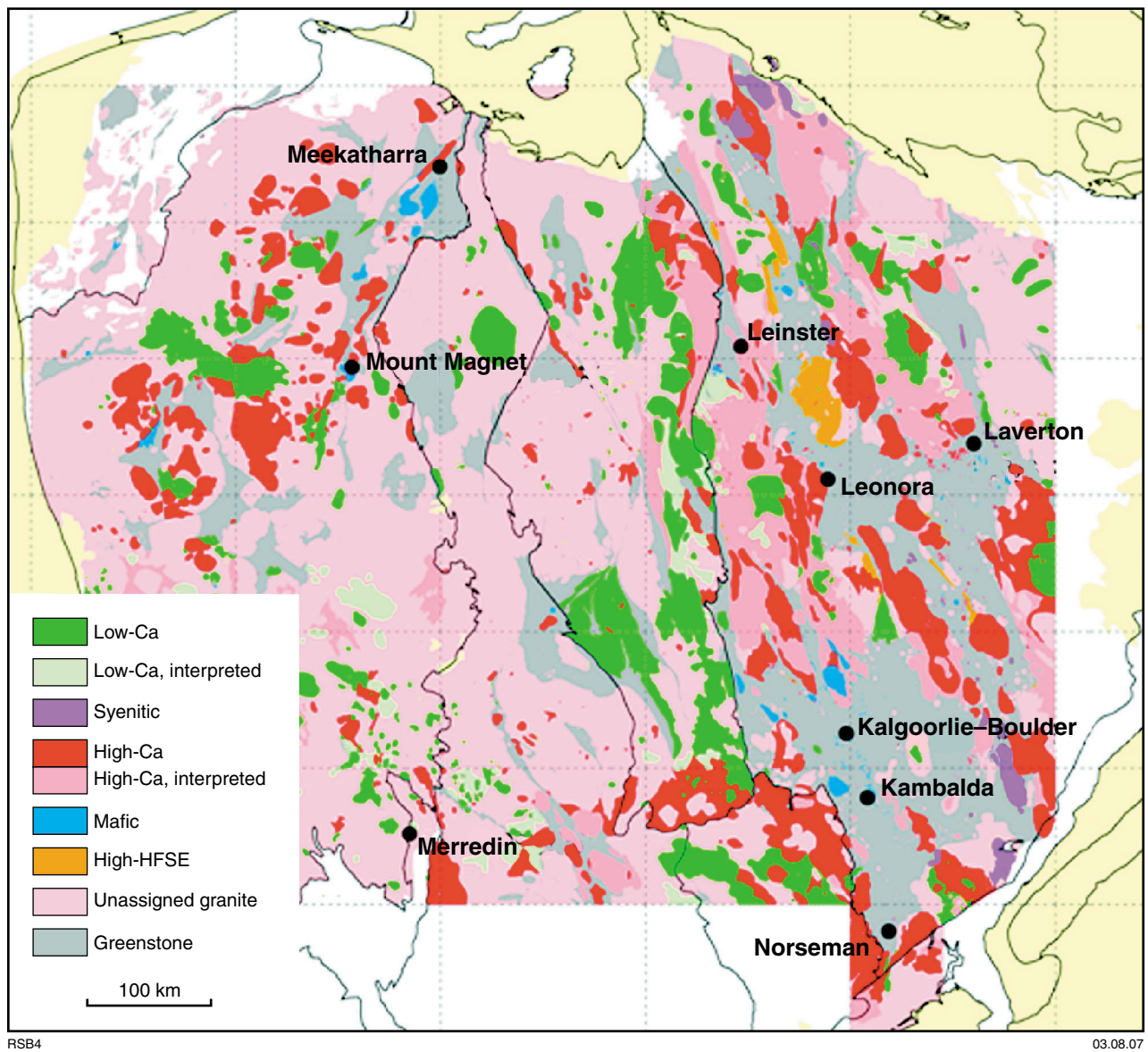


Figure 4. Map of the ve granite types of the Yilgarn Craton (after Cassidy and Champion, 2004). Note the large area of low-Ca granites (green) along the north–south strip to the west of Kalgoorlie

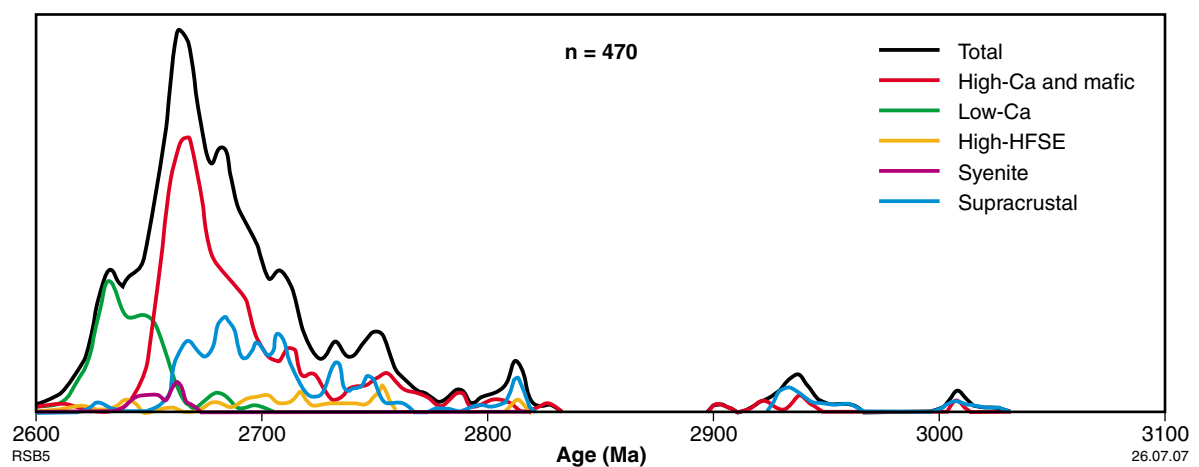


Figure 5. Histogram of granite and greenstone ages for the Yilgarn Craton (after Cassidy and Champion, 2004). Note the peak in ages at around 2660 Ma, and the change from high-Ca magmatism to low-Ca magmatism

their genesis (Champion and Sheraton, 1997). The Nd model-age map of these granites (Fig. 7) shows that the crust within the EGST becomes older both east and west of a north-northwest zone approximating the western part of the Kurnalpi Terrane and its northern extension (Fig. 7). In addition, there is a clear isotopic change between the Kalgoorlie Terrane and the Youanmi Terrane that must represent a major crustal boundary (Fig. 7), i.e. the eastern Yilgarn crust represents younger crustal growth onto the pre-existing Youanmi 'proto-craton' (Cassidy and Champion, 2004).

Favoured tectonic models indicate a variety of arc environments before c. 2.655 Ga that maintain a pre-existing continental crust component with or without various rifting regimes (Cassidy, 2006). Earlier (>2.655 Ga) changes in the type of felsic magmatism are interpreted to represent variations within an overall subduction-related environment, with melts sourced directly off the descending slab. The change at c. 2.68 Ga, from high-Al TTG-type mafic and bimodal/high-HFSE to transitional TTG-type high-Ca-dominated, may relate to some form of terrane accretion at this time. In the EGST this change to mafic-type magmatism reflects access to the metasomatized mantle wedge, which has profound implications for a region's fertility and access to metal and sulfur sources. This change in magmatism is also observed to the west, where widespread magmatism within the Youanmi Terrane effectively ceased at this time (Cassidy et al., 2002b).

The change at c. 2.655 Ga to widespread, continued, and voluminous low-Ca-dominated magmatism indicates a distinct change in the thermal regime of the crust and a similar process occurring craton-wide for the first time (Fig. 4). Low-Ca magmatism continued from 2.65 to c. 2.63 Ga across the entire craton and reflects low-pressure (crustal) melting (Cassidy and Champion, 2004). This period of change in granite magmatism is also marked by metamorphism and significant gold mineralization. Smithies and Champion (1999) suggested these low-Ca melts were developed due to lower crustal delamination.

Previous structural frameworks

Because the gold deposits of the EGST 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 draws 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 Craton until the studies of Platt et al. (1978), Archibald et al. (1978), and Swager (1989). These workers were the first to publish regional deformation-event histories that were subsequently adopted as a framework by later workers.

The pronounced north-northwesterly oriented structural trend of the EGST (the so-called 'D₂' trend) is defined 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, and separate different greenstone successions. The characteristic map pattern of the EGST was developed by a succession of compressional and extensional deformation events that have been interpreted as regional (province-wide) in extent. Swager (1997) summarized many of the interpretations of the regional deformation history, and it is this framework that has been further refined. Henson and Blewett (2006) produced a structural event history that honoured the 2D and 3D map patterns, and was built on the Swager (1997) and Blewett et al. (2004b) work. The map pattern analysis of Henson and Blewett (2006) defined the essential structural elements and their timing, and these are further refined and integrated in this study.

A nomenclature of 'D₁'* to 'D₄+' has been most widely used to describe the various deformation events of the EGST. Swager (1997) is the 'standard' terminology most workers have adopted (Fig. 7). Unfortunately most workers did not emphasize or enumerate the extensional deformation events (other than 'D_e' or 'D_E'). Swager's (1997) paper was a synthesis of over 10 years of research and extensive mapping, and he was also one of the few workers to attempt to integrate the rock record into the structural history. Swager (1997) also attempted to integrate the granites but, due to limited geochronology at the time, the result was not very reliable (see Weinberg et al., 2003).

Broadly, the recognized deformation (compressional history) involved early 'D₁' recumbent folding and thrusting during north-south shortening, followed by east-west shortening through large-scale upright 'D₂' folding and thrusting, and then a period of strike-slip 'D₃' faulting with associated folding that was 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, although these are not enumerated as separate events.

The following section outlines the generally used structural framework (Fig. 8) and is mostly based on Swager (1997) and references therein.

D_E: early extension

A number of workers have suggested that early extension predated 'D₁' thrusting and may represent the last stages of development of the basin in which the greenstones accumulated (e.g. Williams et al., 1989; Hammond and Nisbet 1992, 1993; Williams, 1993). These workers argued that the external granites represent the substrate on which the greenstones were deposited, within an overall north-south-directed core-complex extensional setting. With recent advances in geochronology, the majority of these 'external' granites have been shown to be younger than the

* Deformation in quotes are from other workers. The new deformation framework presented here is not placed in quotes.

surrounding greenstones (Weinberg et al., 2003), thereby negating this model. SRK Consulting (2000) suggested that the core-complex model applied to the deposition of the Black Flag Group and younger sediments within an overall S-directed extensional model (Fig. 9). Detailed work in the Leonora area led Passchier (1994) to suggest that 'D₁' recumbent folds at Leonora may have formed in an extensional setting.

D₁: north–south contraction

Swager and Griffin (1990) suggested that the 'D₁' event involved large-scale stratigraphic repetition during north–south compression. For example, a regional-scale thrust duplex structure was interpreted to extend from Kambalda to Kalgoorlie and significantly duplicate stratigraphy. Regional 'D₁' in the EGST is thought by many to have developed roughly east–west-trending thrusts and folds as a result of north–south compression (e.g. Swager (1997) and references therein).

More recent interpretations of this map pattern suggest that these so-called 'D₁' thrusts are later than the first compressive event (Fig. 9). This new interpretation is based on the observation that 'F₂' folds are transected by these so-called 'D₁' thrusts (Blewett, 2006). Recognition of 'D₁' north–south contraction has been a long-standing problem in the northern Goldfields (Wyche and Farrell, 2000; Beardsmore, 2002), and it was not observed in this study.

Late basins

Swager (1997) interpreted the late basins (Kurrawang, Penny Dam, etc) as being developed during extension after 'D₁' and before 'D₂' (Fig. 6), 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 east–west and involving synclinal basins developed above rollover anticlines. Other workers have described these basins as 'compressional' basins that developed synchronous with 'D₂' (Liu and Chen, 1998). Krapež et al. (2000) and Weinberg et al. (2003) suggested that they were developed post-D₁ amalgamation in a strike-slip event (that is not enumerated by a separate event). However, it is difficult to reconcile how elongate north–south-trending terranes can be amalgamated by north–south contraction.

D₂: east–west contraction

The regional 'D₂' deformation was interpreted to have involved considerable east–west (east-northeast–west-southwest) crustal shortening, producing major regional-scale upright 'F₂' folds (seen as granite-cored domes), together with a pervasive metamorphic foliation (Swager, 1997). The subvertical penetrative foliation developed in all rock types and across a widespread region has been interpreted in most cases as a composite 'S₁–S₂' fabric. However, interpretation of the penetrative fabric across the EGST as pure-shear flattening has been shown by this

study to be problematic. One of the main themes of this field trip is to demonstrate that not all north-northwesterly trending penetrative foliations are the 'main S₂' fabric and therefore this fabric can not be used as the sole means for structural correlation purposes.

The 'D₂' event has been attributed with the development of the major elements of the EGST architecture, including well-preserved regionally extensive 'F₂' granite-cored anticlines, commonly with doubly plunging to horizontal fold axes. The synclines are commonly more complex fault-related structures, with late 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 west-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., 2002a,b; 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 map pattern and seismic architecture was developed during mostly east-northeasterly directed extension.

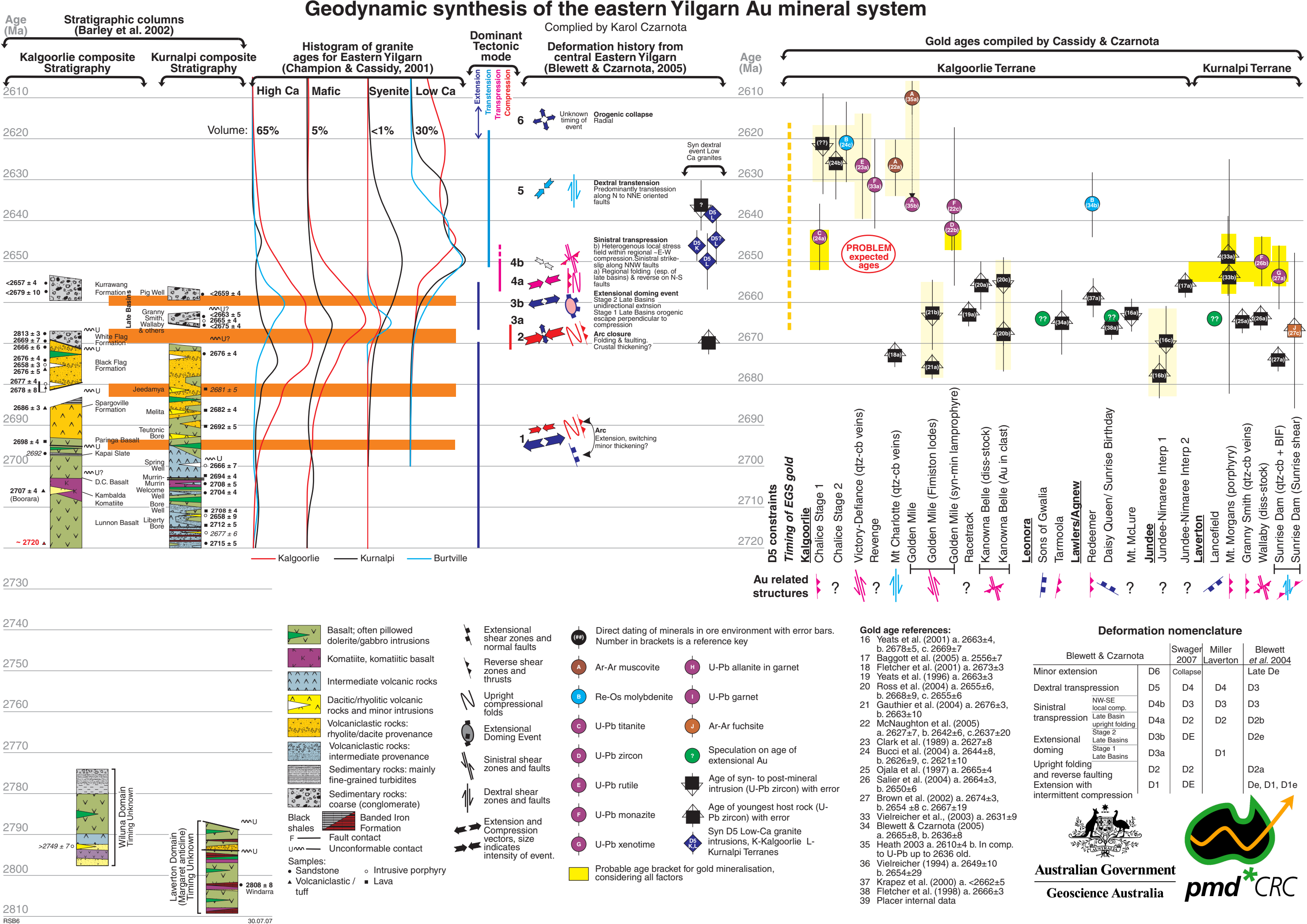
The regional 'D₂' event is considered by most workers to post-date the late basins. For example, the Kurrawang, Merougil, and Penny Dam Basins lie in regional 'D₂' synclines in the southern part of the EGST (Swager, 1997; Krapež et al., 2000; Weinberg et al., 2003). Similarly, in the Welcome Well area the Pig Well–Yilgarni basin is folded by the northwest-trending Butcher Syncline (Gower, 1976) and is overprinted by a well-developed fabric interpreted as 'S₂' (Williams et al., 1989; Passchier, 1994; Liu and Chen, 1998; Stewart, 1998). Swager (1997) suggested 'D₂' was c. 2665 Ma, while Krapež et al. (2000) suggested that it was less than c. 2650 Ma*. Weinberg et al. (2003) stated that 'D₂' occurred after the deposition of the late basins and used Krapež et al.'s (2000) young age of about 2655 Ma for his 'D₂'.

Local extension

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. Swager and Nelson (1997) noted local extension (after 'D₂') of the high-grade granite–gneiss

* Krapež et al. (2000) interpreted the detrital zircon data to give a 10 m.y. younger maximum age for the late basins by using the youngest grain rather than the youngest statistical population.

Figure 6. Integrated time–space synthesis of greenstone stratigraphy, granite ages by type, structure, tectonic mode, and Au mineralization for the Eastern Gold elds Superterrane (after Czarnota and Blewett, 2007)



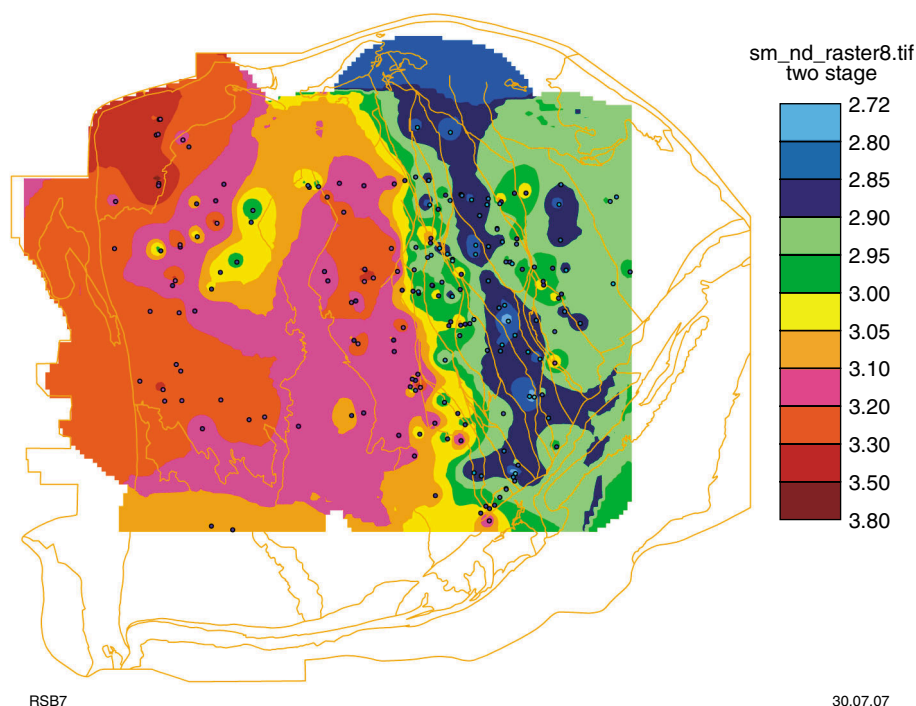


Figure 7. Fundamental architecture of the Eastern Goldfields Superterrane is revealed in the crustal residence ages (T_{DM}). Note the north-northwesterly oriented grain marked by the Ida Fault System located around the orange–green colour change. ‘Cooler’ colours are younger T_{DM} ages (after Cassidy and Champion, 2004)

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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Figure 8. Comparative deformation chronology of various workers in the Eastern Goldfields Superterrane

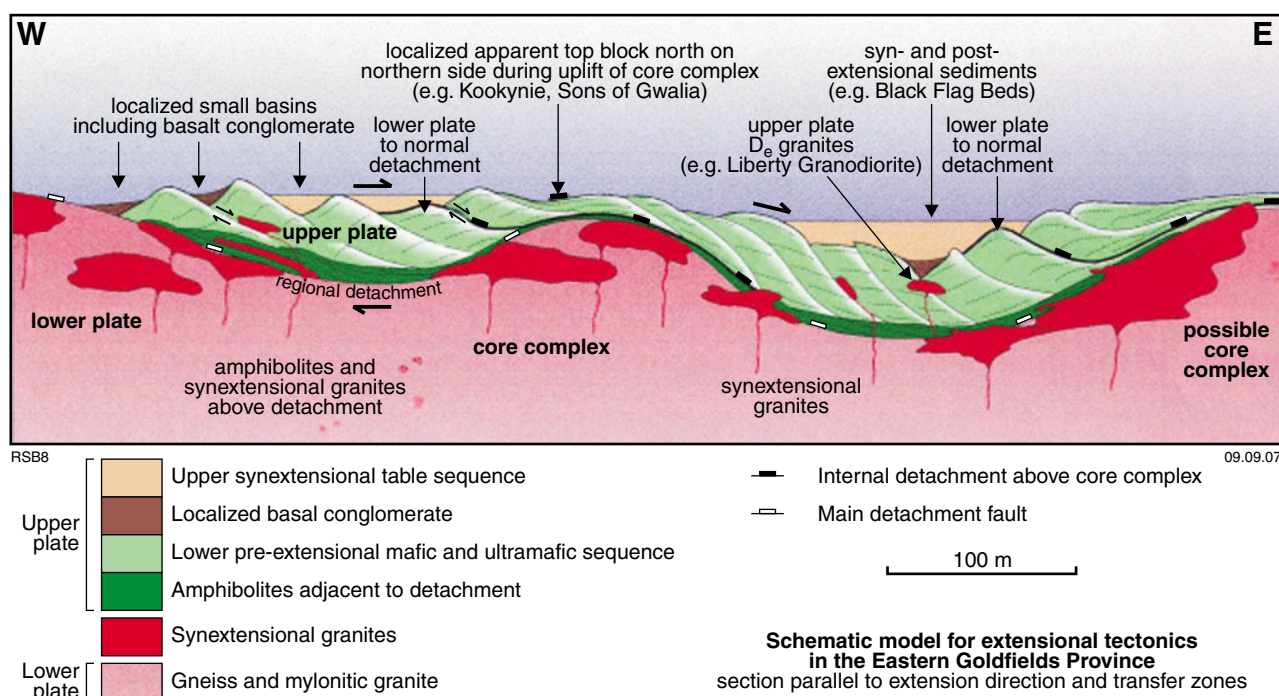


Figure 9. Schematic diagram from SRK Consulting (2000) illustrating the geometry of the extensional architecture of the system. The model has errors of fact such as assuming the late basins are the same age as the Kalgoorlie sequence (Black Flag Beds), but the overall picture is appealing. We have switched the view from one of east-northeast to one of north as we interpret the fundamental polarity of extension to be east–west not north–northwest–south–southeast

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 c. 2660 Ma. Wyche and Farrell (2000) described similar relationships along the Ockerburry Fault System in the northern Goldfields.

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) have documented important extensional events during or just after the major ‘ D_2 ’ contractional event. Blewett et al. (2004a) suggested that ‘ D_2 ’ involved two contractional (‘ D_{2a} ’, ‘ D_{2b} ’) events separated by an extensional event (‘ D_{2c} ’) together with the deposition of the ‘late basins’, and that this more complex ‘ D_2 ’ was diachronous (younging to the west or southwest). The timing (diachroneity) and relationship of the ‘late basins’ to a regional ‘ D_{2c} ’ extensional event was a significant departure from the established Swager (1997) framework (see Figs 6 and 8).

D_3 : ongoing east–west contraction

Continued regional ‘ D_3 ’ east–west shortening resulted in the development of north–northwesterly striking sinistral strike-slip faults and late-stage foliations (Swager, 1989). En echelon ‘ F_3 ’ folds with very steep plunges developed as a consequence of sinistral strike-slip shearing along the already steeply tilted sequence. Hammond and Nisbet (1992) questioned the significance of the ‘ D_3 ’ sinistral strike-slip event. They proposed that most of the so-called

late movements were rotated north-directed ‘ D_1 ’ 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) has cast doubt as to the significance of steep strike-slip shearing in the EGST. The results of this work showed that most shear zones dip moderately to shallowly to the east (Blewett et al., 2002a,b), an **apparently** unlikely geometry for a significant strike-slip orogen. However, the limitation of seismic imaging is its inability to directly image steeply dipping features. Detailed analysis of reflector truncations is required to pick steep structures. With continental seismic work this often proves to be a challenge. However Henson and Blewett (2006) were able to resolve the steeply dipping Hootanui Shear Zone (or Far Eastern Shear Zone) at Laverton in their more detailed 3D model of Laverton.

D_4 : late contraction

Post ‘ D_3 ’ compressional structures (‘ D_4 ’) 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 northeast-trending faults are mostly dextral, and the east-to east-southeasterly trending faults are mostly sinistral, suggesting renewed east–west compression. However, Mueller et al. (1988), attributed this change in tectonism to a small anticlockwise rotation in the main shortening direction. Swager (1997) considered the ‘ D_4 ’ structures to be c. 2620–2600 Ma.

Granite studies

Another feature of most structural studies in the eastern Yilgarn Craton was the emphasis on the greenstone sequences. Many of the granites of the central-eastern Yilgarn Craton 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 et al., Geoscience Australia unpublished data), allowed Blewett et al. (2004a) 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 in a range of regions in terms of the distribution of regional strain.

Metamorphic patterns

Peak metamorphic (low- to intermediate-pressure) conditions are considered to be related to late ‘D₂/D₃’ deformation (Swager et al., 1992). Binns et al. (1976) recognized both static and dynamic (shear zone) styles of metamorphism. The regional patterns they mapped (supported by Hallberg, 1985) show lowest grades (greenschist and lower) in the internal and thickest parts of the greenstone belts, furthest from the external granites. Metamorphic temperature increases towards the margins of the greenstone belts, towards the external granites. These regional patterns transect the domain boundaries (Fig. 6), illustrating relatively late or long-lived multiple metamorphic event(s).

More recently, Mikucki and Roberts (2003) reported two metamorphic events, with a low-pressure event associated with the late-stage low-Ca granites. A more thorough and widespread metamorphic study is being conducted at the time of writing of this field guide as part of the *pmd**CRC Y4 project by Dr Ben Goscombe. For confidentiality reasons the more recent findings can not be reported here.

Late extension (collapse)

Late-stage crustal-scale extensional faulting is recognized on the Ida Fault (Fig. 1) by an abrupt eastward change in metamorphic grade, with exhumed higher 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. (2002a,b) and Goleby et al. (2002) noted a similar east-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 with a change in granitoid magmatism to the low-Ca suite below

the base of the greenstone sequences (Champion and Sheraton, 1997).

New structural framework

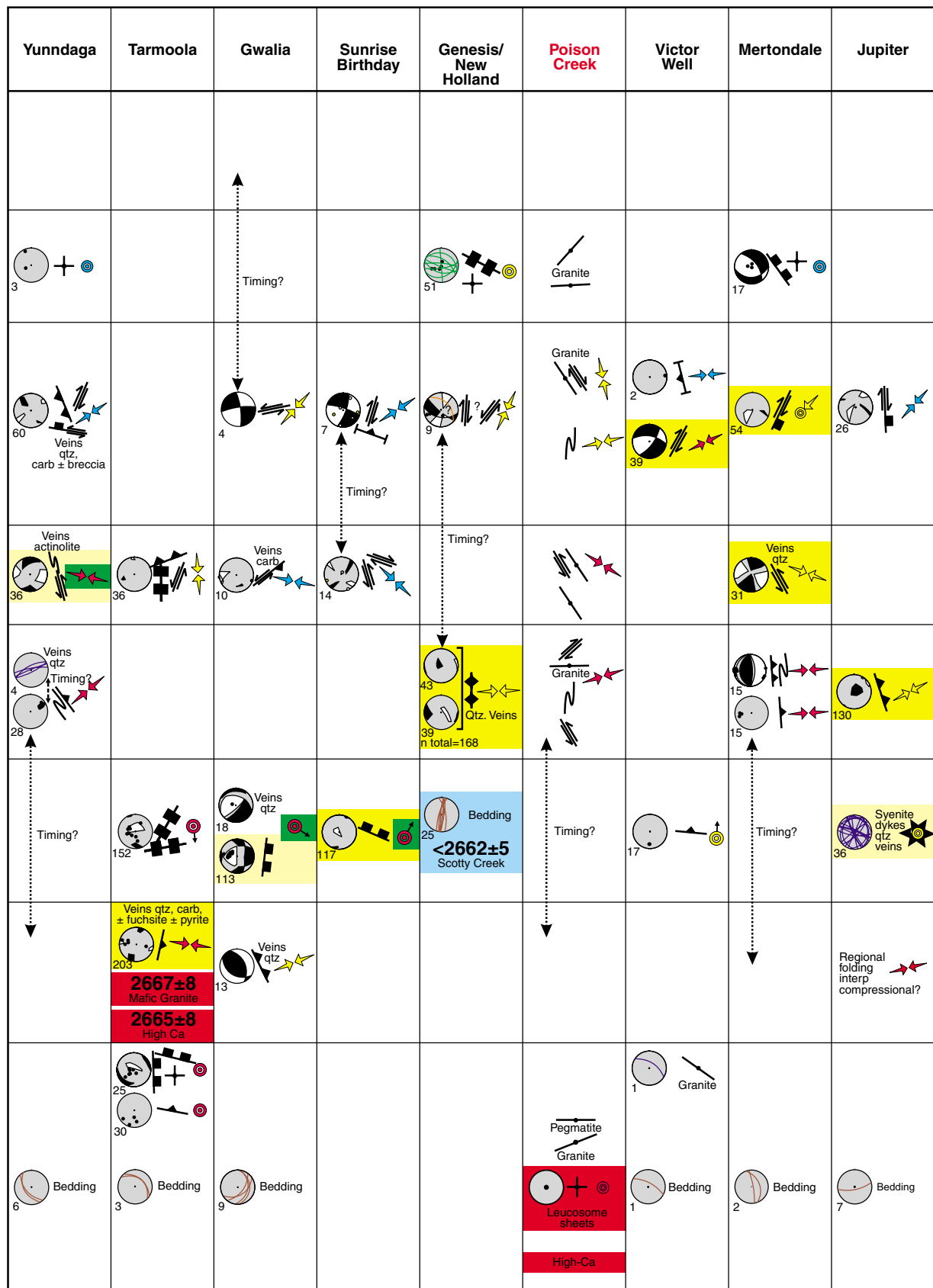
Strain was heterogeneously partitioned across the EGST. The preservation of vast areas of relatively intact greenstone stratigraphy that envelope and young away from broad elongate, gently north-northwest – south-southeasterly plunging granite domes, contrast with localized (up to 5 km wide) highly deformed zones (of intense shear foliation) with steeply dipping stratigraphy (and steeply plunging folds). These high-strain zones are commonly areas of significant reworking and were subject to intense east-down extension (D₃^{*}) and subsequent various contractional events with σ_1 oriented from east-northeast (D_{4a}) through east-southeast (D_{4b}-sinistral) to northeast (D₅-dextral). These four events developed most of the foliations in the region, but there are many areas where these fabrics are weakly developed.

Most mineral deposits of the Eastern Goldfields Superterrane are structurally controlled, so knowledge of their structure and tectonics is critical to understanding the region’s endowment and to predicting new resources. A nomenclature of ‘D₁’[†] to ‘D₄₊’ has been most widely used to describe the various deformation events of the EGST. Many workers adopted the Swager (1997) terminology which is: 1) early ‘D₁’ recumbent folding and thrusting during north–south shortening, followed by; 2) east–west shortening through large-scale upright ‘D₂’ folding and thrusting, then; 3) sinistral strike-slip ‘D₃’ faulting along north-northwesterly oriented structures with associated folding, followed by; 4) continued regional ‘D₄’ transpressive dextral oblique and reverse faulting along north to north-northeasterly oriented faults. Some authors have proposed extension throughout parts of this compressive history, although these are not enumerated as separate events (other than D_c or D_e). Swager’s (1997) paper was a synthesis of over 10 years of research and extensive mapping; he was also one of the few workers to attempt to integrate the rock record into the structural history.

Building on the work of Swager (1997) and references therein, we present a new integrated tectonic framework for the EGST that incorporates a decade of new geochronology, geochemistry, isotopes, stratigraphy, deep seismic profiles, 3D models, and structural mapping from various Geoscience Australia (GA), Geological Survey of Western Australia (GSWA), Australian Mineral Industries Research Association Limited (AMIRA) and *pmd**CRC projects. This new framework (Fig. 6) integrates the greenstone stratigraphy, granite evolution, structure, tectonic mode, and mineralization into a coherent history in time and 3D space.

* D₃ is separated into D_{3a} and D_{3b} stages in detail, but when described collectively it is referred to as simply D₃.

† Deformation in quotes are from other workers. The new deformation framework presented here is not placed in quotes.



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Figure 10. Synthesis structural-event chart of the localities visited in this field guide (adapted from Blewett and Czarnota, 2007b). Stereonets are lower hemisphere projections of P–T (comPression–Tension) dihedra and their associated structures. See Angelier (1984) and Blewett and Czarnota (2007a) for a description of the method. The white sectors in the stereonet show the 3D region of possible σ_1 and the black sectors show the 3D region of possible σ_3 . These dihedra are analogous to fault-plane solutions used in seismology

King of Creation	Lancefield	Hanns Camp	Brief description of events			
			New Swager Average Age of nomen- (1997) orientation of σ_1 in Ma			
			~E-W striking brittle faults cross cutting major shear zones	7		
			Regional orogenic collapse	6		
			Dextral strike-slip along N to NE striking faults, locally intense	5		<2638±2 start to ~2650
			Sinistral wrenching along NNW striking faults, Reverse on N-S striking structures	4b		~2645 to ~2655
			Upright folding of late basins and greenstone sequence	4a		
			Late basins forming event. Granite doming and core complex formation.	3		~2655 to ~2665
			Upright folding of greenstones and dextral shearing in external granites.	2		~2668
			Earliest extension related to: 1. mafic-ultramafic sequence deposition 2. voluminous granite emplacement and doming initiation	1		

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- 2645±3 Low-Ca granite age (Ma)
- 2665±3 High-Ca/mafic granite age (Ma)
- 2665±3 Syenite/HHFSE granite age (Ma)
- <2662±5 Maximum age of metasediments (Ma)
- Gold event
- Inferred gold event

A new integrated tectonic framework

The tectonic grain of the EGST was established as a result of predominantly east-northeasterly directed extension (D_1 and D_3) and predominately east (east-northeast)–west (west-southwest) (D_2 , D_4) to northeast–southwest (D_5) compression. The result has been a succession of north-northwesterly striking coplanar, but temporally discrete, fabric elements that can be difficult to reliably interpret at any single location. Past workers have incorrectly interpreted the nature of the north-northwesterly striking penetrative fabric (usually termed ‘ S_2 ’), and used the interpretation as a basis for correlating structural events across the region. However, this fabric can not be used as the sole correlation marker (Czarnota and Blewett, 2005, 2007). We present a new seven-fold (D_1 to D_7) deformation nomenclature based on kinematic analysis and cross cutting relationships, with the main areas of advancement from Swager (1997) outlined as follows:

- Extension, and trans-tension/pression, characterized by extensional and strike-slip shear zones, are considered the dominant tectonic mode (not thrusting cf. Drummond et al. 2000). This mode is reflected in 3D map patterns, stratigraphic considerations, and important deep seismic-reflection imaging.
- The EGST essentially faced east-northeast and inherited this grain during D_1 extension (‘ D_E ’ in Swager, 1997), which caused the deposition of most of the EGST greenstone stratigraphy on the eastern margin of the Younami Terrane. All subsequent events reused and modified this initial architecture.
- Many areas with intense D_3 extension do not record a significant contractional overprint, despite them being favourably oriented (e.g. the north–south-striking margin of the Raeside Batholith at Leonora).
- Late basins were developed in a complex extensional-tectonic mode (D_3) following the first contraction (D_2), which resulted in arc accretion and termination of volcanism. This D_2 contraction did not develop significant foliation. Granite doming and late basin sedimentation are linked by a common process of D_3 extension.
- **Major** crustal thickening did not occur and the contractional events largely inverted a previously extended architecture.
- Upright folding (D_{4a}) and sinistral strike-slip shearing (D_{4b}) overprinted all greenstones and all but the low-Ca granites.
- The first north–south contraction (Swager ‘ D_1 ’) is older than the late basins, is now considered regional D_{4b} , and was developed during sinistral strike-slip transpression with regional σ_1 oriented east-southeast–west-northwest.
- Low-Ca granites are associated with D_5 dextral strike-slip tectonics, which was long-lived and was a result of an inclined σ_1 that plunged southwest.
- Gold is associated with all events, with D_3 to D_5 being the most productive.
- Late extension or ‘orogenic collapse’ (D_6) may not have occurred at the same time everywhere, and its intensity is variable.

D_1 : long-lived extension and granite–greenstone formation

The D_1 event was extensional, with a dominantly east-northeasterly directed polarity, and was likely to be the result of east-northeasterly directed rollback of a subduction zone(s). Evidence of D_1 extension is preserved in the broadly north-northeasterly trending distribution of the greenstone stratigraphy (Swager, 1997); the north-northwest trends in the granites, ϵNd model-age map (Cassidy and Champion, 2004); the subduction signature of the high-Ca granites (Champion and Sheraton, 1997); metamorphic patterns (Goscombe et al., 2005, 2007); the presence of unconformities and the excision of stratigraphy in the greenstone sequence (Swager, 1997; Krapčez et al., 2000); and mesoscale structures in gneisses and older greenstone fragments (Blewett et al., 2004a; Blewett and Czarnota, 2007b).

D_1 extension in the EGST was active from the earliest greenstone rock record (c. 2720 Ma and probably earlier) through to the onset of the first significant contraction at around 2665 Ma. Relicts of the older basement (maybe Younami Terrane) are preserved as the small slivers of greater than 2750 Ma greenstones at Leonora, Duketon, Dingo Range, and Laverton (Figs 3 and 6). These may represent the rifted remnants of the older Younami Terrane. The voluminous high-Ca plutonism that occurred during this period (Fig. 6) is likely to have initiated early elongate domes — ‘sowing the seeds’ of the domal architecture seen today (Henson et al., 2005).

D_2 : termination of an arc and east-northeast–west-southwest contraction

The first significant contraction (D_2) occurred around 2670–2665 Ma, terminating volcanism in the greenstones (Fig. 6). During this time interval disparate associations (in chemistry and age distribution) were juxtaposed at a time when the late arcs shut off in the Kalgoorlie Terrane (Fig. 3).

In general, D_2 developed without significant regional foliation development. Although in areas away from late basins and D_3 extension, structures here correlated with D_4 may well be associated with D_2 (as D_2 and D_4 are coplanar and may lack overprinting relationships). D_2 macroscopic structures indicate that shortening was oriented east-northeast–west-southwest, perpendicular to the grain of the D_1 extensional orogen. Accretion of an external body (an oceanic plateau) into the receding subduction zone is interpreted to have terminated volcanism and sent a wave of D_2 contraction across the orogen.

Blewett et al. (2004b) described two examples of regional macroscale F_2 folds. The first, in the Kalgoorlie Terrane, was the S-plunging regional anticline–syncline pair at Ora Banda, which is overlain by the Kurrawang Basin. The second, in the western Kurnalpi Terrane, was the S-plunging upright Corkscrew Anticline at Welcome Well, which is overlain by the Pig Well Basin. At both these examples Stage 2 late basins lie across folded greenstone sequences, providing an age constraint of

greater than 2660 Ma for the development of these folds (Blewett et al., 2004b). These authors described the regional folds as 'D_{2a}'.

To the east in the Kurnalpi Terrane, the map patterns of the Mount Margaret Anticline around Laverton also show that old greenstone sequences are folded more tightly than the upper surface of the domal batholith and the base of the folded Stage 1 (2665 ± 5 Ma) Wallaby late basin. This relationship suggests that east-northeasterly oriented shortening had at least commenced before the Stage 1 late basins were initiated. In the southern EGST, the east-northeasterly directed Foster Thrust at Kambalda is interpreted as a D₂ structure.

D₃: extensional granite doming, mafic granites, and late basin formation

The D₂ contraction was followed by a dramatic change in tectonic mode, as well as greenstone and granite type. The D₃ extensional event was associated with significant granite doming (Henson et al., 2005), a peak in high-Ca granite emplacement, late basin formation, and deformation (Fig. 6). The event is characterized by extensional high-strain shear zones that wrap around major granite-dome margins.

Late basins (Krapč et al., 2000) display two geometrical forms (and ages). Stage 1 late basins are arcuate and located in the hangingwall of extensional shear zones along the south-southeast margins of some major granite domes. The polarity of D_{3a} extension of the Stage 1 basins is orthogonal to, and within the strain shadow of, the east-northeast–west-southwesterly directed regional D₂ contraction. This D₂ contraction has been estimated to have occurred at around 2665 Ma, which is within error of the formation of the Stage 1 Wallaby Basin (c. 2665 Ma), but on geometrical arguments (above) is likely to have initiated late- to post-D₂ contraction (Fig. 6). In contrast, Stage 2 late basins are north-northwesterly trending elongate 'rifts', interpreted here to have developed as a result of D_{3b} unidirectional east-northeast-down, asymmetric extension (inversion of ?D₂ thrusts). The formation of the Stage 2 late basins equates to the 'D_{2e}' extension of Blewett et al. (2004b).

The D₃ event is associated with the introduction of mafic-type granite magmatism across the EGST (Fig. 6). These magmas, with sanukitoid affinity, were derived from a metasomatized mantle source (a good source for gold and sulfur). Earlier high-Ca magmas (peaking around c. 2670 Ma) are of the high-Al type, whereas after this they change to a more transitional type (Cassidy and Champion, 2004). Syenite magmatism (mantle sourced) commenced in the Kurnalpi and Burtville Terranes at this time (Fig. 6). This dramatic change in felsic magmatism suggests that a fundamental geodynamic adjustment occurred, rather than the system returning to the previous D₁ extensional setting. Beakhouse (2007) attributed the equivalent change from slab melting (TTG) to metasomatized mantle melting (sanukitoid) in the Archean Superior Province of Canada to be a function of slab detachment following collision.

Major granite domes controlled the locus of this D₃ extension, with a strong meso- and macroscale record of extension at Lawlers, Leonora, and Mount Margaret. The accumulation/preservation boundaries of the main greenstone belts also record greenstone-down extension along the Ida Fault to the west and the Pinjin shear zone to the east (Swager and Nelson, 1997). At Leonora on the eastern margin of the large Raeside Batholith, extensional S–C–C' shear zone fabrics are well developed at the mesoscale, and at the macroscale in seismic reflection images (Czarnota and Blewett, 2007). Furthermore, large metamorphic-grade jumps consistent with excision of stratigraphy have also been documented across extensional shear zones at Leonora (Williams and Currie, 1993). All scales infer granite-up and greenstone-down sense of movement (down to the east), with Stage 2 late basins (Pig Well <2665 Ma) developed further east in the hangingwall to extensional shear zones.

A working model is therefore proposed where the D₃ extension, and its associated rock record in the EGST (Fig. 6), were the result of detachment (or delamination) of the D₁ slab following D₂ collision. This detachment provided drivers, pathways, and access to fertile sources for subsequent heat, gold-bearing fluids, and magmas. The gross architecture of the EGST is therefore attributed to have being developed during the D₁ and D₃ phases of extension as opposed to during contraction as suggested by Drummond et al. (2000).

D₄: sinistral transpression

D₄ was a progressive sinistral transpressional event recorded across the terranes of the EGST, both within the granites and the greenstones. It has been subdivided into two distinct stages (Fig. 6) as follows:

- The first stage (D_{4a}) involved horizontal compression with σ_1 just north of east–west and a vertical σ_3 (coplanar to the D₂ stress field). D_{4a} is characterized by pure shear (significant flattening), late-basin inversion, north-northwesterly striking upright folding and associated cleavage formation, reverse faulting, and tightening of earlier domes and D₂–D₃ folds. The geometrical result was the rotation and steepening of stratigraphy (including late basins) along the margins of east-facing granite domes (e.g. the Bardoc Tectonic Zone north of Kalgoorlie, Scotty Creek Basin at Lawlers, and the Mount Varden area north of Laverton). This event was termed 'D₂' by Swager (1997) and 'D_{2b}' by Blewett et al. (2004b) since it overprints the late basins.
- The second stage (D_{4b}) involved the development of north-northwesterly striking, steeply dipping, ductile sinistral shear zones associated with a slight clockwise rotation of σ_1 to east-southeast–west-northwest and a horizontal σ_3 (see also Weinberg, et al., 2003). Sinistral strike-slip shear zones have been best developed in regions with steep-dipping stratigraphy (where thrusting and flattening ceased to be effective in dissipating the stress) and within the internal granites. This D_{4b} event equates to the 'D₃' deformation of Swager (1997).

Low-strain structures associated with the D_{4b} event resolve a locally highly variable stress field with σ_1 ranging from east-southeast–west-northwest to north–south in orientation (e.g. the main gold event at Wallaby; Miller, 2006). This large variation in the local stress field is inferred to be a direct consequence of the development of sinistral strike-slip shear zones on a pre-existing highly anisotropic architecture, primarily composed of doubly plunging granite domes overlain by folded greenstones.

In a significant change from the Swager (1997) framework, the south-over-north thrusts from the Kambalda and Kanowna areas (such as Tramways, Republican, and Fitzroy), described as ‘ D_1 ’ (Swager, 1997), are reassigned to D_{4b} . This is based on regional map-pattern superposition relationships where the ‘ D_1 ’ thrusts overprint north-northwesterly trending upright ‘ F_2 ’ folds (see Henson et al., 2004b). An analogy of how north-directed thrusts developed at a high angle to north-northwesterly trending D_{4b} sinistral strike-slip faults exists in the eastern Gobi–Alty region of Mongolia (Bayasgalan et al., 1999). Thrusts in this example develop at the terminations of major strike-slip faults, acting as accommodation structures to rotational strain, and at restraining step-overs where they accommodate displacement between parallel strands of a strike-slip fault system. Locally σ_1 was oriented northwest- to north-striking across these transfer structures and restraining bends despite the regional stress field being oriented east-southeast–west-southwest (Fig. 6).

D_5 : dextral transtension and crustal melting

The D_5 event was developed in an overall dextral transtensional-tectonic mode accompanying the emplacement of low-Ca granites and characterized by brittle–ductile north- to north-northeasterly striking dextral strike/oblique-slip faults. This D_5 event equates to the ‘ D_4 ’ event of Swager (1997). Many past workers have suggested that it was a progressive event from earlier ‘ D_2 ’ (Weinberg et al., 2003 and references therein). However, this study has shown that a significant rotation of the palaeostress field ($\sim 60^\circ$) occurred between the D_{4b} sinistral (σ_1 east-southeast–west-northwest) and the D_5 dextral (σ_1 northeast–southwest) events, so the transition was not progressive, but probably marked a major plate reconfiguration such as occurred in the Pacific Plate at 38 Ma.

This event is remarkably consistent across the EGST and thereby forms a good marker for structural correlation across the region. D_5 ductile high strain and locally transpressional shear zones occur along the most significant terrane boundaries such as the western and eastern margin of the Kalgoorlie Terrane (Ida–Waroonga Fault System and the Ockerburry Fault System respectively) and the eastern margin of the Kurnalpi Terrane (Hootanui Fault System). Distant from these terrane boundaries, the D_5 event is expressed as brittle faults with very well-developed quartz–carbonate slicken lines (e.g. Wiluna, Mertondale, and Jupiter). The development of local transpressional–transtensional structures is controlled by pre-existing fault strike and the

geometry of adjacent granite batholiths within a system where σ_1 was inclined towards the southwest (Blewett and Czarnota, 2007b).

D_5 was a long-lived event and was associated with a significant change in magmatism to low-Ca granites (Fig. 1). These are significant because low-Ca granites are high-temperature crustal melts emplaced late in the evolution of the Yilgarn Craton (<2655–2630 Ma), marking a fundamental change in the thermal regime of the crust. These granites make up 20% of the exposed area of granites and so are likely to be volumetrically significant (Fig. 4). These magmas were intruded into granite domes below the greenstone base (Henson et al., 2005, 2007), indicating the doming and uplift continued throughout D_5 .

D_6 : low-strain systemic collapse

The last event inferred to be part of the EGST tectonic cycle (cratonization of the Yilgarn) is systemic collapse. This event is characterized by mostly low-strain crenulations, with subhorizontal 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. No specific vector of extension has been defined; and the driver for this extension may have been a readjustment of localized topographic highs from earlier events rather than a regional or far-field control. Structures ascribed to this event have been noted previously by Swager (1997), Davis and Maidens (2003), and Weinberg et al. (2003).

D_7 : Proterozoic contractional events

The D_7 event occurred across the EGST and was associated with minor east-northeasterly oriented contraction and the emplacement of dolerite dyke swarms and minor east–west sinistral strike-slip faults. Numerous small displacement faults occur in the granite pavements of the external granites (Blewett et al., 2004a). Swager (1997) also described similar structures. These are all likely to be Proterozoic in age and may reflect events at the craton margin (e.g. the Albany–Fraser and Capricorn Orogenies).

Timing constraints of deformation

The best dataset available for constraining the ages of the deformation framework is available for 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. (2002a), Dunphy et al. (2003), and Black et al. (Geoscience Australia unpublished data). The EGST was deformed by a series of what appear to be long-lived extensional stages associated with granite emplacement, interspersed with short-lived contractional stages (Fig. 6).

A graphical representation of the timing constraints on deformation is presented in Figure 6 and a comparison

with the deformation framework of Swager (1997) is presented in Figure 8. The classical 'D₁' north–south contractional event of Swager (1997) appears to be absent.

D₁ constraints

The D₁ period is interpreted as long-lived extension, with the space creation and formation of the rock record itself as the best evidence. A question remains as to 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 at around 2692 ± 4 Ma (Claoué-Long, et al., 1988). The Kalgoorlie sequence (Black Flag Formation) has age ranges from 2690 to c. 2665 Ma (Krapčez et al., 2000). The Kalgoorlie sequence has a number of unconformities, with one at around 2675 Ma (Fig. 3). At the same time in the 'external' granites, a major melting and exhumation event occurred. The ages of the gneissic fabrics are in the range of 2672 ± 2 Ma (Two Lids Soak); 2675 ± 2 Ma (Barrett Well); 2670 ± 10 Ma (Ivor Rocks); 2681 ± 4 Ma (Isolated Hill), and 2674 ± 3 Ma (Wilbah; ages reported in Cassidy, 2006). Such consistent data, across regionally separate sites (similar ages are reported from Duketon: Champion, D, 2005, pers. comm.), indicate a maximum age for metamorphism and D₁ extension of around 2672 Ma.

D₂ constraints

The first contractional event, D₂, has a maximum age range constrained by the dates of deformed granites and a minimum age range from crosscutting granites. Direct age constraints for D₂ were only available in the study of Blewett and Czarnota (2005) from the Burtville and Kurnalpi Terranes. In the Burtville Terrane, D₂ is constrained by being younger than the 2668 ± 4 Ma granites at Ironstone Point and older than the 2664 ± 2 Ma syenites at Hanns Camp. In the Kurnalpi Terrane, D₂ was younger than the 2667 ± 4 Ma granite at Pindinnis, the 2665 ± 4 Ma granite at Granny Smith mine, and the 2667 ± 5 Ma granite at the Porphyry mine, and was older than the 2660 ± 5 Ma granite at Bulla Rocks (ages reported in Cassidy, 2006).

D₃ constraints

D₃ is a strong extensional event associated with the development of late basins and the commencement of the emplacement of the mafic and syenitic granites. 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 overprinting extensional fabric on granites such as the 2664 ± 2 Ma Hanns Camp Syenite and 2660 ± 5 Ma Bulla Rocks Monzogranite. If the mineralization at Sunrise Dam is related to the D₃ extension, then the overlap in Au mineralization ages at Sunrise Dam can be used to constrain the timing of D₃ to 2658 ± 4 Ma (ages reported by Miller, 2006). The maximum depositional ages of the late basins provide constraints on the age of D₃ basin

formation, their initial burial, and deformation. Late basin ages include 2662 ± 5 Ma (Scotty Creek: Dunphy et al., 2003); 2665 ± 5 Ma (Jones Creek: Krapčez et al., 2000); 2657 ± 4 Ma (Kurrawang: Fletcher et al., 2001); 2664 ± 6 Ma (Merougil: Krapčez et al., 2000); 2666 ± 5 Ma (Mount Belches: Krapčez et al., 2000); 2664 ± 4 Ma (Pig Well – Yilgarn: Barley et al., 2002); and 2663 ± 5 Ma (Granny Smith: Barley et al., 2002). These ages around 2665–2660 Ma (reported in Cassidy, 2006) are consistent with regional extension post-dating the D₂ contraction and final closure of the arc(s).

D₄ constraints

The age of D₄ can only be inferred from crosscutting relationships. It is obviously younger than the 2665–2660 Ma D₃ extension. The D_{4a} event was previously known as 'D₂' (Swager, 1997) and is the first contraction inverting the late basins. A maximum age for D_{4a} is obtained from the youngest phases of the D_{4a}-deformed Kanowna Belle Batholith and associated porphyries in the Kanowna Belle gold mine. These felsic rocks have U–Pb SHRIMP ages of 2655 ± 6 Ma (Ross et al., 2004). The D_{4b} east-southeast–west-northwest sinistral transpressional stage occurred prior to any low-Ca granite-type magmatism that is present across all terranes (and the Yilgarn Craton as a whole). The low-Ca granite-type granites were emplaced following a switch in paleostress to southwest-directed transtension (D₅).

D₅ constraints

The low-Ca granites provide a maximum age for D₅ of less than 2652 ± 5 Ma (Pink Well), less than 2650 ± 8 Ma (Mount Denis), and less than 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 further developed D₅ dextral shear zones (demonstrating the syntectonic nature of these magmas). A minimum age for D₅ (ages reported in Cassidy, 2006) was obtained from low-Ca granite-type dykes that overprint D₅ fabric elements of 2638 ± 2 Ma (Ironstone Point). The D₅ event is likely to have developed after about 2650–2645 Ma.

Post-D₅ and younger event age constraints

The ages of post-D₅ events are poorly constrained. The D₆ event is a late collapse and may not have occurred at the same time throughout the whole region. 'Young' ages of about 2600 Ma from various isotopic systems may reflect these late events in the final cratonization of the Yilgarn Craton. Significant east-northeasterly trending Proterozoic mafic dykes transect the Yilgarn Craton, and these are interpreted to be associated with the D₇ contraction. Blewett et al. (2004a) described a number of poorly constrained very minor deformation events in the granites. These were interpreted by these authors as Proterozoic in age and related to distant reworking events on the margins of the craton (e.g. Capricorn Orogen in the northwest and the Albany–Fraser Orogen in the southeast).

Implications for predictive gold discovery

Gold is associated with all of the events throughout the geodynamic history of the EGST; however, significant gold mineralization did not occur until the D_3 extension event (Fig. 6). The genetic link between D_3 extension and late basin formation provides insight into the empirical observation that large gold deposits occur in proximity to late basins (Hall, 2007). This is because late basin distribution is associated with crustal-penetrating shear zones developed during D_3 extension. These shear zones are necessary to tap deep fluids and metals (from the mantle). The emplacement of mantle-derived mafic and syenitic granites into the upper crust during D_3 extension reflects this deep connection. Furthermore, extension is an efficient way to draw fluids down shear zones to facilitate fluid mixing (Sheldon et al., 2007). Significant gold mineralization is hosted in high-strain, extensional ductile shear zones at Gwalia, Lancefield, and the Lawlers camp. Extensional shear zones occur in other areas of the Yilgarn Craton, so there is significant potential for finding Sons of Gwalia-like ore deposits. The D_3 extension is also responsible for setting up the domal architecture of the EGST that is critical for fluid focusing during subsequent events.

The D_4 sinistral transpression event was imposed on the highly anisotropic architecture developed largely during D_3 . This resulted in the creation of numerous depositional sites with significant structural complexity, and the development of locally variable and complex stress fields as the anisotropy in the orogen was being 'ironed out'. Gold is associated with brittle-ductile sinistral strike-slip shear zones at deposits such as Wallaby and Sunrise Dam, St Ives camp, Kalgoorlie, Kanowna Belle, Lawlers, and Wiluna (Swager, 1997; Weinberg et al., 2003; Miller, 2006 and references therein).

The final gold event was associated with D_5 dextral shearing (brittle transtension), with deposits including Sunrise Dam and Wallaby, Transvaal, Wiluna camp, New Holland, Golden Mile, St Ives camp, and Kundana being examples. In contrast to the earlier gold-dominated events (D_{3-4}), the mineralogy associated with D_5 included base metals and tellurides and may reflect the influence of basinal fluids (Goscombe et al., 2007).

Excursion localities — Menzies to Leonora

Day 1

We are driving from Kalgoorlie northwards to Leonora (approximately 220 km) and will be traversing through the Kalgoorlie sequence up the Bardoc Shear Zone, which is a narrow zone of reverse shearing and sinistral strike-slip deformation between the Mount Pleasant and Kanowna Batholiths (west and east respectively). We will pass the KCGM smelter and historical mines such as Paddington, Goongarrie, and Sand Queen en route to the Menzies township and Yunndaga.

Locality 1: Yunndaga—a sinistral shear-hosted gold deposit (MGA 311580E 6707563N)

The purpose of visiting Yunndaga is to illustrate gold mineralization in metasedimentary rocks with dolerite intrusions providing a local competency contrast and the classical 'D₂–D₄' deformation framework of Swager (1997). The main foliation is associated with the initial development of upright folds and subsequent bedding-parallel sinistral strike-slip shearing. This foliation will be contrasted with superficially similar (in intensity, strike, and metamorphic grade — but not kinematics and timing?) foliations throughout the EGST.

The Yunndaga gold deposit is located approximately 6 km south of Menzies along the northern part of the Bardoc tectonic zone (Fig. 2). Yunndaga yielded approximately 8.75 t (approx. 31 000 ounces) of gold between 1897 and 1935 (Witt, 1992). Recent openpit operations (1995–98) have produced approximately 2.02 t of gold (Evans, 2003). The deposit is hosted by clastic sedimentary rocks and carbonaceous shale, along with a central dolerite–gabbro dyke, which locally is a chlorite schist.

Morey (2007) reported that gold mineralization is associated with a strike-parallel laminated vein located at the contact between the western margin of the dolerite and the quartz-rich sedimentary units (Fig. 11). Wallrock alteration is characterized by quartz–carbonate–biotite–chlorite–arsenopyrite–pyrrhotite–gold assemblages. Gold is associated with fine fractures within the arsenopyrite.

Two progressive major contractional events (D_{4a} and D_{4b}) and a late transtensional event (D₅) deformed the area (Figs 11 and 12). Gold was likely associated with the D₄ events. The main fabric elements (D_{4a}) were developed under a horizontal east-northeast–west-southwest contraction, and associated with upright tight to isoclinal folding of the sedimentary sequence and axial planar cleavage. Evidence of this folding is clearly displayed in the northeastern wall of the pit (best viewed from the southern end of the pit) and as upright outcrop mesoscale folds in the pavement (Fig. 13a). Most authors would equate these D_{4a} structures with the classical 'D₂' event of Swager (1997).

The upright folds (Fig. 13d) are overprinted by D_{4b} north-northwesterly striking sinistral strike-slip shearing associated with a clockwise rotation of σ_1 to an east-southeast–west-northwest orientation (Fig. 12). This event is responsible for the majority of the structures that can be observed in the pavement of the Yunndaga ramp, including boudinage of gold-bearing quartz veins (Fig. 13b,e); typically approximately 20°S-plunging stretching lineations on the main bedding-parallel foliation (Fig. 13c); and drag folds with near vertically plunging fold axes (Fig. 13f). Clear S–C' structures associated with sinistral strike-slip deformation (Fig. 13b,e,f) are developed within the less competent units within the sedimentary rocks. East-northeasterly striking dextral quartz veins with actinolite wallrock alteration developed late during this event (Fig. 14a,b). These veins are best exposed along the northeastern wall of the pit.

Structural elements of the D_{4b} event are overprinted by a series of D₅ brittle faults. The most notable of these is the east-northeasterly striking sinistral fault associated with a large quartz vein at the northern end of the pit. Outcrop along the northeastern wall of the pit shows a series of what appear to be normal shear veins; however, in detail they are sinistral normal most likely associated with the larger sinistral fault (Fig. 14c,d). P–T (compression–Tension) dihedra analysis of these structures indicates that these structures (like the rest of the D₅ structures) formed under a southwesterly inclined σ_1 . Traditionally these structures would be associated with Swager's (1997) 'D₄' event.

The last event, D₆, is associated with the development of horizontal crenulations that can be observed on D₅ fault surfaces. This event is interpreted to represent the orogenic collapse of the EGST tectonic system.

Locality 2: Tarmoola—contractional gold with an extensional overprint (MGA 320753E 6827328N)

Leave Yunndaga and drive north through the historical town of Menzies (once a bustling centre) to Leonora. We will travel across the Ockerburry Fault System into the Kurnalpi Terrane and greenstones of the Melita belt, which hosts small mines around Kookynie (a popular prospecting location). After crossing Lake Raeside we pass back into the Kalgoorlie Terrane and a narrow sliver of greenstones on the eastern margin of the Raeside Batholith. Keep travelling through Leonora for 31 km to the Tarmoola sign. A locked gate secures the access road to the mine.

The Tarmoola goldmine is an example of the role of competency contrasts (granite–greenstone) in localizing structures and hence permeability, fluid flow, and ultimately mineralization. The purpose of visiting Tarmoola is to illustrate the relationship between contractional gold and later overprinting by extensional shearing, inferred to be related to doming and the development of the late basins. A more extreme version of this extension is found in Gwalia (Locality 3).

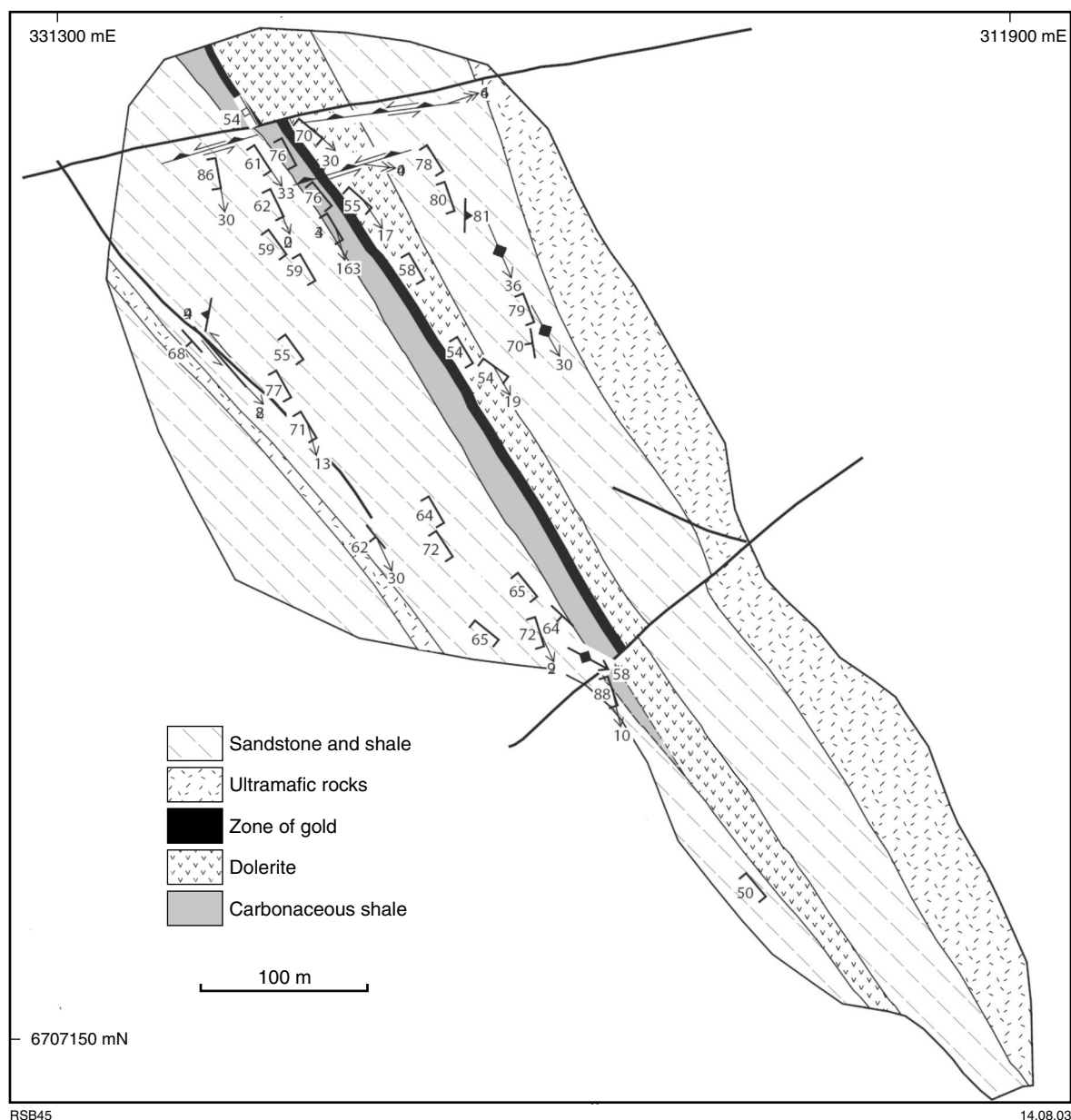


Figure 11. Simplified geological map of the Yunddaga pit near Menzies (after Morey, 2007)

The Tarmoola gold deposit is located approximately 30 km north of Leonora, on the northern end of the Raeside Batholith (Figs 2 and 15). The deposit is 'cored' by a trondhjemite with diorite dykes dated at 2667 ± 8 Ma (Lance Black, unpublished Geoscience Australia data). This current study has elucidated five phases of deformation, and as with other deposits in the area, has a significant component of extensional deformation (Swarnecki, 1988; Vearncombe, 1992).

The greenstone stratigraphy is upward facing, based on numerous pillow lavas. The first fabric(s) is developed in the greenschist-facies mafic and ultramafic rocks that are intruded by the trondhjemite. The fabric is patchy in distribution and preserved as a steeply dipping, east-westerly striking, penetrative foliation. The kinematics on this fabric are uncertain. It is a hard event to correlate

across the Tarmoola pit and the significance of this fabric with respect to regional deformation events is unclear. It is interpreted as part of the long-lived D_1 extensional event (Fig. 16).

The second event involved the development of an extensional S–C' shear fabric that is especially well developed in the talc schists. Sigma 1 was subvertical during D_1 , with extension off to the northeast and southwest (Fig. 16).

Gold is hosted in spectacular D_2 quartz–carbonate (–fuchsite) veins related to dextral strike-slip shearing along the northeast-striking east edge of the Tarmoola trondhjemite. The dominant dextral shear planes are expressed as continuous sheeted quartz veins along the southeast wall of the south pit. Associated with these

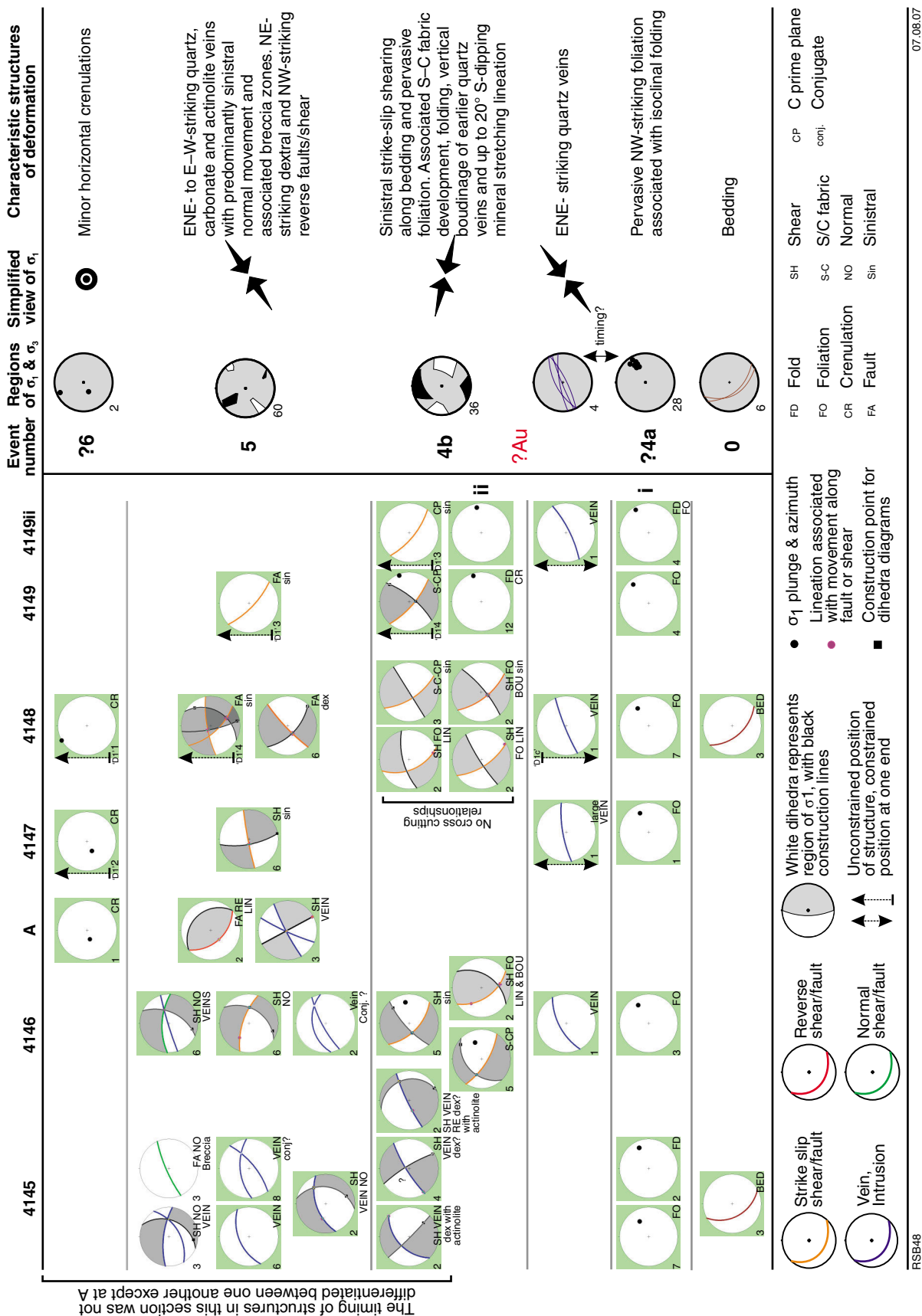


Figure 12. Stereographic compilation of structural elements into discrete events at the Yunnadaga deposit

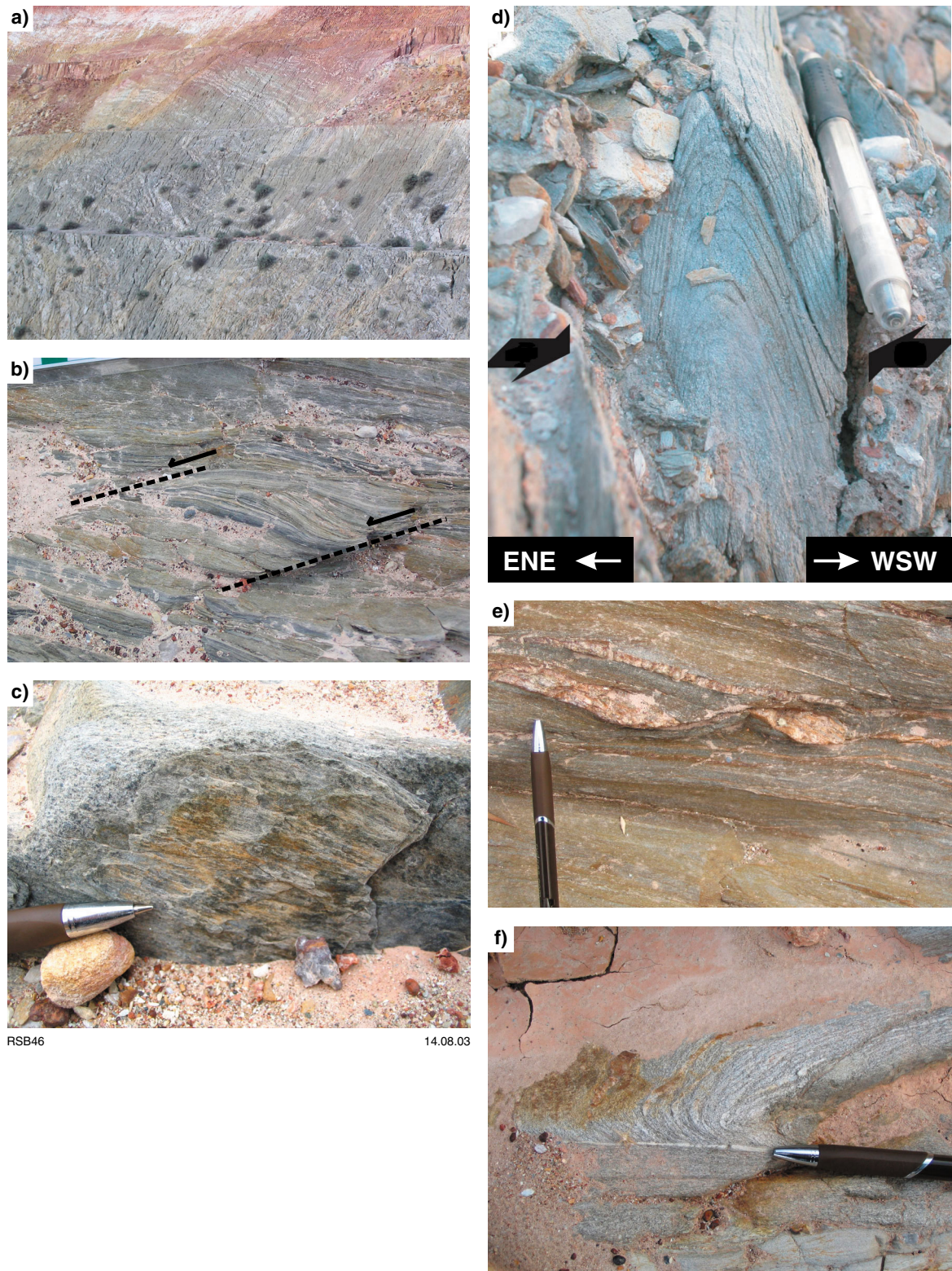


Figure 13. Compilation of photographs from the Yunnadaga pit: a) F_4 folds in the east wall of the pit (view northeast); b) D_{4b} sinistral C' planes in metasedimentary rocks in the western access ramp (view west onto pavement); c) oblique-slip L_{4b} lineations associated with north-northwesterly oriented sinistral shearing (view west); d) upright tight gently north-northwesterly plunging F_{4a} fold of bedding and laminae (after Morey, 2007); e) D_{4b} sinistral C' planes in metasedimentary rocks cutting boudinaged quartz veins (view west onto pavement); and f) D_{4b} drag fold with steep plunge consistent with strike-slip shearing (view west onto pavement)

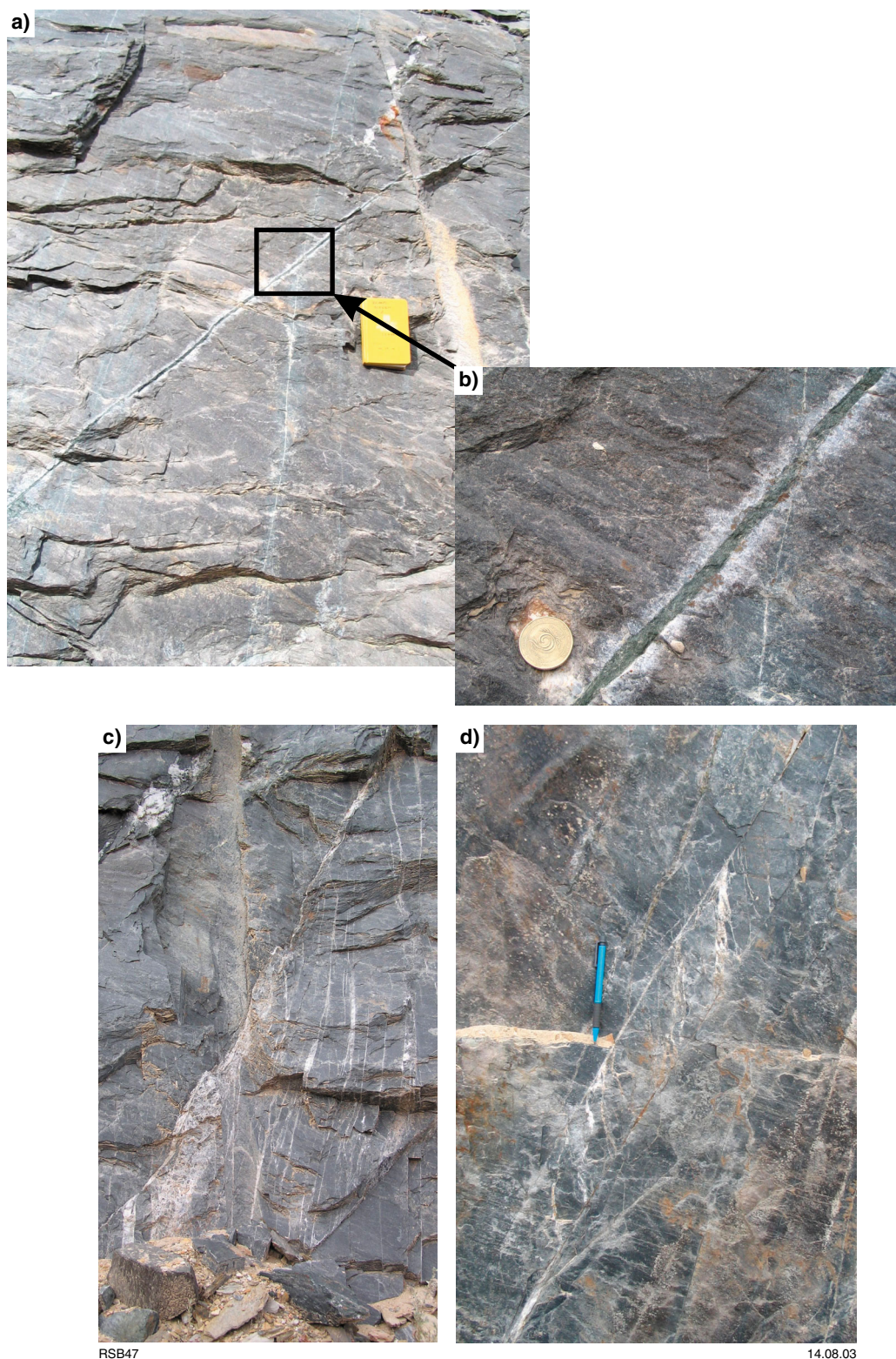


Figure 14. Compilation of photographs from the Yundaga pit: a) D₄ quartz–carbonate–actinolite veins in chlorite schist (view west onto steeply dipping wall); b) detail of carbonate alteration of dolerite host rock adjacent to the amphibole veins (view east onto steeply dipping wall); c) sinistral normal quartz–carbonate veins associated with D₅ southwest-inclined σ_1 (view east onto steeply dipping wall); and e) sinistral normal quartz–carbonate shear and extension veins associated with D₅ southwest-inclined σ_1 (view east)

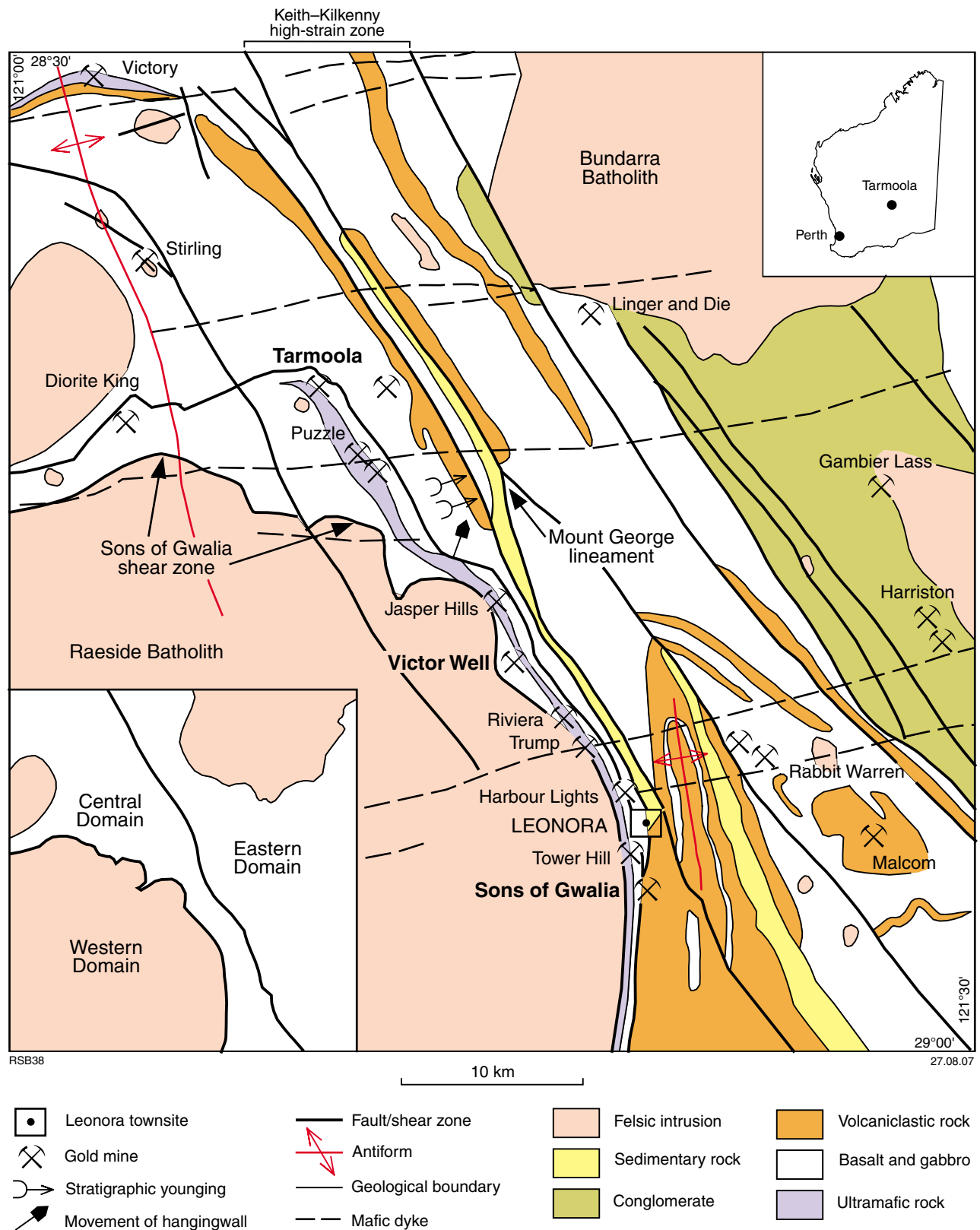
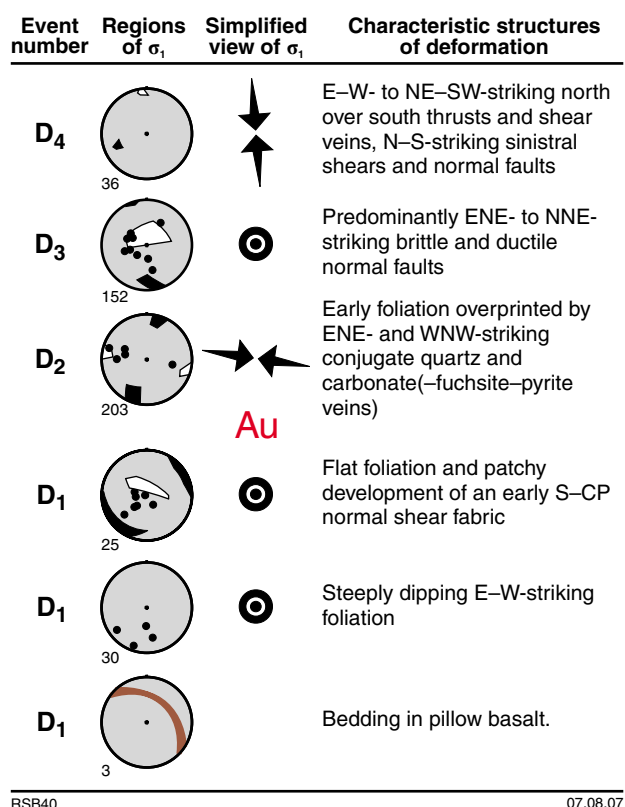


Figure 15. Simplified geological map of the Leonora district with the Tarmoola (Locality 2), Sons of Gwalia (Locality 3), and Victor Well (Locality 7) sites shown. Note the large granite batholith (Raeside) in the southwest of the map and the enveloping shear zones (extensional; after Duuring et al., 2002) that mantle the granite–greenstone contact



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Figure 16. Stereographic compilation of structural elements into discrete events at the Tarmoola deposit. Tarmoola is an example of D₂ gold. Note how more than 200 structural readings resolve a very small σ_1 sector to be just south of east-west and an orthogonal σ_3 that is subhorizontal. It is likely that this subhorizontal σ_3 reflects the overall transpression associated with D₂ contraction (as recorded in the granites), or the geometry of the trondhjemite contact with the greenstones

dominant shear veins are synthetic (dominant set) and antithetic en echelon quartz-carbonate (-fuchsite) veins (Figs 17a-d). Brecciation occurs at many of the intersections of the synthetic and antithetic shear-vein sets, with fuchsite-altered wallrock incorporated into a 'blow out' of quartz-carbonate veins (Fig. 17c).

The above veins cut an associated north- to north-northeasterly striking S₂ foliation associated with the dominant shear veins. Mohr circle analysis by Duuring et al. (2001) showed that the presence of this pre-existing foliation would preferentially localize shear failure along the eastern edge of the trondhjemite. The D₂ contraction is well constrained, with σ_1 oriented just south of east and σ_3 oriented horizontally orthogonal to this with some local heterogeneity in the vicinity of the saddle pit (Fig. 16).

Some gold veins were deformed by a second extensional event, most notable in the saddle pit. This D₃ extensional event involved mostly down-to-the-south transport, with σ_1 again vertical. The final event was the development of D_{4b} north-over-south thrusts and shear veins, together with more steeply dipping sinistral faults and approximately north-trending normal faults.

Locality 2a: Mineralized greenstone with steep contact with trondhjemite

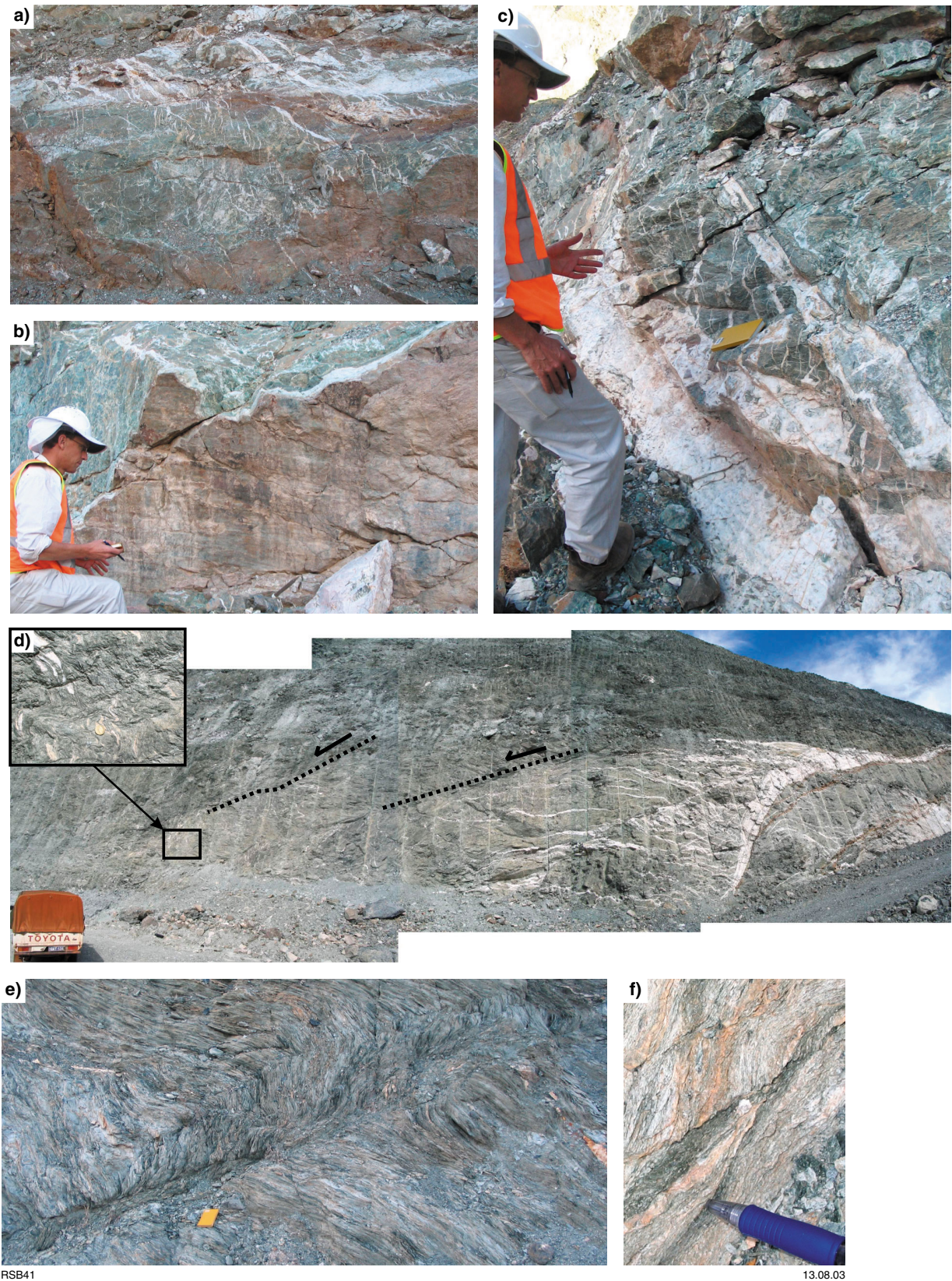
This locality is at the southeastern part of the south pit and shows the steep contact with the main trondhjemite body and mafic schists (Fig. 18). The trondhjemite is largely unfoliated, and irregular apophyses of granite project outwards into the greenstone country rock. Sets of en echelon D₂ quartz-carbonate (gold-bearing) veins cut both the granite and greenstone. Kinematics are both sinistral and dextral, and resolve a maximum compression direction approximately east-west. The dominant vein sets are dextral. They are synthetic to the main sheeted quartz veins up the pit wall. At the trondhjemite contact with the greenstones, notice the east-northeasterly striking brittle sinistral-normal quartz shear veins in the trondhjemite. These veins are consistent with formation during dextral movement along the main dextral sheeted veins under approximately east-west compression (Fig. 16).

Both vein sets overprint an earlier foliation (S₂) in the greenstone. Walk the section up the ramp and note the large steeply east-dipping 'wall' of quartz with extension veins (sinistral and dextral en echelon sets) striking at acute angles to this main vein (Fig. 17c). Notice the horizontal lineation on the main quartz vein, consistent with dextral strike-slip shearing along this vein (Fig. 17b). The large veins that appear in the walls above are further examples of this vein set and the view is onto their dip direction so that they appear subhorizontal in this section provided by the openpit.

Locality 2b: Extensional overprint of contractional gold

A spectacular east-dipping dextral D₂ vein with associated wing-crack veins is exposed in the west wall of the small saddle pit at the edge of the trondhjemite (Fig. 17d). This large vein is interpreted to be of the same set as the most prominent veins at Locality 2a (but in this case strikes north-northeast). There are three minor vein sets associated with this vein, indicating a dextral and reverse-slip component of shear along the main vein. Using the P-T dihedral, the stress direction resolves as northeast-southwest compression (Fig. 16). This local variation in the stress field is due to a strike change of the greenstone-trondhjemite contact and the establishment of a restraining jog along the trondhjemite contact (Fig. 19). This feature is analogous to the north-northwest-south-southeast compression observed along some structures related to the regional sinistral strike-slip event. That is, the resolved stress field at a location may be influenced more by the fault orientation than the regional stress direction.

To the north (down the ramp), the wing-crack veins are overprinted by increasingly intense extensional shear zones and vertically flattened folds and crenulations (D₃). In the highest strain domains, the original vein geometry is largely obliterated by the extensional shearing (Fig. 17d inset). Analogies with the high strains at Gwalia are thus drawn. The extension is down to the north and is interpreted to be related to doming from the Raeside Batholith and development of the late basins.



RSB41

13.08.03

Figure 17. Compilation of photographs from Tarmoola: a) en echelon sinistral and dextral shear-vein arrays splaying from the main dextral fault (view southeast); b) dextral strike-slip fault strikes northeast-southwest and mirrors the margin of the trondhjemite (view southeast); c) detail of vein arrays and brecciation and fuchsite alteration associated with D₂ dextral shearing (view northeast); d) compilation of D₂ dextral strike-slip fault and spectacular wing-crack veins overprinted by normal (extensional) shearing during D₃. Inset shows detail of S₃ extensional crenulations (view southeast); e) top to the northeast D₅ thrusting overprints S₃ extensional crenulations in ultramafic schist (view northwest); and f) detail of D₅ thrusts (view northwest)

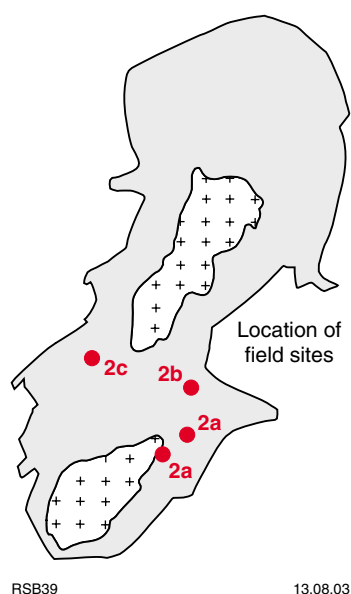


Figure 18. Location of field sites in the Tarmoola pit

Locality 2c: Late thrust overprinting extension

On the decline leaving the pit, a series of D_3 extensional shears are developed in talc–chlorite schists. These extensional shears are overprinted by D_{4b} thrusts with top-to-the-northwest shear (Fig. 17e,f).

Locality 3: Sons of Gwalia mine—gold in extension during formation of the late basins (MGA 337665E 6800124N)

Leave Tarmoola and turn right (south) back to Leonora. Veer right just south of Leonora, around Mount Leonora (a kyanite–sillimanite–andalusite locality) to the Gwalia mine of St Barbara. Park at the St Barbara main office and we will be escorted in their transport down the openpit to the entrance to the underground portal.

The Sons of Gwalia mine is an excellent example of an extensional shear zone developed in greenstones of the Kalgoorlie Terrane that are exposed as a narrow (<10 km) sliver adjacent to a major granite batholith (Raeside). The granite margin, like the adjacent greenstones, is sheared with extensional kinematics (Williams et al., 1989). The shear zone ‘faces’ the dominant contractional vector that has been traditionally assigned to ‘ D_2 ’ (Swager, 1997). In this example, the dominant ductile fabric is an extensional schistosity to mylonite in places, which dips moderately to gently to the east. It is not a contractional ‘ S_2 ’ fabric, illustrating the contention here that foliation intensity and orientation makes an unreliable marker for correlating structural events.

Sons of Gwalia is the third largest gold deposit in the Eastern Goldfields Superterrane. It is the southernmost deposit in the Leonora camp (Fig. 15), and is located 3 km south of the township along the Sons of Gwalia shear zone (SGSZ). Parallel shear zones host the other major gold deposits in the camp, namely Tower Hill and Harbour Lights (Figs 15 and 20a). The deposit is hosted in a sequence of tholeiitic pillow basalts and minor interflow sedimentary rocks (Fig. 21a); which are intruded by dolerite sills. The greenstones of the Leonora camp are thought to be older than 2750 Ma, based on a Re–Os age on molybdenite at Tower Hill (Witt, 2001). The Raeside Batholith is a high-Ca granite-dominated batholith with intrusions ranging in age from 2760 ± 4 to 2669 ± 7 Ma (Cassidy, 2006). The youngest of these intrusions display the extensional kinematics observed at the Gwalia deposit and hence date the extension and associated Au mineralization to less than 2670 Ma.

Williams et al. (1989) identified the main tectonic mode in the camp as extensional, with high strains being accommodated along east-dipping shear zones that juxtaposed amphibolite- and greenschist-facies rocks. Using P–T estimates of rocks in a deep diamond drillhole through the Gwalia shear zone, Williams and Currie (1993) estimated around 3 kb of pressure and greater than 200°C temperature differences (extensional exsiccation) had occurred across this shear zone. Work by Blewett and Czarnota (2007b) also confirmed that the dominant tectonic mode was extensional ductile shearing with downthrows towards the east for the entire camp district.

The Gwalia orebody (three vertically stacked en echelon lenses) lies within the pervasive S_3 foliation

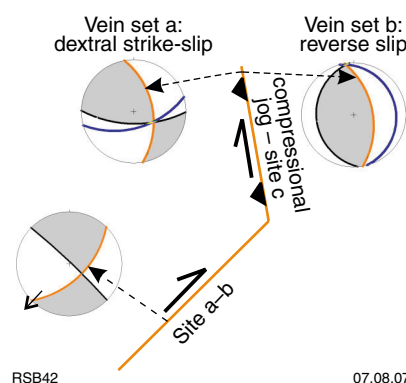


Figure 19. Schematic diagram illustrating how the geometry of faults (caused by a heterogeneous body like a granitoid) influences the structures observed at each location. Note how the structures change from reverse faults and veins to strike-slip under the same regional east–west contractional stress regime

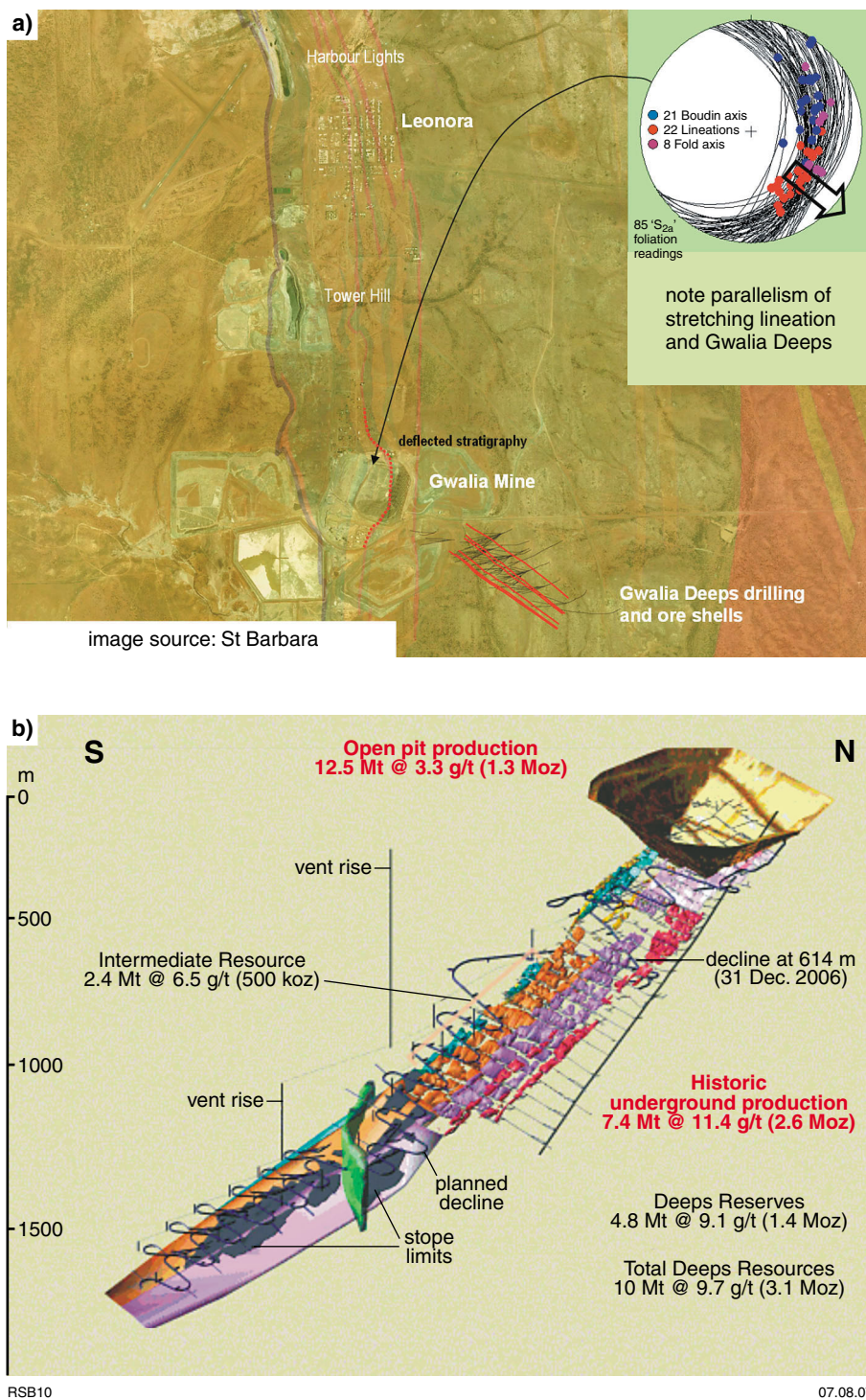
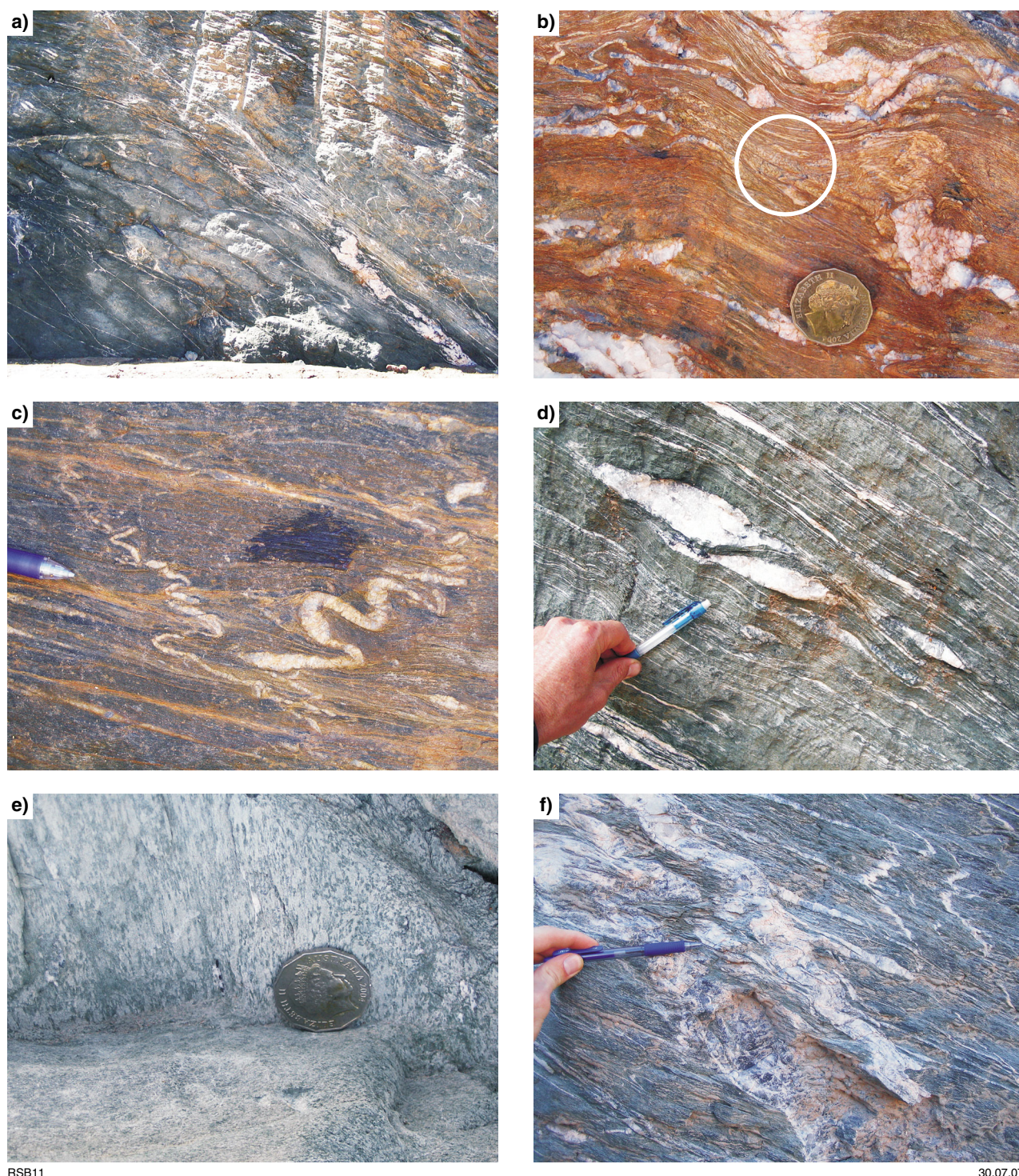


Figure 20. a) Orthophotograph of the Leonora area showing the location of the Gwalia mine and the 'deeps' to the southeast of the openpit and parallel to the stretching lineation (courtesy St Barbara Mines); b) geometry of the Gwalia openpit and associated Gwalia deeps. Note the extremely attenuated aspect ratio of the ore zone, despite the host lithologies and shear zones extending north and south of the mine (courtesy St Barbara Mines)



RSB11

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Figure 21. Compilation of photographs from Gwalia openpit: a) Relict pillow lavas showing the basalt stratigraphy is upward facing to the east (view north); b) complex crenulations of early foliation ($S_{1/2}$ shown in the circle) overprinted by the main S_3 extensional fabric (view north onto wall); c) conjugate veins attened by a steeply inclined σ_1 (developed during extension) and developing gently dipping axial planes to F_3 folds (view north onto wall); d) S–C–C' extensional fabric elements all showing down-to-the-east and southeast extension (view north onto wall); e) amphibole defining a downdip stretching lineation (view west); and f) D_3 extensional overprint on earlier veins that may be originally developed during D_2 contraction (e.g. Tarmoola; view north onto wall)

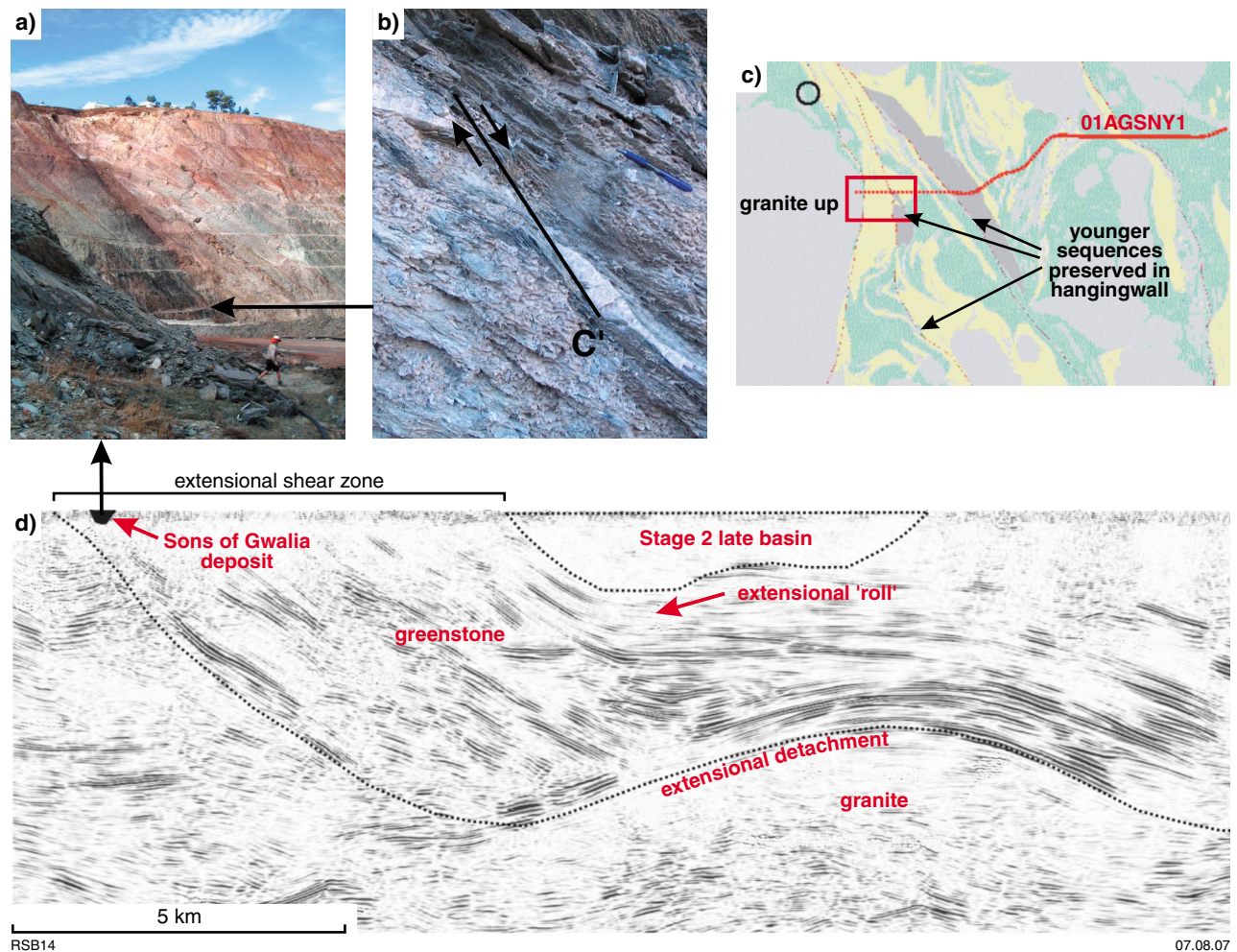


Figure 22. Compilation of extension recorded on a range of scales in the Leonora area: a) note parallelism of the layering (foliation) in the pit (view north) with the seismic events imaged in the section (d); b) extensional C' plane at the mesoscale; c) map of the seismic line crossing major faults with the youngest sequences (late basins) in the hanging wall; and d) east–west seismic line through the Gwalia pit vicinity to around 6 km depth shows extensional S–C and C' planes in the events at this scale. These intense bands of reactivity (shearing) are up to 5 km wide and roll onto a granite dome at depth. This rolling of the fabric onto a detachment is consistent with extension (see Fig. 8 for an analogue)

in a chlorite–sericite schist with numerous quartz–carbonate veinlets (Coates, 1993) and plunges within the SGSZ down to the southeast, parallel to the stretching lineation (Fig. 20a). The extreme linear–aspect ratio of the orebodies and the parallelism of the stretching lineation indicates that extension was the principal control on the formation of this gold deposit.

Locality 3a: View north of the Sons of Gwalia openpit

Views to the north show the main fabric elements consisting of the stratigraphy, lodes, and pervasive foliation, all of which dip around 35° to the east (Fig. 22a,b). The western lode is exposed just west of the portal and the main lode is characterized as a distinct bleached and brown layer east of the portal, halfway towards the eastern edge of the pit.

The dip of the pervasive fabric is consistent with the dip of reflectors imaged on the east–west NY1 seismic line across the Sons of Gwalia deposit (Fig. 22d). The strong reflectors define a 5 km-wide zone parallel to the Raeside granite batholith margin. Through extrapolation of the kinematics from the Sons of Gwalia line of deposits we infer this zone to be a 5 km-wide extensional shear zone. This interpretation is consistent with the geometry outline in the seismic data. In the hangingwall to this shear zone, the youngest part of the Yilgarn Craton stratigraphy (late basin) is preserved, consistent with extensional tectonics (Fig. 22c). A similar relationship occurs with respect to the Pig Well late basin, although the granite batholith controlling the localization of the shear zone does not outcrop but is imaged at 3 km depth. The reflectors related to the SGSZ roll into a detachment above a granite dome displaying an open concave geometry consistent with development in an extensional tectonic mode (Fig. 22d). Compare this seismic section with the cartoon sketch of core complexes (Fig. 9).

Locality 3b: Extensional kinematics of the Sons of Gwalia shear zone

The SGSZ is expressed as a pervasive foliation (D_3) within the pit (Fig. 21a–f). The pervasive fabric overprints an earlier set of quartz veins and foliation that appear locally to be early reverse shear veins (Fig. 21b,f). These veins may represent evidence for an earlier phase of contraction before the dominant extensional fabric-forming event (cf. Tarmoola). While most asymmetric folds indicate extensional tectonics, some folded veins have conflicting senses of vergence, indicating that the axial-plane foliation contains a strong flattening component of strain. These folded veins are likely to be the result of the particular angle between one conjugate vein set and the later extensional shearing (Fig. 21c). However, some quartz veins appear to have been formed during the extensional fabric-forming event. These veins are less deformed and cut the foliation, but have asymmetric folds with axial planes parallel to the main foliation, consistent with down-to-the-east normal kinematics (Fig. 23b).

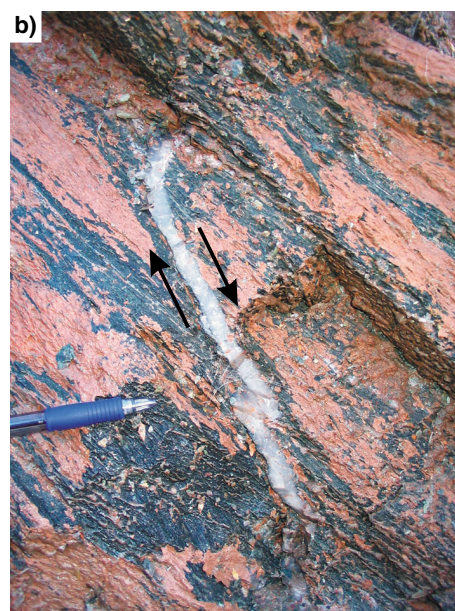
Across the pit, the L_3 boudins and fold axes rotate towards the stretching lineation, suggesting a tendency towards sheath-like folding related to normal down-to-the-southeast shearing along high-strain zones (Fig. 20a). While the spread of fold-axis orientations may be a function of the original vein orientation, the spread of boudin neck lineations suggests strong transposition into the 'a' or shear direction (Fig. 20a).

Consistent S–C and C' planes at a range of scales and most asymmetric folds indicate extensional tectonics. A large-scale extensional C' plane is evident in the northwest corner of the pit, west of the portal entry (Fig. 23a). In rare outcrops the main shearing fabric (S_3) also hosts a crenulation in the microlithons between the phyllosilicate domains, implying a likely earlier phase of deformation (Fig. 21b).

Sets of white carbonate veins, many conjugate with northwest and southeast dips, are locally cut by related brittle sinistral-reverse faults that dip steeply to the northwest (Fig. 23c). These structures are assigned to D_{4b} and the resolved shortening direction (σ_1) associated with this event is approximately east–west (east–southeast–west–northwest) compression. An example of this set of veins is evident at the northern end of the western wall. The last event observed in the pit are east–northeasterly striking sinistral faults associated with carbonate veining. These are brittle faults associated with D_5 approximate northeast–southwest compression (Figs 23c and 24).

We are staying two nights at the old Sons of Gwalia camp. For those that are interested we will hold evening talks in the Recreation Room starting at 8 pm.

Figure 23. Compilation of photographs from Gwalia openpit: a) steep C' extensional shear planes developed over a limited vertical height (see arrow). Their depth extent may be related to the rheology contrast and thickness of layers being extended and boudinaged (view north); b) quartz veins overprint the main S_3 extension foliation and are dragged and offset by ongoing progressive D_3 extension (view north); and



RSB12

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c) S_3 foliation cut by later D_4 veins which are cut by a D_{4b} sinistral reverse fault. View west-southwest of a moderately inclined surface

Day 2

In the morning you may like to walk out of the camp gates at the south entrance and traverse along the track heading west. Exposures of chlorite schist may be found and it is interesting to speculate whether you would be able to determine that this fabric is extensional! This is the sort of outcrop that much of the regional geological mapping has had to rely on.

Excursion localities—Lawlers area

Drive north out of Leonora for 130 km to Leinster. We will pass the VHMS Tectonic Bore deposit and one of the latest exploration successes, the Thunderbox gold mine. Turn left (west) off the main road and head for 17 km to Agnew. Turn right (north) at the T-junction for 4 km and turn left at the Barrick New Holland signs. Caution: this is an active mine haul road and all visitors need to report to the site office and receive an induction.

The group will split into two so we can be accommodated underground at New Holland. One group will join the bus and travel to Locality 4 via the main haul road (with an escort) and will return later to swap with the other group.

Locality 4: Sunrise Birthday—extensional gold in gabbro on a regional dome nose (MGA 258846E 6896914N)

Access to Sunrise Birthday is via the haul road some 8 km from the main Barrick office at New Holland.

The purpose of visiting Sunrise Birthday is to show that the main foliation in this pit is extensional and related to doming and exhumation of the Lawlers Tonalite to the south. We contrast a ‘field’ example of a penetrative foliation where it is difficult to determine the kinematics of the fabric (usually interpreted as contractional) with the 3D exposure of an extensional shear zone in the pit. This deposit also illustrates that gold is hosted by extension-only structures and is likely early in the overall deformation sequence.

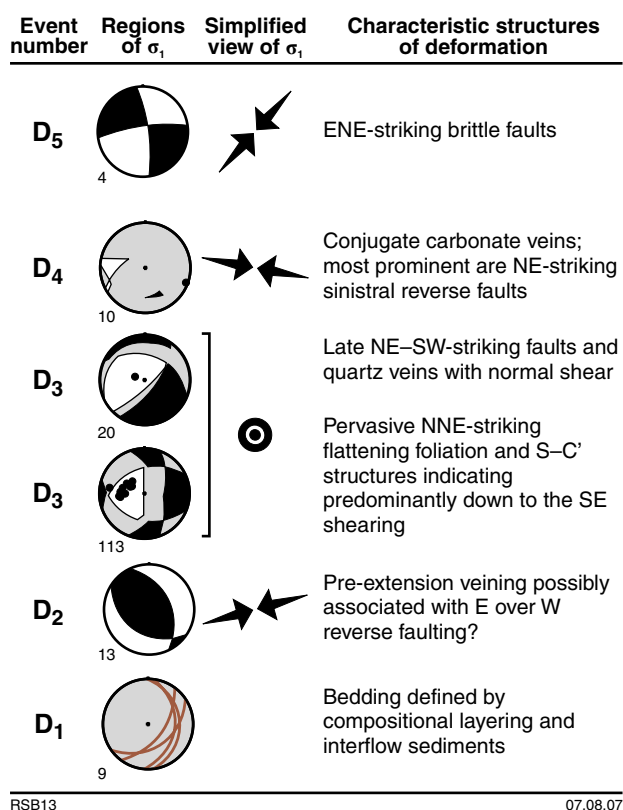
The Sunrise Birthday gold deposit is about 7 km north-northeast of the Barrick (Lawlers) camp on the northern hinge of the Lawlers Anticline (Fig. 25). It was the site of the first discovery of gold in the McCaffery Group of workings, and was also a site of an original alluvial field. The earliest mine workings were an underlay shaft sunk 84 m on an east-striking quartz reef. Historical production up until the mine closure in 1917 was 9313.66 t of ore processed for 4396 oz (136 725 g) of gold grading about 14.68 g/t Au (Beardsmore, 2002). The Sunrise Birthday deposit was most recently mined during 1995–96, when over 30 000 oz at about 3.8 g/t was recovered (Beardsmore, 2002).

The Sunrise Birthday orebody was mined to a depth of nearly 80 m below surface, with a maximum thickness of about 12 m. The ore zone occurs in a steeply north-northeasterly dipping shear zone (the Cascade Shear), and individual lodes plunge west. Free gold was associated with pyrite, in two near-parallel, white quartz reefs each up to 2 m thick, hosted by chloritized and sheared metagabbro. These quartz reefs were less than 10 cm wide close to the surface, but thickened substantially with depth, and demonstrated conspicuous pinch-and-swell along their lengths (Gibson, 1907). Mineralization also occurs to a lesser extent in the intensely foliated talc–chlorite schist associated with chlorite, carbonate and pyrite alteration (Beardsmore (2002) and references therein).

The Cascade Shear at Sunrise Birthday dips more steeply than the sheared stratigraphic boundary between two gabbro units. The down-dip lineation, the pronounced pinch-and-swell of the main ore horizon, together with the along-strike plunge of individual shoots, are consistent with development of mineralization within an extensional down-to-the-north D_3 shear zone.

Locality 4a: Regional north-northwesterly striking foliation

The structural history of the Eastern Goldfields Superterrane has been commonly established based on the premise that the regional ‘ D_2 ’ foliation can be used as



RSB13

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Figure 24. Stereographic compilation of structural elements in the Gwalia pit. Note the dominant fabric elements developed during D_3 extension

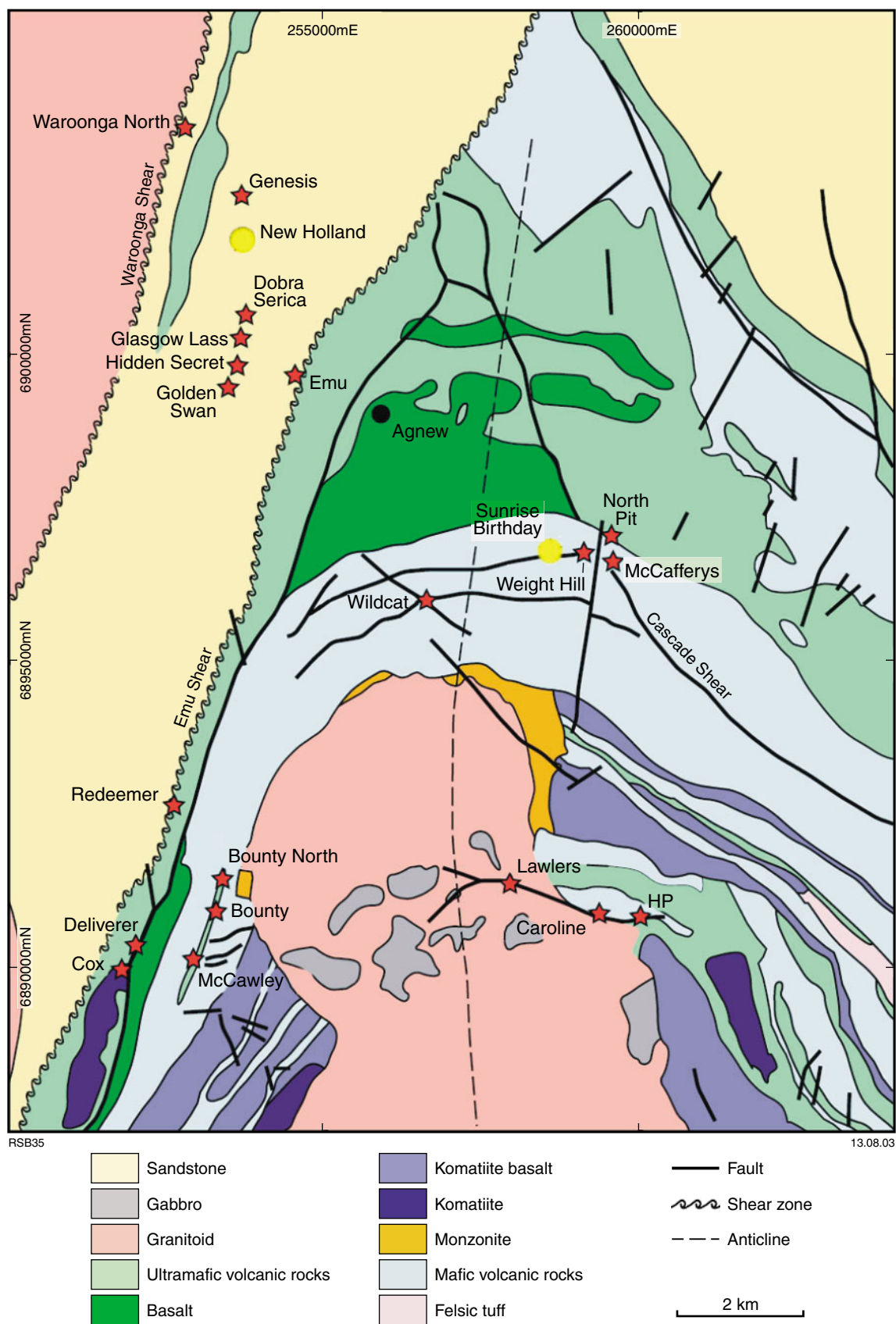


Figure 25. Simplified geological map of the Lawlers area with the location of Sunrise Birthday and New Holland (modified from Beardsmore, 2002)

a time marker related to upright folding and reverse–thrust faulting. The purpose of this short stop is to examine a typical outcrop facing a regional geologist (Fig. 26a), and to determine if it is possible to establish the real significance of this foliation that will become apparent in the deposit.

Locality 4b: Gold in an extensional shear zone

The dominant structural feature of the Sunrise Birthday deposit is a strongly partitioned extensional shear zone within high-Mg basalt above a competent gabbro. The S_3 foliation is characterized by a strong amphibole stretching lineation and displays S–C and C' planes that indicate extension down to the north-northeast (Fig. 26b,c,e). Zones of greatest D_3 shear strain host the Au mineralization. Examples of these features can be seen in high-strain zones in the eastern wall of the pit (Fig. 26b).

Within the competent gabbro, the D_3 extensional event is expressed as brittle carbonate–amphibole veins, with extensional kinematics determined from well-developed slicken lines (Fig. 26d,f). Examples of these faults can be seen adjacent to the slip on the southern wall of the pit. On the other side of the landslide on the southern side of the western wall an almost vertically dipping gold-bearing quartz vein associated with the extension event can be observed.

The resolution of the stress vector by applying the P–T dihedral method (Angelier, 1984), using both the ductile S–C fabrics in the high-Mg basalt and the brittle faults within the gabbro, consistently resolve σ_1 to be vertical and σ_3 to strike north-northeast in the horizontal plane (Fig. 27).

Two phases of brittle deformation, with uncertain crosscutting relationships, overprint the D_3 extensional shear zone (Fig. 27). The first is expressed as a series of north-northeasterly striking sinistral and east–westerly striking dextral carbonate–amphibole veins formed under northwest–southeast transpression. This event is inferred to be related to the regional D_{4b} event. The second is expressed as north-northeasterly striking carbonate in filled dextral faults (Fig. 26g,h), and these structures have formed during the regional D_5 deformation. These brittle faults and associated crenulations can be observed in the southern and eastern wall of the pit respectively.

Locality 5: New Holland—low-displacement contractional gold in competent late basin sandstones (MGA 253840E 6902649N)

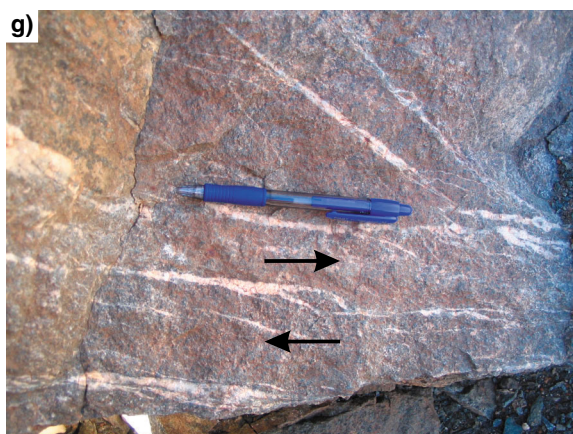
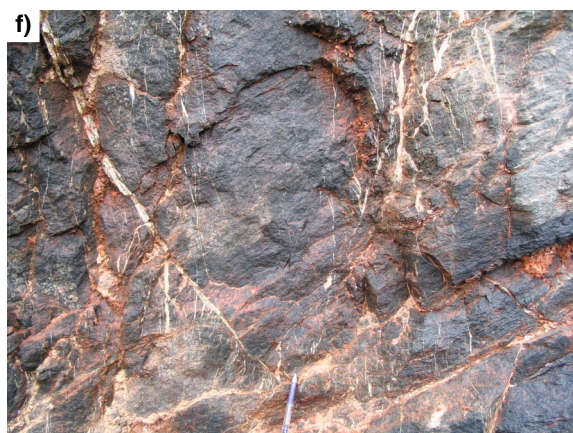
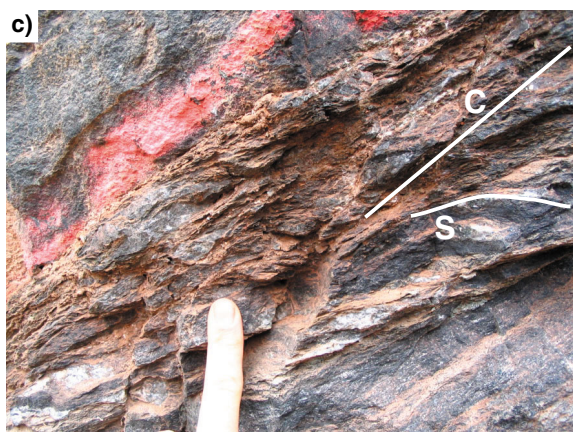
The purpose of showing this mine is to contrast the mostly mafic rock-dominated host lithologies with a solely metasedimentary host rock. Permeability creation through fracturing is strongly influenced by rheology and competency. At New Holland, spectacular vein arrays are

developed within the competent and brittlely deformed sandstone within the more ductile (less competent and barren) siltstone units. The idea that major deformation events are required for the formation of significant gold mineralization is questioned at this deposit. Here, low-displacement fractures are responsible for establishing the permeability, focusing fluid flow, and final deposition of significant gold.

The New Holland mine is located about 12 km north-northwest of Lawlers and is hosted by steeply west-dipping and west-facing metasedimentary rocks of the Scotty Creek late basin (Fig. 25). The deposit contains over 1 Moz of gold, and is mineralized to depths in excess of 750 m (Ackroyd et al., 2001). It was discovered in 1991 and its deeper extensions in 1996. The mine has changed hands a number of times through various mergers and acquisition and is now held by Barrick.

The Scotty Creek Conglomerate has a maximum depositional age of 2662 ± 5 Ma (Dunphy et al., 2003). It crops out along the western limb of the Lawlers Anticline as a fault-bounded unit. To the east it is bound by the north-northeasterly trending Emu Shear Zone and to the west by the north-trending Waroonga Shear Zone. The sandstone units that host the mineralization (Figs 28 and 29a) occur as subparallel medium- to very coarse-grained 10–90 m-thick beds with a lateral extent of up to 1500 m (Beardsmore, 2002).

Figure 26. Compilation of photographs from the Sunrise Birthday pit: a) view east of foliated gabbro (atypical exposure). The kinematic significance of this foliation is difficult to ascertain at outcrops such as these, and they are likely to have been interpreted as contractional fabrics in the past; b) view west into the Sunrise Birthday pit showing the 'rolling' of the foliation. The majority of this host gabbro is unfoliated, with the penetrative fabric connected to high-strain zones. This is a neo-formed S_3 fabric that was developed during down-to-the-north-northeast extension; c) high-strain D_3 S–C shear zone fabrics indicate extensional kinematics on the shear zone. Photo taken (view east-southeast) from the main shear zone (photo b) intersecting the access ramp; d) well-developed down-dip stretching lineation. These L_3 lineations are orthogonal to the intersection lineation of the S and C planes (view southwest onto oblique fault plane); e) view west-southwest of boudinage and extension, with the development of extensional C' planes. Note extension veins in filling the boudin necks (encircled). A pecked line highlights an asymmetric boudin (between the arrows); f) steeply dipping extension and shear veins developed in low-strain competent and unfoliated gabbro. P–T dihedra analysis suggests that these structures are low-strain temporal equivalents of the high-strain shear zones; g) D_5 dextral strike-slip structural elements (shear and extension veins) developed under northeast–southwest contraction (pen is north–south on a pavement); and h) view east-northeast onto steep D_{4b} sinistral fault plane showing slicken lines plunge gently (consistent with a strike-slip tectonic mode)



RSB36

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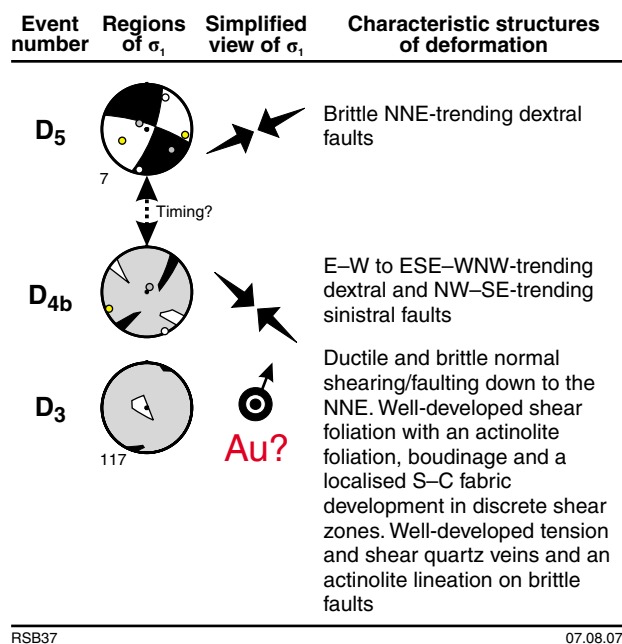


Figure 27. Compilation of structural elements from the Sunrise Birthday pit. The timing of the D₄ northwest–southeast contraction and the D₅ northeast–southwest contraction was not resolved, but on regional considerations this order of events is inferred

The Scotty Creek Conglomerate was tilted into its' present north–south-striking vertical orientation during the regional D₄ event (that inverted the basin). Boudinage of the sandstone units indicates this occurred under east–west compression. Palaeostress analysis of quartz shear veins from New Holland and Genesis resolve σ_1 to be east–west and σ_3 to be vertical, which is consistent with progressive deformation during the D₄ regional event. Many of the veins form sigmoidal en echelon conjugate arrays (Fig. 29b,c). Intersections of the conjugates commonly blow out into massive quartz–carbonate veins and breccias.

In detail, the gold-bearing quartz shear veins at New Holland display both reverse- and extensional-sense kinematics with consistent west-over-east transport along the major shear veins, consistent with folding of the west-facing stratigraphy. Reverse-sense (west-over-east) kinematic shear veins occur predominantly on the western side of the subvertically dipping sandstones and normal

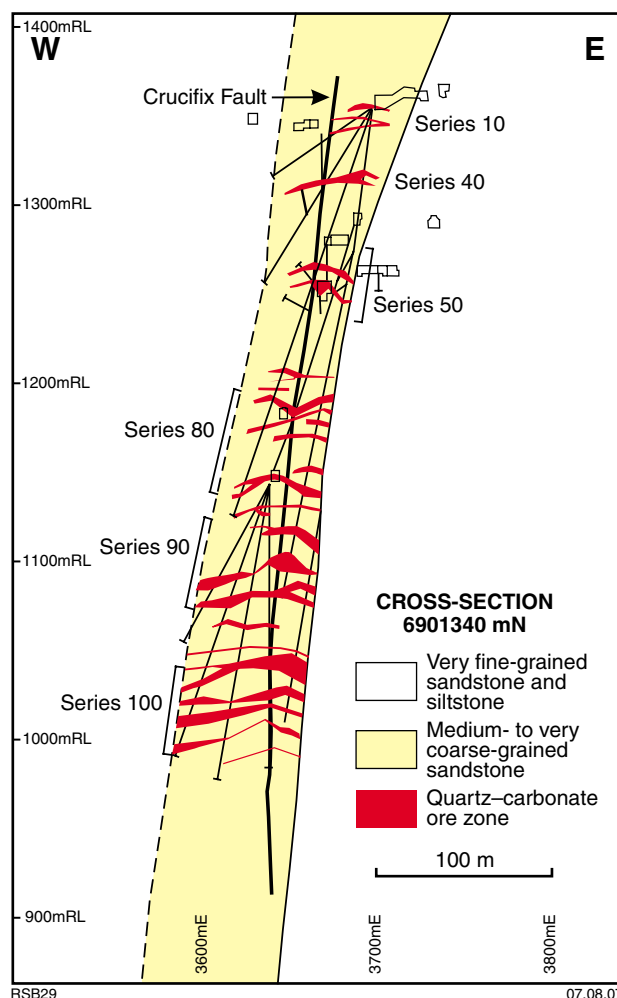
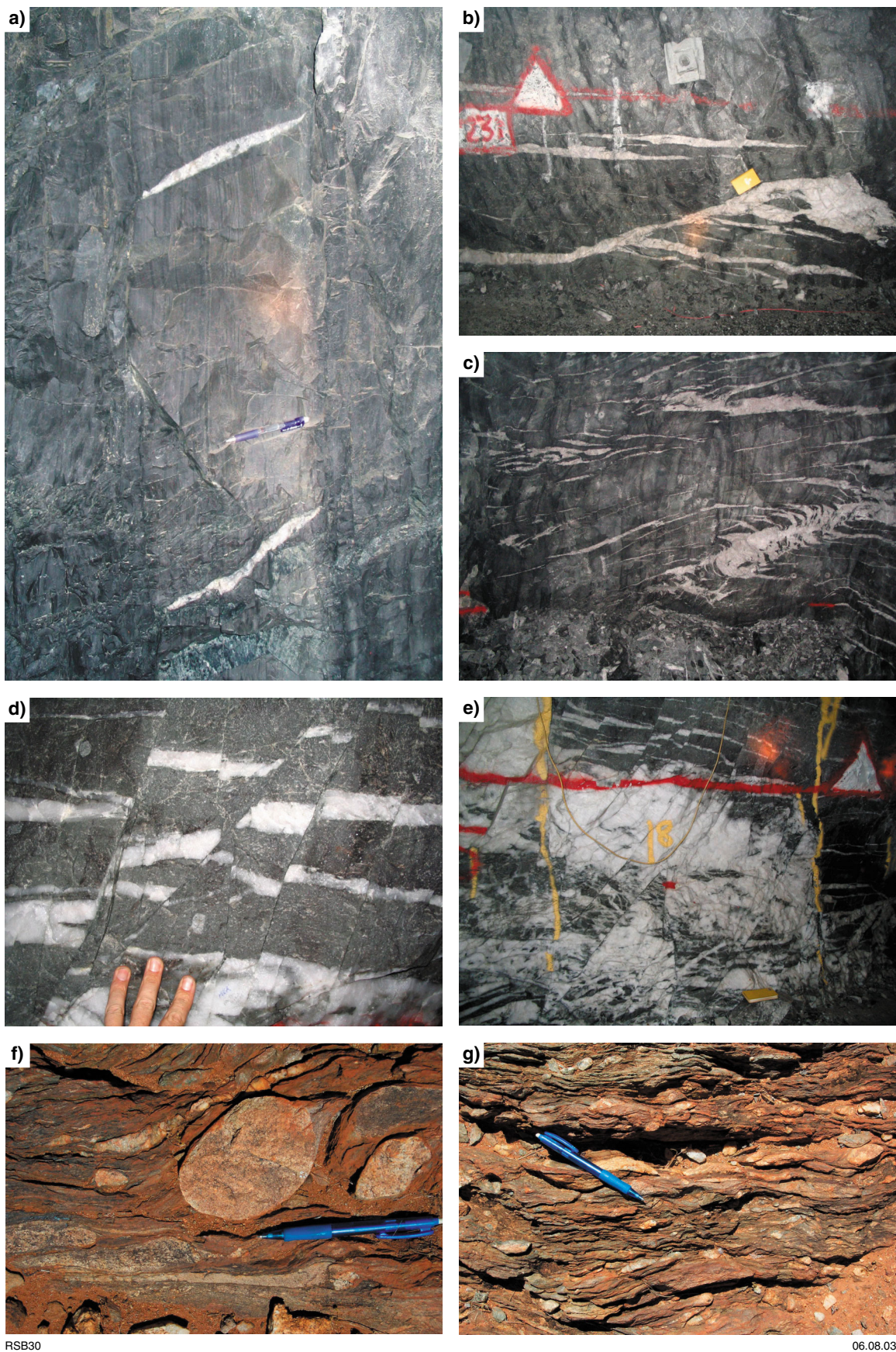


Figure 28. Cross section from New Holland mine (after Beardsmore, 2002) showing the development of stacked ore zones restricted to a steeply west-dipping sandstone horizon. The competency contrast between the sandstone and surrounding siltstones favoured brittle fracturing in the former and development of open space and subsequent mineralization during D₄

Figure 29. Compilation of photographs from the New Holland mine and region: a) view north onto wall with gently dipping extension (?shear) veins developed in the subvertical sandstone bed and not in the surrounding shales. This relationship is analogous to the larger scale mine control (Fig. 28); b) classic wing cracks associated with D₄ contraction (view north); c) classic wing cracks associated with D₄ contraction (note the sigmoidal vein arrays). Although these veins are visually spectacular (and they host gold), there is minimal displacement (strains) along these structures. These veins and this contractional event were imposed on a sequence of rocks that were tilted to vertical prior to the emplacement of the veins (view north); d) down-to-the-south normal faults cut the quartz veins. These faults are locally hosts to quartz veins and are considered part of the mineralizing event by Ackroyd et al. (2001) (view west); e) down-to-the-south normal faults cut the quartz veins (view west); f) the western margin of the Scotty Creek Basin (host of the New Holland deposit) with strong north-northeasterly trending D₅ dextral strike-slip shear fabric (developed during D₅; view east onto pavement); and g) ner grained metasedimentary rocks with well-developed north-northeasterly trending D₅ dextral S–C and C' planes (view east onto pavement)



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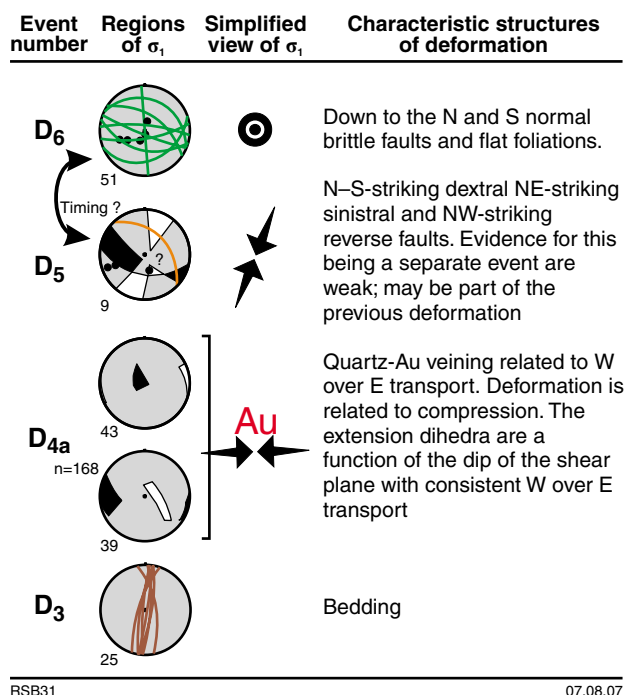


Figure 30. Compilation of structural elements from the New Holland mine. The main veins resolve in the P–T dihedra analysis to be tightly constrained east–west and is recorded as west-over-east thrusting in the mine. The south-dipping normal faults are here interpreted as D₆ extension

Metamorphism at the time of mineralization attained greenschist-facies conditions with a mineralogy comprising calcite–albite–biotite–chlorite–epidote (–actinolite; Ackroyd et al., 2001). Gold mineralization was also associated with base metals (galena and sphalerite). P–T conditions during gold mineralization were typically ‘mesothermal’ and ranged from 250 to 390°C and 1.5 to 3.5 kb. Interestingly, base metal associations with gold generally occur with the youngest (D₅) mineralization event (Goscombe et al., 2007).

Ackroyd et al. (2001) described three vein types that host gold mineralization and were interpreted as forming in one structural event. However, microstructural examination of the sandstones and siltstones around the Crucifix Fault shows that the alteration assemblages (dominated by biotite) overprint the quartz veins (Fig. 31a). This raises the question about whether there was only a single mineralizing event. Ackroyd et al. (2001) described the following mineralized veins:

- type 1: low-angle, 30° east- and west-dipping, weakly mineralized (<10 g/t Au) shear veins;
- type 2: north–south-trending, subhorizontal, highly mineralized (>50 g/t Au) shear veins; and
- type 3: east–west-trending, 40°–60° south-dipping extension veins (<1 g/t Au).

Gold-bearing quartz veins at New Holland are overprinted by two subsequent brittle deformations of unknown relative timing with respect to one another. One consists of north-striking dextral (Fig. 31) and northeast-striking sinistral faults formed under northeast–southwest

compression inferred to be related to the regional D₅ dextral event, which is prominent along the Waroonga Shear Zone to the west (Fig. 29f,g), and Emu Shear Zone to the east. The other event is expressed as mostly east–west-striking normal faults (Fig. 29d,e) and some gently dipping foliations.

Evidence for the dextral event is visible on steeply dipping bedding planes (Fig. 31a,c) where dextral slicken lines occur (Fig. 31b,d), and these dextral shears may be part of the regional D₅ event. In contrast to Ackroyd et al. (2001), it is likely that two mineralizing events (D₄ and D₅) occurred at New Holland (and in the region). The D₅ dextral event may have contributed to the gold budget on the basis of:

- a young (D₅ time) age of 2638 ± 6 Ma (reported in Blewett and Czarnota, 2007b) for the Redeemer deposit located on the Emu Shear Zone to the south (Fig. 25);
- the overprinting relationship between some of the alteration (and foliation) of the D₄ quartz veins (Fig. 31e), and;
- the base metal associations with the gold.

More work is needed to further test these ideas, including dating the inferred to be earlier D₄ gold event (anticipated to be c. 2650 Ma); linking alteration to different structures; and developing an understanding of the base metals (plus their host structures) to gold.

Due to the nature of constantly changing active-underground operations like New Holland, no specific sublocalities are described here (they will have been likely mined out between the time of writing and the visit!). The field excursion will visit accessible quartz-vein arrays within the sandstone and contrast these with the barren siltstones.

CARDINAL RULES APPLY: This is an ACTIVE mine requiring an underground induction and wearing of all underground PPE (provided). Most important—full attention is to be given to ALL instructions by the onsite Barrick underground mine geologists.

Locality 6: Poison Creek complex granites with multiple phases of intrusion and structure (MGA 0331455E 6811653N)

Leaving New Holland mine turn left (south) onto the Old Agnew Road for 32 km. Stop 200 m north of the creek (usually dry) crossing of the road and follow a faint track to the right (west) towards the northern bank of Poison Creek and a spectacular rockhole.

This site is an example of the complex magmatic and structural relationships visible in the granites (which make up 70% of the Yilgarn Craton). Although this locality is not dated, it is representative of many that are (but not easily accessible in a tour bus!). The most favourable time of day to visit a granite site like this is when the sun is high (midday).

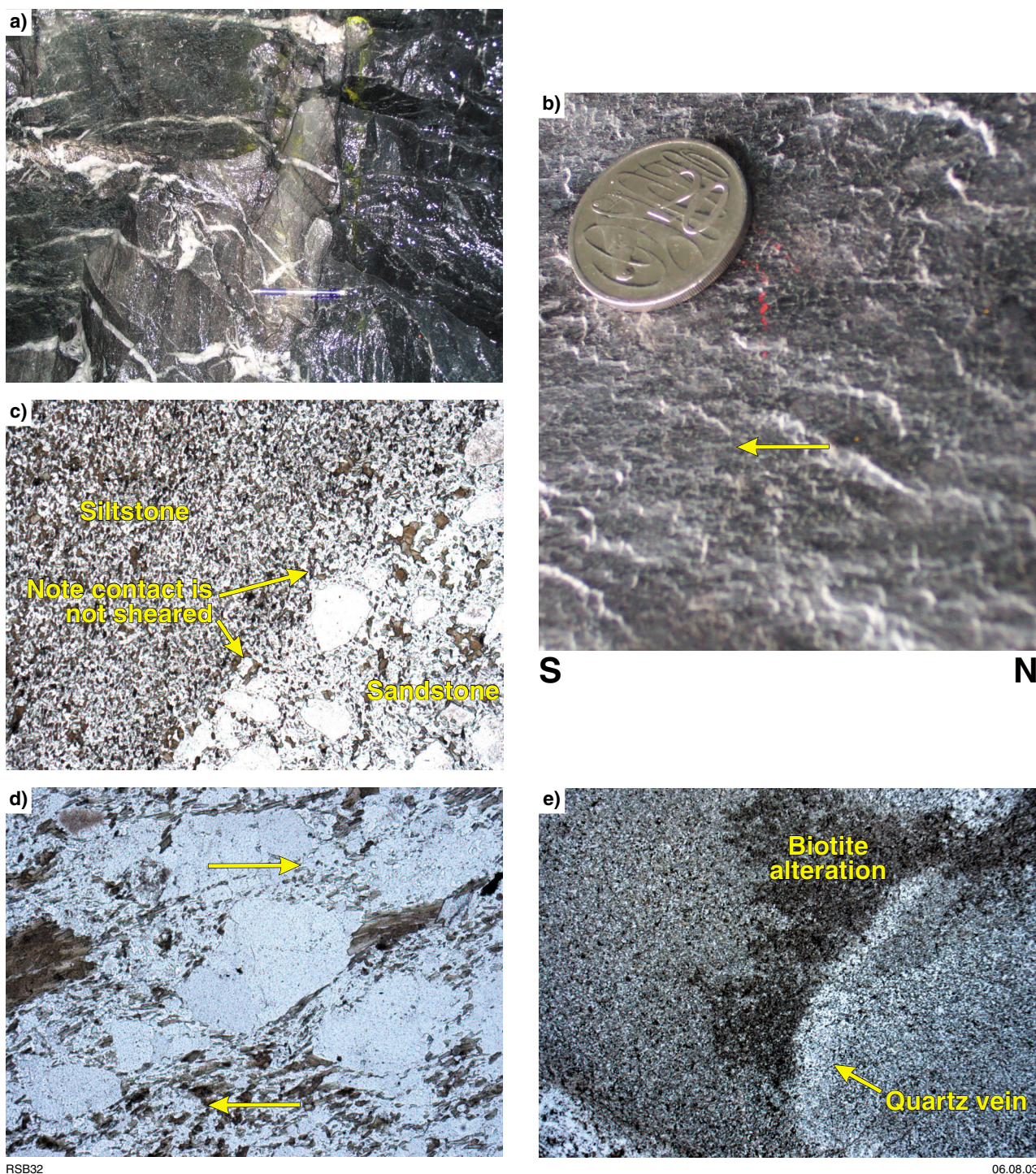
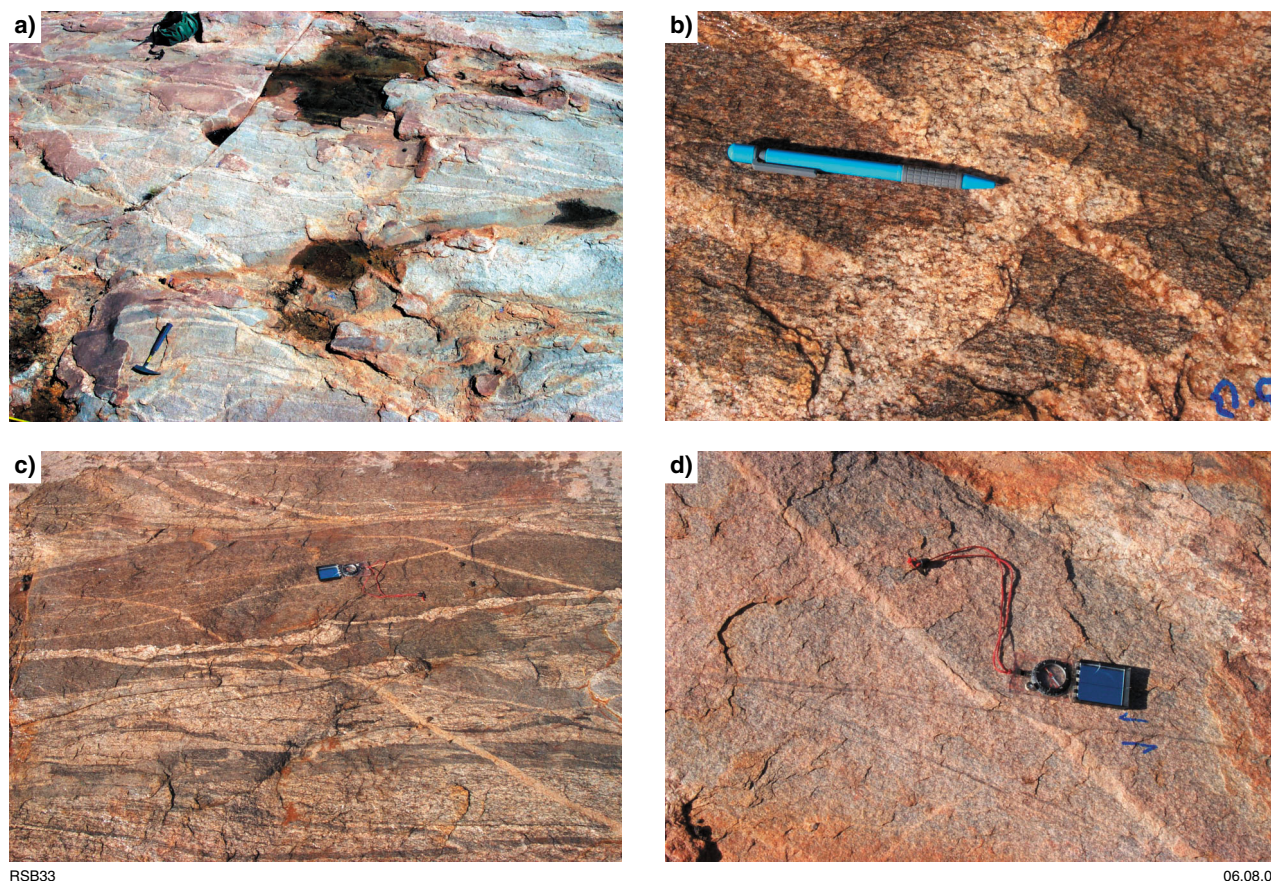


Figure 31. Details of the dextral shear at a sandstone–siltstone interface (Crucifix Fault): a) view north of the Crucifix Fault, with sample taken from near the pen; b) view west of subhorizontal lineation and slickenites (with dextral kinematics) from hand specimen sourced at (a); c) photomicrograph of sandstone–siltstone contact with minimal shearing. The S_4 foliation is oblique the layering; d) view vertically downwards (parallel to the lineation) of north–south dextral shear defined by asymmetric fabrics and biotite beards on large quartz grains; and e) quartz vein cut by biotite alteration (top right of section) showing post- D_4 quartz vein flooding by fine-grained biotite



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Figure 32. Compilation of structures from a typical granite pavement (Poison Creek) in the EGST. These photos demonstrate the composite nature of these granite batholiths: a) general oblique view to southwest of Poison Creek pavement with abundant dykes of different phases; b) tight to closed coarse-grained folded granite vein with axial-plane foliation parallel to main fabric cuts earlier granite phases and the main S_1 fabric (view northeast onto pavement); c) complex relationship between north-northwesterly trending granite dykes and their transposition and folding during sinistral shearing. Late dextral faults and granite dykes are also recorded (parallel to compass); and d) northwest-trending D_4 sinistral shear with biotite seams cuts 'W₃' dyke

The granitoids at this site are not dated, but on comparison with similar granitoid complexes are likely to have phases aged from 2675–2665 Ma for high-Ca granite types and approximately 2640 Ma for low-Ca granite types (dykes and sills). The site is located on the east limb of the Lawlers Anticline (Fig. 2), with the main fabric dipping east, parallel to the limb of this regional fold. Regionally, a pervasive foliation such as this developed during extensional doming (e.g. at Sunrise Birthday; Blewett et al., 2004). Extensional kinematics (during D_3) are inferred but not proven at this site.

The main host rock is a coarse-grained granodiorite with gneissic banding and numerous granite and pegmatite sheets and dykes (Fig. 32). A prominent sinistral-shearing event transposed layering and folded the dykes into gentle plunging asymmetrical folds (Fig. 32b,c). This shearing event was likely imposed on a previously developed S_3 extensional fabric. These shears, together with a series of dykes, sinistral and dextral faults, and shear zones, are all interpreted to have developed during approximately east–west D_{4a} and D_{4b} contraction and transposition (Fig. 32d). Careful mapping of shears/faults and dykes/sills reveals up to seven discrete stages of

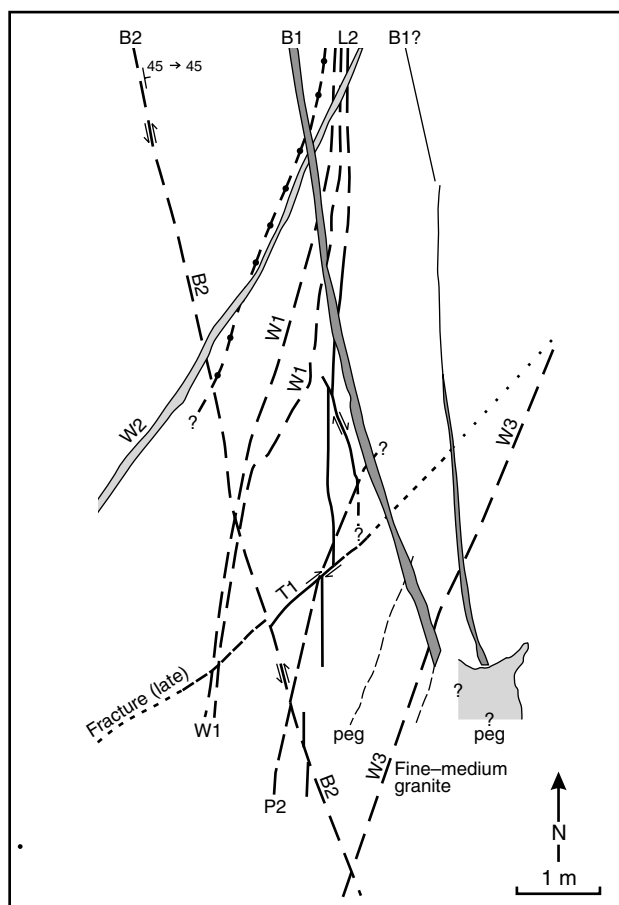
deformation making up the regional D_4 event at this site (Fig. 33)

Locality 7: Victor Well—dextral shear and gold (MGA 0331455E 6811653N)

Travel along the Old Agnew Road from the Poison Creek granite locality to the bitumen Leonora–Leinster road. Turn left (north), travel 800 m and turn left (west) onto a dirt track for 400 m. At the crossroads of two tracks turn left (south) for 1 km and turn left (east) for 300 m to the locality.

Danger: OPEN SHAFTS are present in the immediate vicinity

Victor Well is an example of north-northwesterly trending, ductile, dextral strike-slip shear zones that host gold. The exposure demonstrates the highly partitioned nature of the dextral event as it is only developed over a few metres in width and is absent at the margins of this pit.



Chronology

- Oldest ↑
- L1 Host: variably banded granite
 - B1 Bands in host, probably dykes, cut layering (L1) in host T1, offsets L1 (dextral), not seen at Poison Creek
 - T1 Cuts L2 with 10 cm throw (dextral); elsewhere appears to be reactivated as late fracture which cuts all, but with no offset
 - P2 Cuts T1, L1, and B1, cut by B2
 - W3 Cuts L1, B1 (no offset), cut by B2
 - B2 Sinistral, cuts P2 and W3, cut by P3
 - W2 Cuts B2, but also foliation
 - W1 Cuts W2 and B1
 - W4 Cuts nearly everything
 - W5 East-west pink medium granite (?low Ca), late fractures
- Youngest ↓

- B1 Various biotite granodiorite and leucogranite dykes in host
- W5 Thin pink (?low Ca) medium biotite granite
- W4 5 cm-wide characteristic white medium granite with coarser pegmatite/granite core and biotite-rich selvages
- W3 Thin fine-medium granite dyke
- W2 Thin pink named granite dyke; good foliation with elongate quartz
- B2 Thin (1 cm) biotite-rich schlieric shears that offset layers in host (sinistral)
- L2 Felsic and biotite-rich bands in host, mostly < 10 cm wide with 2–4 thin schlieren layers
- L1 Variably banded, variably feldspar porphyry

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Figure 33. Detailed pavement map of Poison Creek, showing the various phases of dykes and faults/shears

The foliation could be interpreted as a typical 'S₂' fabric, but kinematically is different to that seen at Yunndaga (sinistral) and Gwalia (normal).

Victor Well is a small pit 3–4 m deep and 25 m long, located 17 km north-northwest of Leonora (Fig. 15). Gold is hosted in a pyritic quartz vein within a north-south-striking dextral shear zone that crosscuts the regional east-west-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 this north-dipping fabric represents the regional D₃ extensional foliation that wraps around the Raeside Batholith and is exposed at the nearby Sons of Gwalia and Tarmoola mines (Fig. 34).

The east-west S₃-trending fabric has been rotated into the central D₅ dextral shear zone, which is characterized by a pervasive shear fabric with well-developed S–C foliations (Fig. 34). Cross cutting C' dextral shear bands are also common (see Fig. 34). The stretching lineation plunges gently to the south-southeast.

This dextral shearing stage is associated with quartz veins and the gold event, and is interpreted to be related to northeast-southwest regional D₅ contraction (Fig. 34). The last stage of deformation is recorded by sparsely developed steeply dipping north-south-trending D₅ crenulations.

Excursion localities— Leonora to Laverton

Day 3

Locality 8: Mertondale—gold in sinistral transpression (MGA 357972E 6828340N)

Leave Leonora at the north end of town and drive 31 km along the Nambi road. As you approach the Mertondale area there is an old chimney on the right. Turn right onto the mine's access road and take the left fork at 400 m. This road swings south and then east around the Mertondale 3 and 4 pit. The main decline into the Mertondale 3 and 4 pit is from the northeast.

The purpose of visiting the Mertondale pit is to demonstrate the regional superposition pattern of north-northwesterly striking sinistral transpressional shear zones overprinted by north-striking dextral transtensional faults. Gold at Mertondale is associated with sinistral transpression localized on the edges of the central porphyry intrusion.

The Mertondale group of gold deposits is located 30 km northeast of Leonora (Fig. 35). Mineralization is localized along high-strain shears at basalt-porphyry contacts in the north-south-striking Mertondale 3 and 4 pit and along low-strain shear zones within

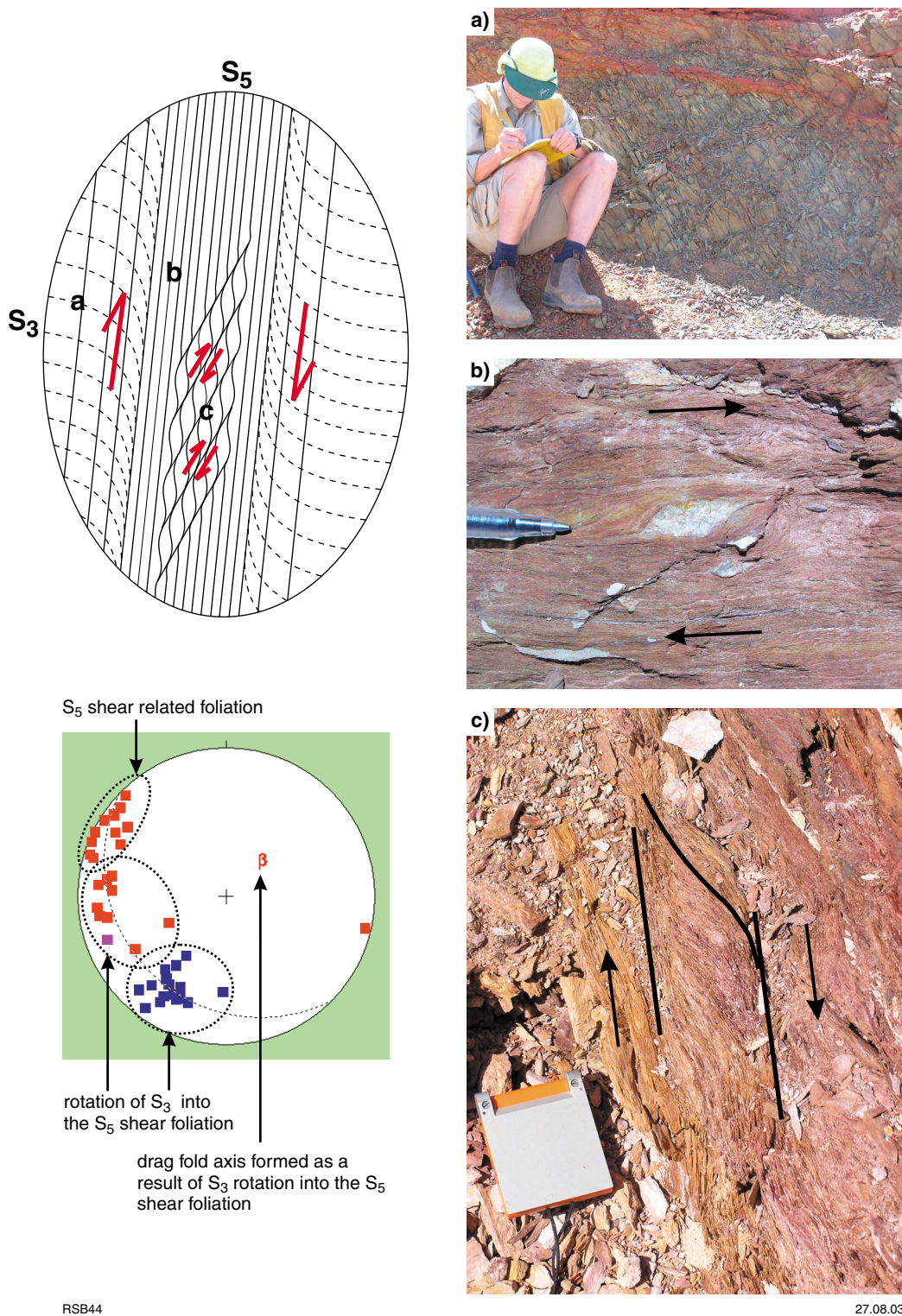


Figure 34. Schematic diagram of Victor Well pit illustrating the rotation of S_3 into the D_5 dextral shear zone and the development of C' planes in the central part of the shear zone. Letters indicate photo locations. Stereographic representation of the schematic diagram showing the rotation of the S_3 fabric into the D_5 dextral shear zone: a) view west of pencil intersection lineation of S_3 and S_5 dextral shear-related foliation; b) view east of dextral stair stepping indicating that S_5 is a shear plane; and c) view south-southwest of dextral C' plane in central dextral shear zone

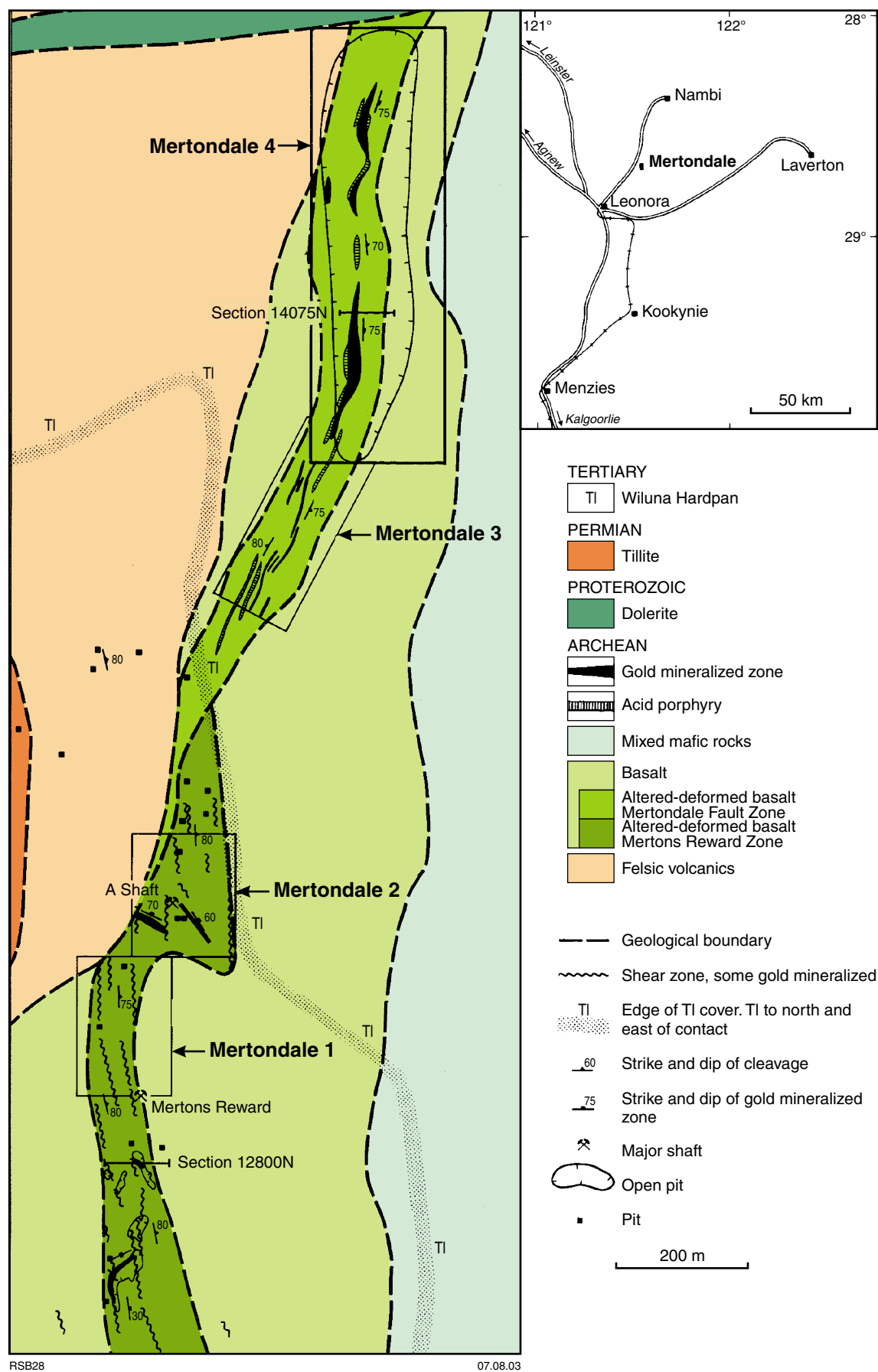


Figure 35. Location map and geology of the Mertondale line of deposits (after Nisbet and Williams, 1990)

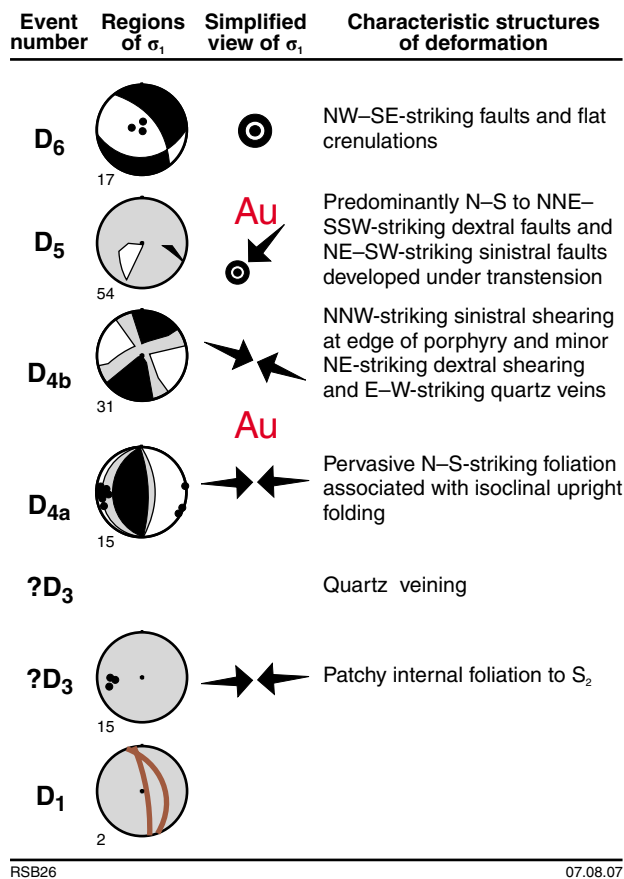


Figure 36. Compilation of structural elements from Mertondale

the east–west-striking Mertondale 2 pit (Nisbet and Williams, 1990). The deposits are located along the Mertondale shear zone, a large north–south splay of the north–northwesterly trending Keith–Kilkenny shear zone to the south.

Gold is associated with quartz, carbonate, and silicic alteration. Nisbet and Hammond (1989) and Nisbet (1991) recognized 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 north–northwesterly striking faults. This study supports this result while demonstrating a greater level of complexity in the structural history.

The structural stratigraphy of the Mertondale group of pits comprises up to five events (Fig. 36). The earliest structural element preserved is an upright foliation within low-strain microlithons of the pervasive north–south-striking foliation. It is unclear as to whether this remnant fabric represents an early deformation or if it is part of the progressive deformation history associated with the development of the penetrative foliation.

The second structural element at Mertondale is expressed as foliation-parallel quartz veins, which are

boudinaged within the pervasive foliation. The timing of these veins is restricted to pre- to syn-main S_{4a} fabric formation (Fig. 36).

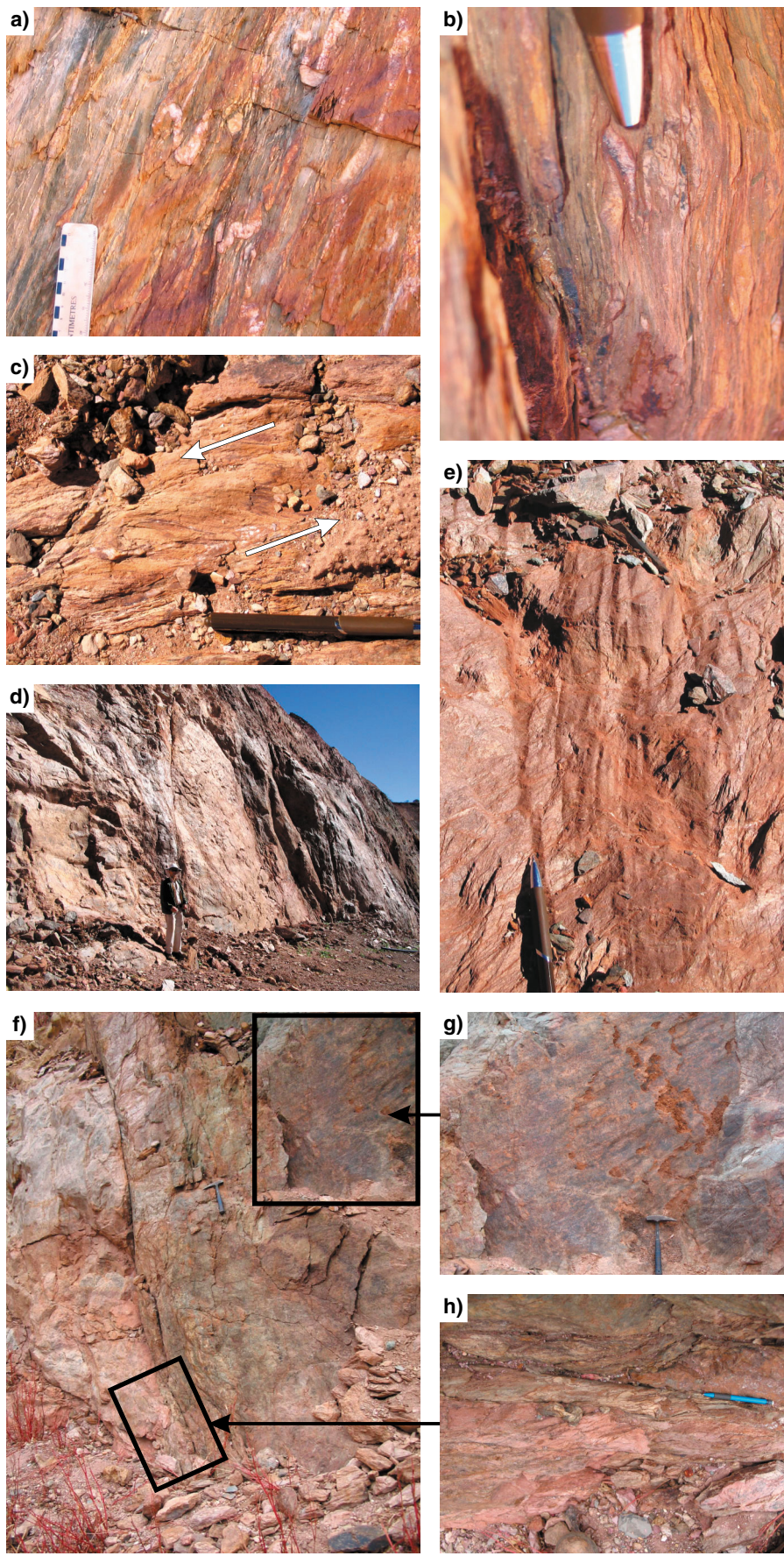
The dominant structural feature of the Mertondale deposit is the D_{4a} north–south-striking pervasive foliation. This foliation is associated with reverse-shear sense kinematic indicators (Fig. 37a,b) and rare downdip stretching lineations. The inferred stress vector for the formation of this foliation is east–west contraction (Fig. 36).

The pervasive reverse-sense shear fabric is overprinted by a sinistral strike-slip shear zone localized on the edge of the central porphyry (Fig. 37c). The porphyry is inferred to have intruded parallel to the S_{4a} pervasive foliation. Sinistral strike-slip shearing during the D_{4b} phase was the result of a clockwise rotation of σ_1 from east–northeast – west–southwest to east–southeast – west–northwesterly directed shortening and a switch in the other principal stresses σ_2 and σ_3 , (similar to the history at Yunndaga at Locality 1). An example of the sinistral strike-slip shear zone can be observed in the pavement halfway down the decline.

Overprinting the reverse-sense shear pervasive foliation and the sinistral strike-slip shear zone are brittle, predominantly north–south-striking, dextral strike-slip (transtensional) faults. These faults are associated with quartz–carbonate veining along the fault planes (Fig. 37d,f) and northwest–southeasterly striking crenulations of the S₄ fabric (Fig. 37e). P–T dihedra analysis of the brittle dextral strike-slip faults indicates σ_1 was inclined to the southwest during this event (Fig. 36), indicating a transtensional mode of deformation. Excellent examples of the dextral strike-slip faults can be observed along the western wall of the pit. This dextral D₅ event in the Mertondale group of pits probably correlates with the main gold events and dextral shearing in the Nambi and Mount Redcliffe pits along strike to the north (Blewett and Czarnota, 2007b).

The dextral strike-slip faults are overprinted by D₆ normal faults and horizontal foliations associated with extension (Fig. 36).

Figure 37. Compilation of photographs from Mertondale: a) view south (onto wall) of downplunge of asymmetric F_{4a} folds consistent with east-over-west reverse faulting and shear; b) view east-northeast (onto pavement) of dextral strike-slip sigma structures associated with D_{4a} approximately east–west shortening; c) view southwest (onto pavement) of D_{4b} sinistral S–C shear zones developed on edge of the porphyry dyke; d) view northwest of D₅ dextral transtensional faults that are common throughout Mertondale; e) D₅ crenulations (view northwest onto wall); and f) D₅ dextral fault dragging a D_{4b} sinistral fault (g) which cuts the S_{4a} foliation (h). View west of wall



Locality 9: Jupiter — syenite-hosted gold (a Wallaby analogue) (MGA 423669E 6813053N)

From Leonora travel 66 km along the highway to Laverton and turn right (south) at the sign to the Mount Margaret community. Travel south for 4.5 km and turn left (east) at the T-intersection at Garden Well. Drive along this road for 17 km past the Mount Morgans deposit and turn right (sign post Mount Margaret). Follow this road for 8.5 km and take another right and drive 3.3 km through the Mount Margaret community and turn onto a small track. Follow this track for 1.1 km and turn right and drive 1.5 km towards the Jupiter mullock heaps. Walk south across the breached causeway towards the lookout at the north-western side of the deposit.

Jupiter is a spectacular syenite-hosted gold deposit. It is an analogue for the Wallaby deposit and shows the interaction of magmatic and hydrothermal fluids. The central syenite body is comprised of multiple radiating dykes and sills of varying magma composition. The geometry of the syenite dykes illustrates how magma can establish a local stress field (σ_1 vertical) during magma emplacement.

Locality 9a: View southeast of the Jupiter pit

The view to the southeast of the main features of the colourful Jupiter pit (Fig. 38) reveals a radial distribution of syenite dykes into pillow basalt. This radial distribution illustrates how magma over pressure can establish a local stress field during magma emplacement with vertical σ_1 and equal σ_2 and σ_3 . The syenite is also intruded by a quartz-feldspar porphyry dyke. Despite best attempts this syenite has not yielded sufficient zircon to be dated. Regionally these syenites are about 2665 Ma (e.g. Wallaby and Hanns Camp), and it is inferred that the Jupiter Syenite is of equivalent age and was emplaced during the D_3 extension and late basin formation in the region.

The D_3 syenite is cut by northeast-over-southwest D_{4a} shear zones and associated quartz veins. An example of a ductile east-over-west shear is also exposed in the southern wall of the pit. Duuring et al. (2000) identified two such shear zones in the pit, with greatest gold grades centred around these shear zones (Fig. 38).

Locality 9b: Syenite dykes, faults, and alteration up close and personal

Walk to the bottom of the pit.

The greenstones at Jupiter are comprised almost entirely of pillow basalts. The pillow basalts face south and are folded about the Mount Margaret Anticline, although no upright foliation associated with this F_2 folding is observed at Jupiter. Here is a good example of the development of major regional folds (F_2) without foliation development

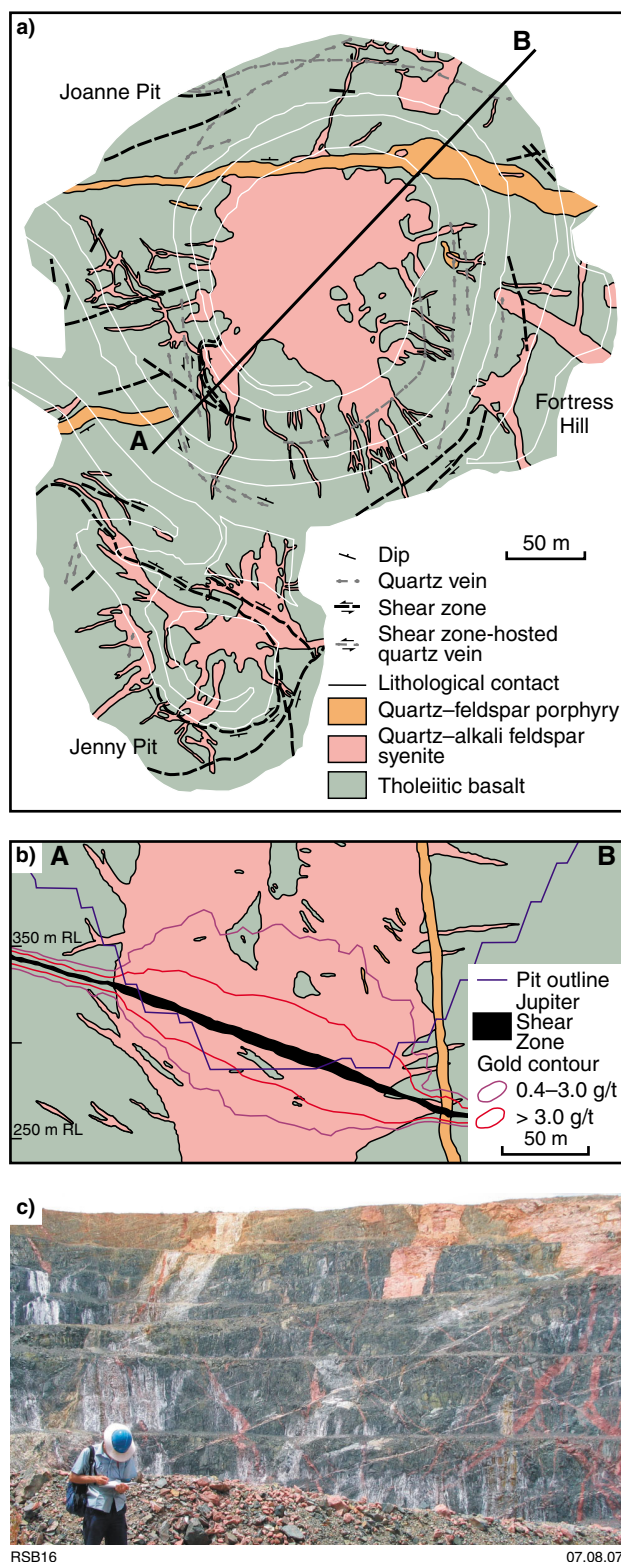


Figure 38. a) Geological map and (b) cross section of the Jupiter deposit, showing zonation of ore grade at the intersection of an east-southeasterly dipping D_4 shear zone with the Jupiter Syenite (after Duuring et al., 2000); and (c) photograph of the syenite dykes cutting the basalt stratigraphy and being cut by D_4 thrusts

(Fig. 39a). This is despite the site's location at the hinge of the major structure and a region where such a foliation would be expected (see **D₂: termination of an arc and east-northeast — west-southwest contraction**).

The pillow basalts are cut by a large variety of syenite and pink, magmatic calcite dykes and minor sills (Fig. 39b,c). Minor quartz and pyrite are associated with the calcite dykes and these are inferred to host gold (as at Wallaby).

D_{4a} quartz veins with reverse-sense kinematics and associated carbonate alteration of the wallrock cut the syenite dykes. The carbonate alteration associated with these veins blows out at intersections with syenite dykes. This relationship implies that the syenite dykes were less permeable than the surrounding basalts during D₄ contraction and shearing. In the western wall of the pit, there is a similar relationship between a vertical zone of alteration and the quartz veins. However in this case, the quartz veins appear to act as a seal to a vertical fluid pathway (Fig. 39d).

Ductile east- (to northeast) over-west (to southwest) D_{4a} shear zones are associated with the quartz veining event. These structures record amazing strain localization (Fig. 39e) and the development of S–C structures. The best examples of this can be seen in the western wall of the saddle between the north and south pit, and along the southern wall at the bottom of the pit. High-grade mineralization (>3.0 g/t) was centred around these two ductile shear zones.

The reverse-sense quartz veins and syenite dykes are cut by D₅ predominantly steeply dipping and north-northeasterly striking, carbonate, dextral normal faults (Fig. 39f). Associated with these faults are northeast-striking sinistral faults. The resultant P–T dihedra analysis of this event indicates that these faults developed under transtension, with σ_1 plunging to the southwest (Fig. 40).

D₆ normal faults, quartz veins and crenulations record the collapse and extension of the system. The relationship of these structures to the D₅ dextral transtensional event is unclear at Jupiter due to a lack of overprinting relationships.

Leave the Jupiter access roads and once at the T-junction with the Mount Margaret road turn right and follow the road east and north to the main bitumen highway. Turn right to Laverton.

Excursion localities — Laverton area

Day 4

After an overnight at Laverton Downs Homestead (north of Laverton) return to the main road and turn right (north) for 33 km until the first graded track (abandoned haul road) on the right. Take this track for approximately 3 km straight to the mine.

Locality 10: King of Creation — transpressional, dextral shear- zone gold (MGA 440615E 6885202N)

This pit is a fine example of extreme partitioning of deformation into a dextral strike-slip shear zone. It is noteworthy as it demonstrates that the penetrative foliation is not developed only by flattening, but has a significant component of shear. This dextral foliation contrasts with sinistral, reverse, and extensional (normal) shearing seen elsewhere on this trip and illustrates why a penetrative foliation striking north–south to north-northwest–south-southeast (the old 'S₂') can not be used as a marker fabric for structural correlations.

The King of Creation deposit is located 53 km north of Laverton (Fig. 2), on the eastern limb of the Mount Margaret Anticline in greenschist-facies greenstones. Strain increases dramatically towards a major dextral shear zone within the centre of the pit, which is assumed to have hosted gold mineralization. Here is another example of where mineralization and regions of intense strain are coupled. It is likely that deformation is required to create 'damage zones' and hence permeability for enhanced fluid flow (Cox, 1999), although in this case permeability formation is dynamic and related to active shearing, rather than brittle faulting.

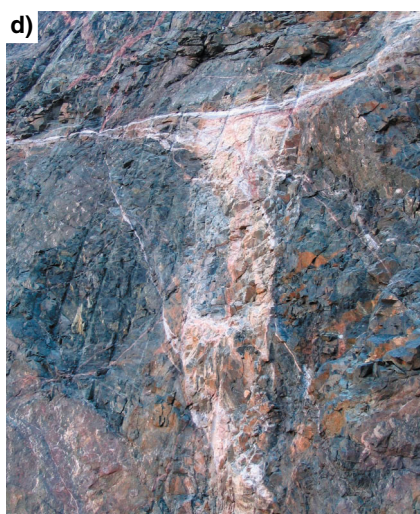
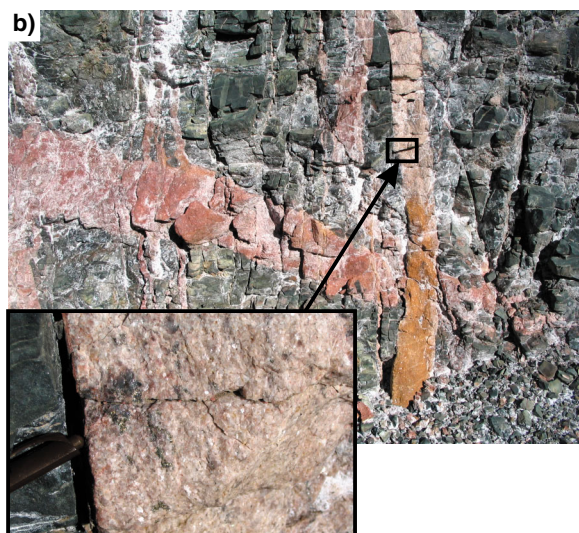
Kinematically the pit is simple, with one progressive period of northeast–southwest contraction responsible for the development of:

- foliations (flattening and shear fabrics);
- veining and porphyry dyke intrusion;
- boudinage of porphyry and veins;
- asymmetric folds, and
- S–C–C' in less competent units; box folds and sheath folds (Fig. 41).

Walk from the east ramp into the central high-strain zone and notice this transition from foliation and veins (which are conjugate) to transposed veins, and finally complex folds (Fig. 41). The central shear zone has spectacular refolded folds. The asymmetry of these is generally Z-shaped, consistent with the D₅ dextral shear couple (Fig. 42c).

Strain is highly partitioned into a narrow north-northwesterly trending mineralized corridor, some 50 m wide. This zone records multiple phases of deformation and transposition under a significant dextral regime, whereas the margins of the pit are strained only by a single, dextral strike-slip penetrative foliation (Fig. 41).

A feature of transpressional shear zones is the separation of the stretch and vorticity within a shear zone (Fossen and Tickoff, 1998) into a vertical component whereas the overall kinematics of the shear zone is strike-slip. The vertical stretching at King of Creation is evident by the development of a patchy vertical-stretching lineation and gently plunging folds, with curvilinear hinge lines (Fig. 42b,c) that tend towards sheath-like development. The dextral strike-slip vorticity or kinematics in the shear zone are evidenced by the boudinage of quartz veins, the



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development of box-shaped folds, and the anticlockwise transection of the foliation across gently plunging fold hinges (Fig. 42a; Blewett and Pickering, 1988).

Late carbonate north–southwesterly (D_{77}) striking dextral faults and extensional normal faults and crenulations (D_{76}), with unclear timing with respect to one another, complete the sequence of events (Fig. 42d).

Locality 11: Lancefield— extensional gold with a dextral strike-slip overprint (MGA 439046E 6840781N)

Leaving King of Creation and join the main road back to Laverton for about 50 km. Turn right at the T-junction (signed Kalgoorlie and Leonora). Take this road for 5 km and turn right onto the Erlistoun road for 200 m and left into Lancefield (Metex Exploration office).

The purpose of visiting Lancefield is to demonstrate the significant down-to-the-southeast extensional shear system developed on the southeastern end of a major granitoid batholith. This contrasts with east-down extension at Leonora and north-down extension on the north end of Lawlers Anticline. Furthermore, Lancefield illustrates a significant dextral-shearing overprint that is characteristic of the Laverton Tectonic Zone and was particularly well developed at King of Creation to the north.

Danger: OPEN SHAFTS are present in the immediate vicinity; please watch your step and do not approach the shafts.

The Lancefield gold deposit is located in the Laverton area, 8 km north-northwest of the town of Laverton (Fig. 2). It is situated at the southeast edge of the amphibolite-grade granites of the Mount Margaret Anticline within amphibolite-grade greenstones (ultramafic schist) with

Figure 39. Compilation of structural events and features at the Jupiter pit: a) view west of undeformed steeply dipping pillow basalts without a foliation. These pillow basalts were folded during D_2 about the Mount Margaret Anticline (without axial planar foliation) prior to D_3 extension and emplacement of the syenite and carbonate dykes; b) D_3 (pink) syenite dykes and sills cut by a D_3 calcite (–quartz–pyrite) dyke parallel to the earlier syenite dykes. Inset shows sulphides hosted by steep calcite dykes; c) collage of photos showing the main Jupiter reverse-sense ductile shear zone offsetting syenite dykes (view north-northeast); d) vertical fluid pathways and damage zone (bleached alteration) restricted or cut by D_4 shears and associated quartz veins (view west); e) D_4 east-northeast over west-southwest reverse-sense shear zones cutting intact pillow basalt. Photo illustrates the extreme strain partitioning over narrow zones and is an analogue for the strain partitioning across the EGST as a whole (view northwest); and f) D_5 dextral-normal brittle faults with well-developed oblique-slip carbonate slicken lines defining the movement sense (view west)

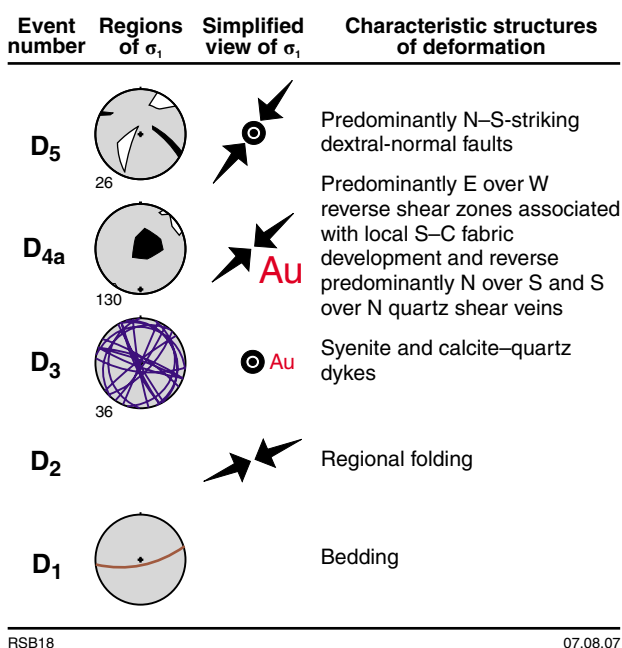


Figure 40. Stereographic compilation of structural elements into discrete events at the Jupiter deposit. Note the D_3 extension event defined by the radial array of syenite dykes. These intersect at the centre of the hemispherical projection illustrating a vertical σ_1 . It is likely that σ_1 was driven from below by a magma chamber at depth. Gold (and sulphides) was likely introduced into the upper crust during the emplacement of the syenite and calcite veins (see Fig. 39b inset) and was remobilized during the D_4 contraction. Note also the switch in σ_3 (black sectors) between D_4 and D_5 from vertical with reverse-sense tectonic mode (D_4) to horizontal with strike-slip tectonic mode (D_5). This pattern illustrates the power of the P–T dihedral method for understanding and unravelling the subtleties of the complex evolution of this system

an underlying domal-granitoid intrusion (Hronsky, 1993). Gold is hosted within two low-angle east- to southeast-dipping shear zones that are defined by so-called ‘shale’ or ‘chert’.

Williams and Whitaker (1993) described significant extension around the southern margin of the Mount Margaret Anticline, with an overall granite to the north-northwest and greenstone to the south-southeast sense of shear. This extensional event formed the main fabric elements at Lancefield, and these are used as a deformation ‘pin’ for other events. This event is regionally linked to the D_3 late basin-forming event (Blewett and Czarnota, 2007b) and this location was likely the footwall to the Wallaby Basin at about 2665 Ma (see also McIntyre and Martyn, 2005). The main extensional fabric is a composite S–C foliation (Fig. 43b,f) at a range of scales (millimetre to decimetre). The fabric and shear zones overprint and show flattened early quartz veins and a locally fine ‘early’ foliation is preserved as crenulations (Fig. 43a,b).

East–west striking crenulations and folds (Fig. 44a) overprint the main S–C extensional fabric (Fig. 45)

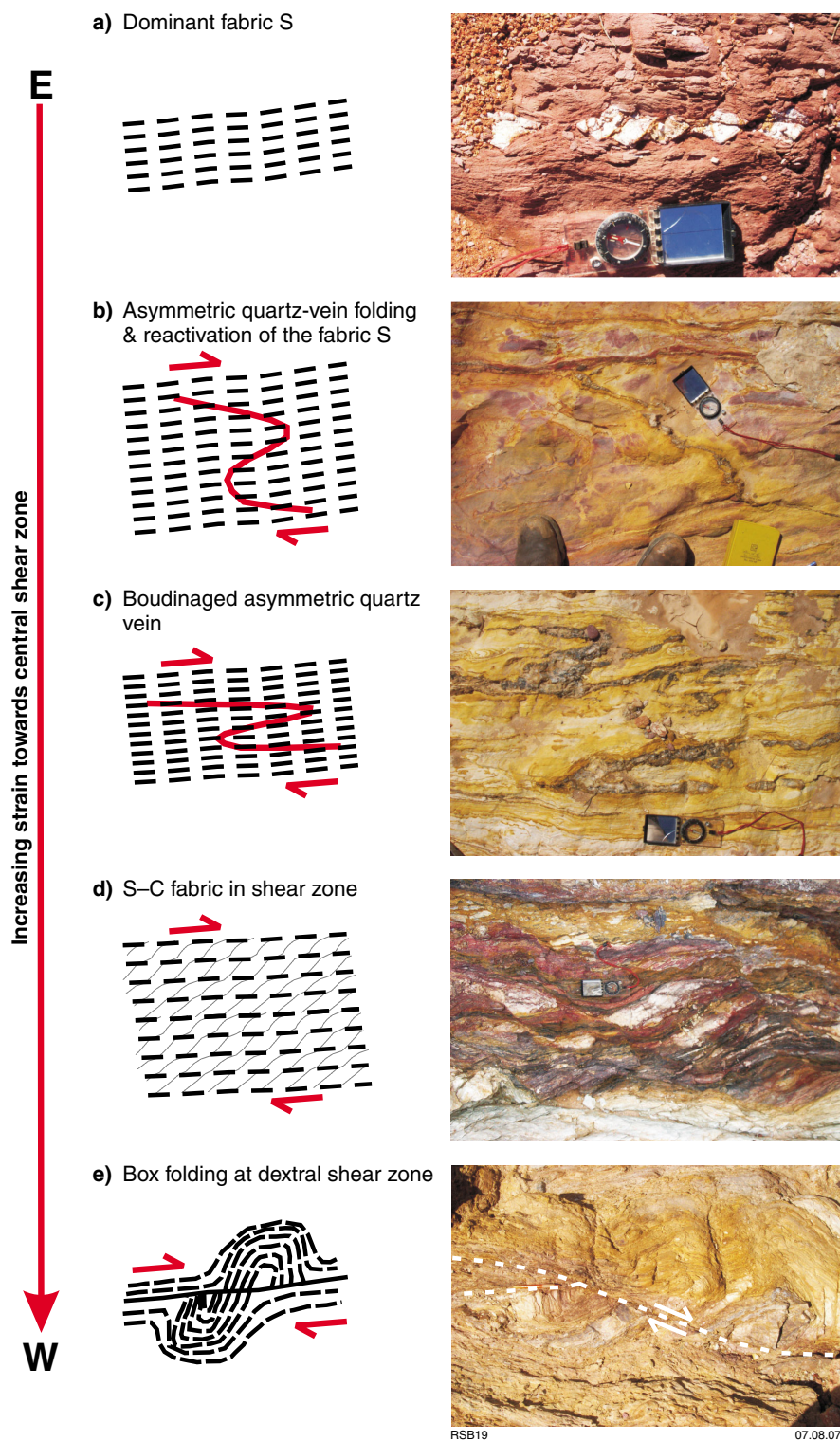
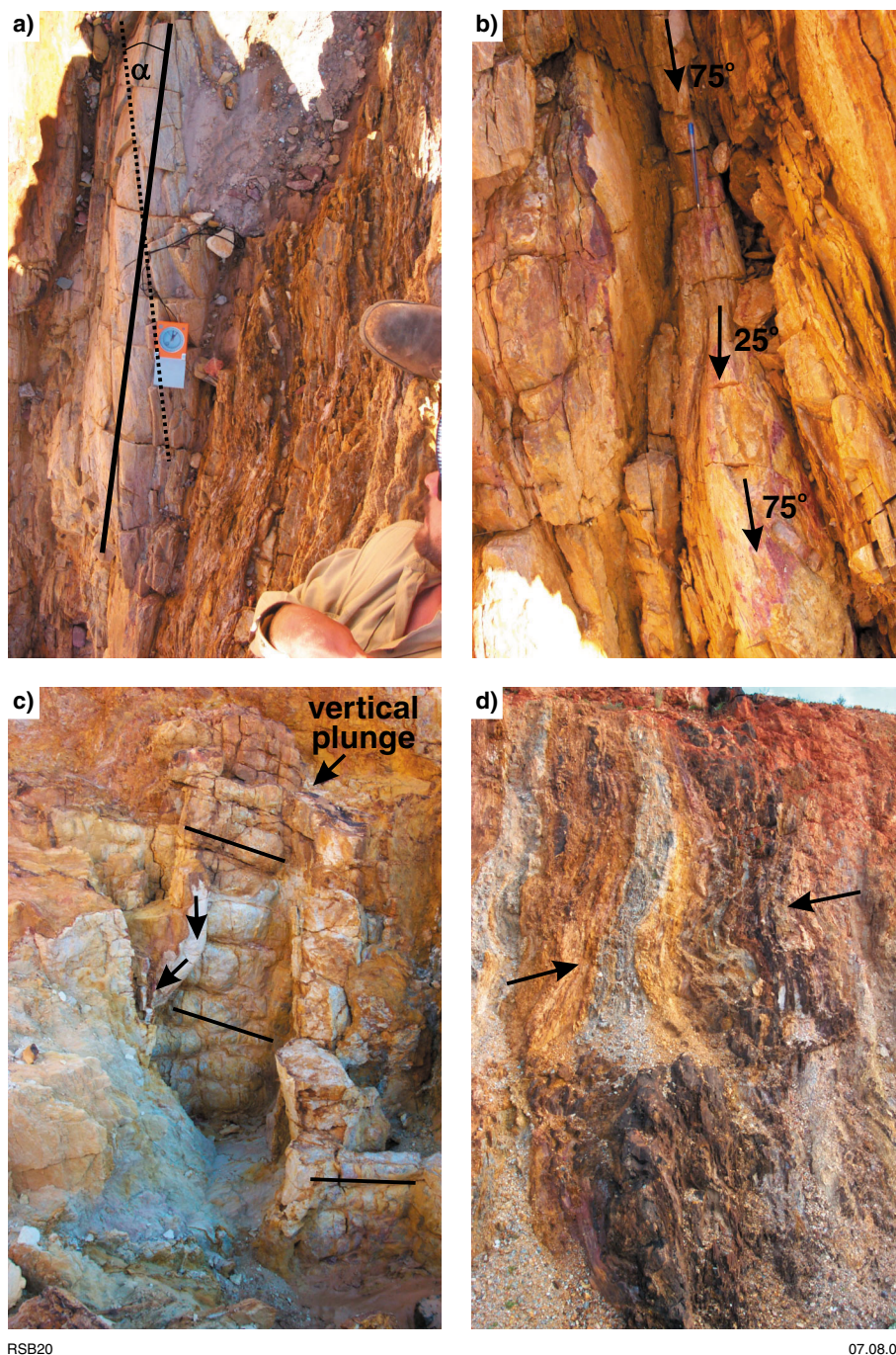


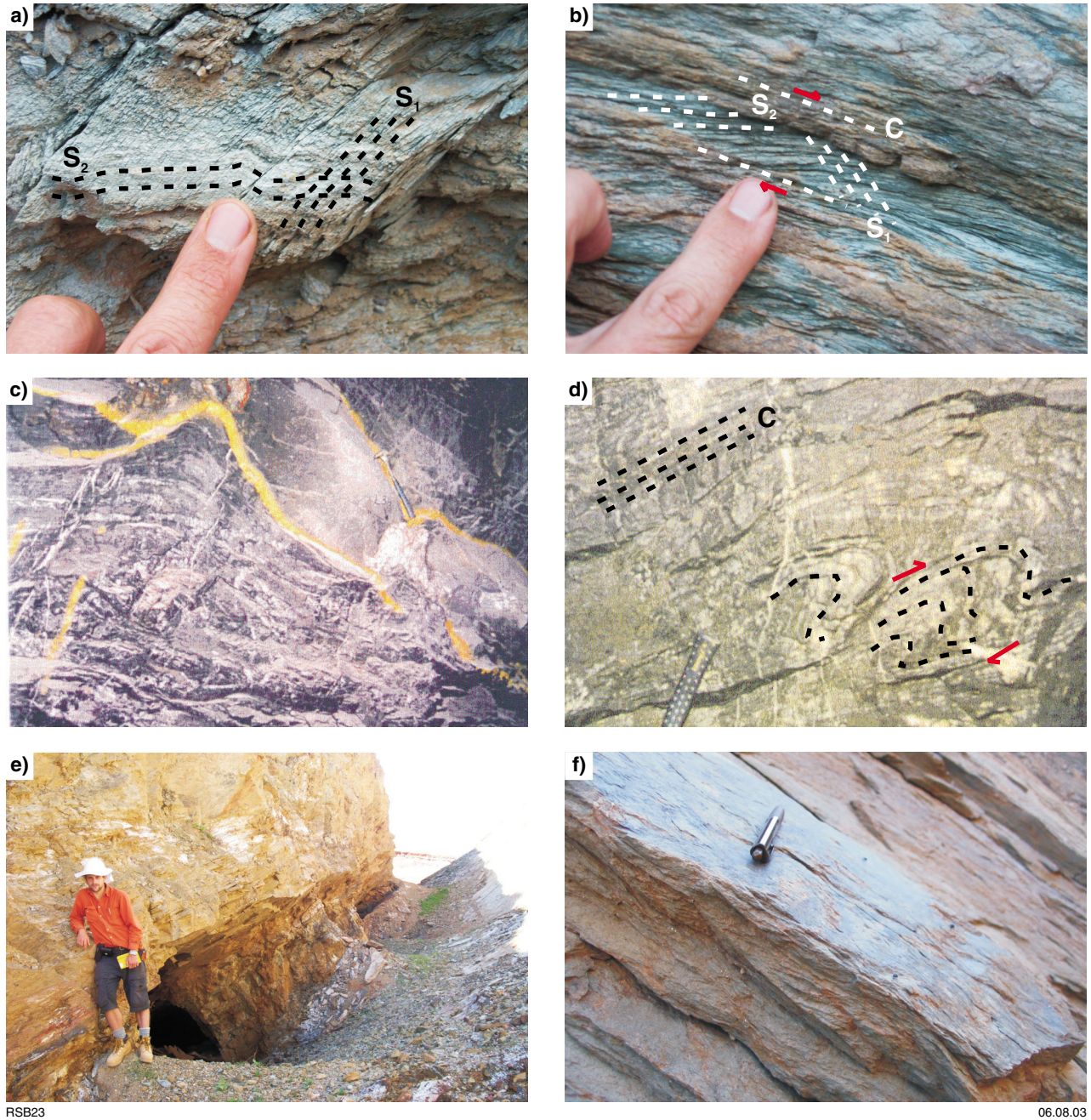
Figure 41. Strain partitioning across the King of Creation shear zone under dextral transpression. All fabric elements (including the main S_0 foliation) are consistent with development under dextral transpression. The increase in strain into the centre of the pit again demonstrates the importance of deformation intensity in focusing fluid flow into the most highly damaged zones (and therefore mineralization). For detailed P–T dihedra see Figure 10. From east to west (over a 50 m distance) into the shear zone centre (all photos view north-northwest): a) S_0 penetrative fabric with minor superimposed dextral strike-slip shearing of boudinaged porphyry; b) asymmetric folding of conjugate quartz veins; c) tight to isoclinal folding and boudinage of conjugate quartz veins; d) S–C–C' dextral strike-slip fabric elements; and e) F_2 box folds related to dextral strike-slip shearing in the high-strain centre of the pit



RSB20

07.08.07

Figure 42. Collage of folds and associated foliation at King of Creation: a) view north-northwest of anticlockwise transection α of S_5 cleavage (pecked line) gently plunging F_5 fold hinges (solid line) in competent quartzite bed, consistent with dextral transpression (see Blewett and Pickering, 1988); b) view south of steep wall with periclinal plunge of F_5 fold axis pitching from 75 to 25° through the F_5 axial surface; c) view west onto a wall with complex F_5 drag fold, with changes in fold plunge (see arrows). Main folds plunge subvertically and have Z-symmetry consistent with dextral shear. A component of vertical stretch is apparent on the bedding planes (as gently plunging mullions highlighted by black bars); and d) view south onto rear wall of King of Creation with late collapse structures defined by gently dipping axial surfaces of F_6 folds in walls of the pit. These are common in the Laverton region (see also Davis and Maidens, 2003), and may reflect a link between high strains during D_5 and subsequent collapse during

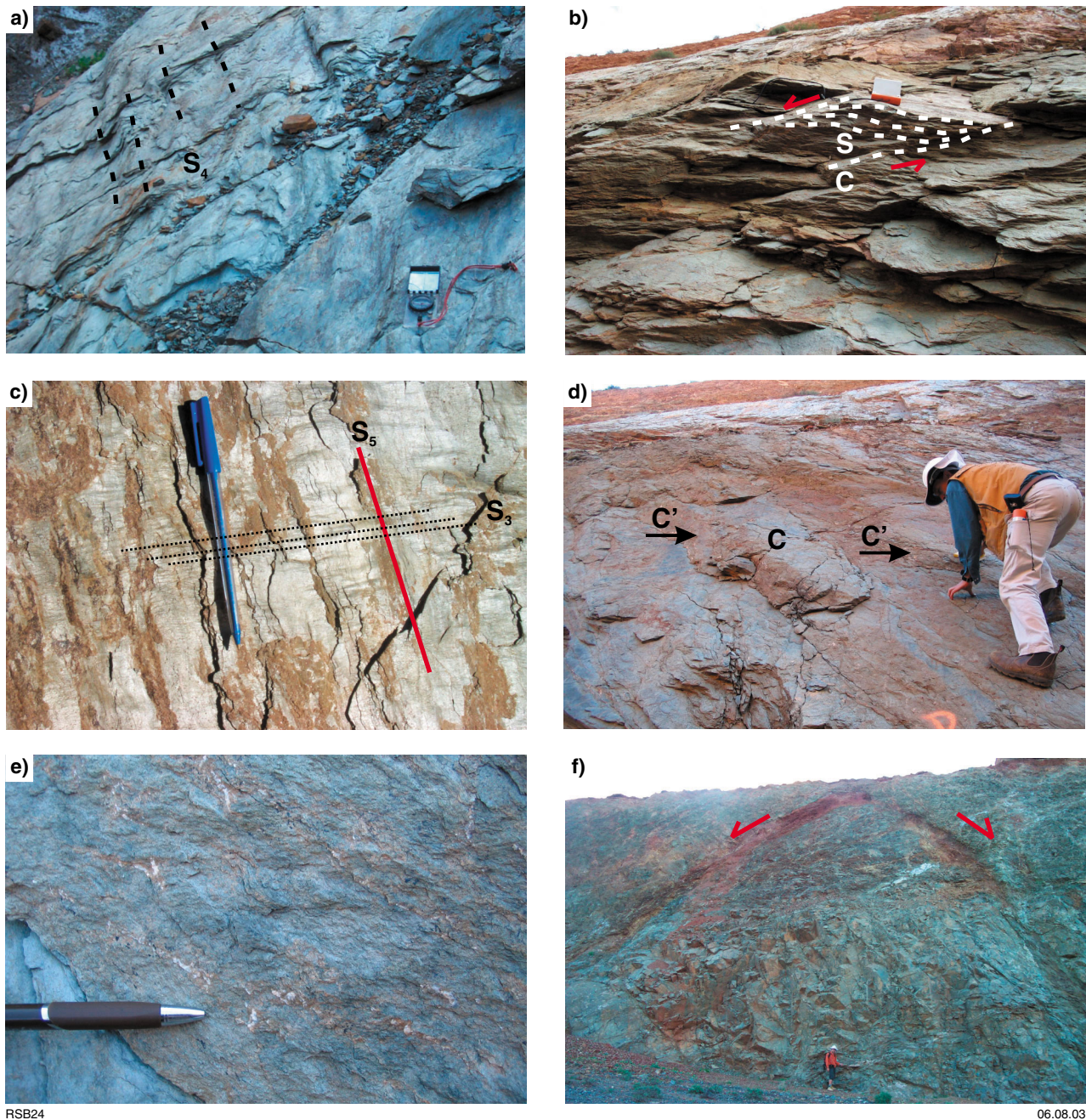


RSB23

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 D_6

Figure 43. Compilation of photos of extension-related ore zones at the Lancefield mine: a) an early S_1 fabric within S_3 S-plane (view north); b) down-to-east extensional S–C shear fabric (S_3) and earlier internal fabric within shear planes (view northeast); c) underground photograph (after Hronsky, 1993) looking east of boudin necks (right-hand side) hosting gold; d) folding resulting from the inversion of D_3 extensional shear zones as a result of $D_{7/4/5}$ reverse up-to-west shearing (photo from Hronsky, 1993); e) view southwest of main line of lode in down-to-east D_3 extensional shear zone; and f) extensional S–C fabric with undulations in main D_3 S-plane due to the intersection with S_3 C' planes (view north). Sense of shear is down to the east



RSB24

06.08.03

Figure 44. Compilation of photographs from post- D_3 extensional events in the Lancefield pit: a) well-developed S_4 crenulations overprint the main extensional S_3 S-C fabric (view west). Inferred contraction was oriented approximately north-northwest. These crenulations could be interpreted as related to D_3 C' planes and late-stage D_3 south-directed extension; b) view west up-dip of dextral D_5 S-C shear zone (which appear as sinistral shear because the view is from below). The intersection of the S-C planes promotes a rhomboid geometry to the outcrop when viewed from below; c) view west onto the main composite foliation that dips moderately to the east (towards the viewer). Here, the earlier S_3 (subhorizontal) crenulations are likely S_3 C' planes of down-to-the-east extension and are overprinted by north-south dextral slicken lines and crenulation cleavage. Slicken lines are concentrated on the downward-stepping C' plane sections (S_5) of the S_3 crenulated main-foliation plane. Here is an example of foliation reuse from down-to-the-east extension to north-south dextral shear about gentle east-dipping foliations; d) view west looking up of D_5 dextral reactivation of S_3 extensional main foliation. Stair stepping of long section C plane (dip right in this view) with shorter section S_5 C' plane (dip left in this view). Note that carbonate mineral veins are located on the short C' extensional step overs (arrows); e) view west onto oblique fault plane showing detail of dextral strike-slip slicken line defined by carbonate; and f) D_6 extensional faults are the last event to deform the Lancefield pit (view northwest)

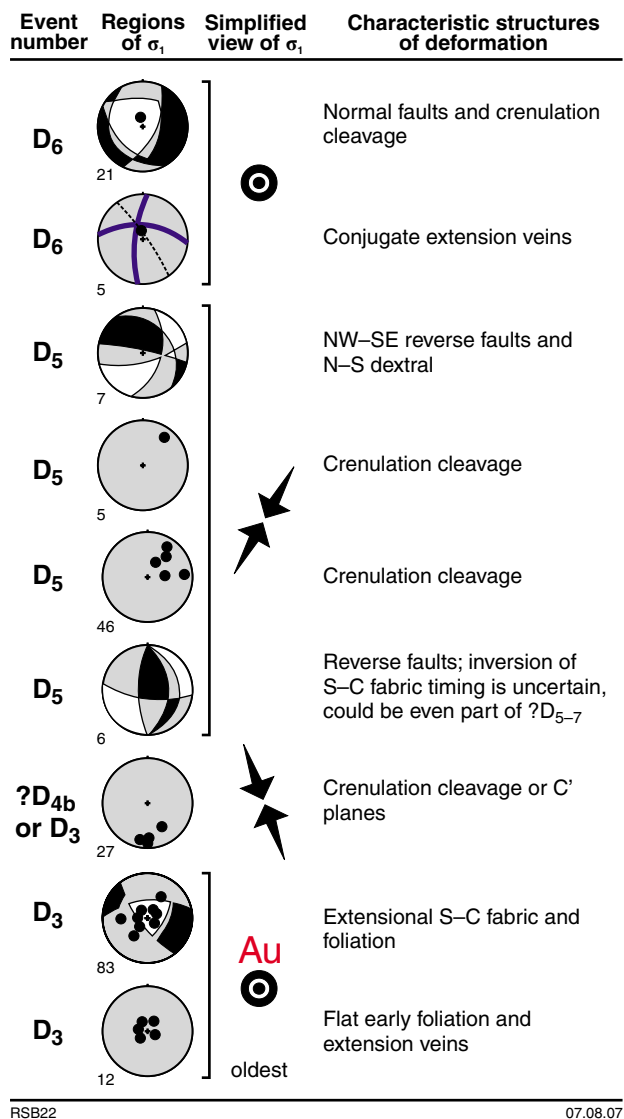


Figure 45. Compilation of structural elements at the Lancefield pit

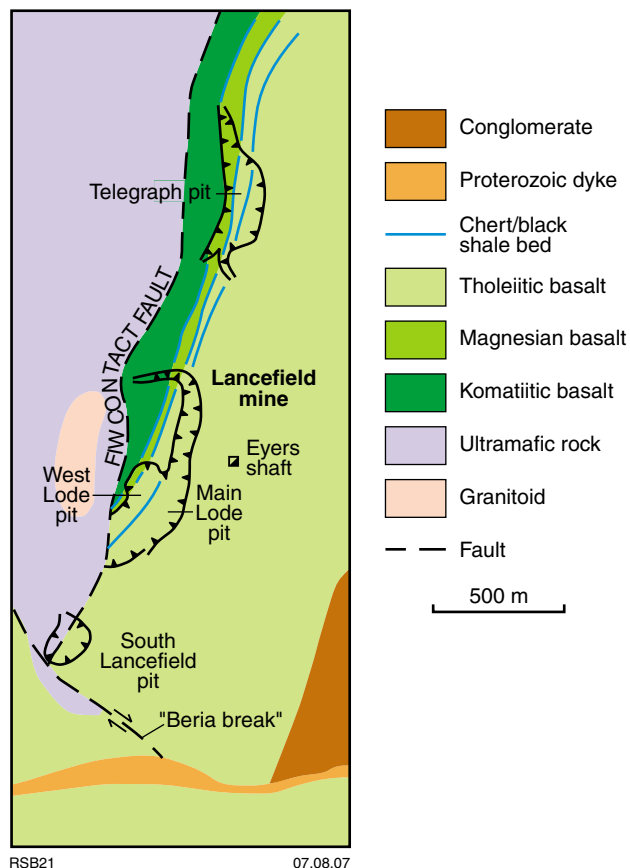


Figure 46. Simplified geological map of the Lancefield deposit and region (after Hronsky, 1993). Note the proximity of the granitoid intruding the footwall ultramafic rock and the location and geometry of the Lancefield pit



RSB25

06.08.03

Figure 47. Panorama of the Lancefield deposit highlighting the convex nature of the pit and the Lancefield shear zone

and are linked with the regional sinistral event known as D_{4b} (Blewett and Czarnota, 2007b). However, these crenulations could be interpreted as late-stage D_3 south-directed extension. A more significant reworking occurred during D_5 dextral shearing (Fig. 45), and these are well developed along the north-trending sections of the pit. S–C fabrics and crenulations are developed in this event and the outcrop breaks with a distinctive rhomboid geometry (Fig. 44b–e). The last stage, D_6 , was the development of low-angle crenulations and normal faults during extension or vertical flattening (Figs 44f and 45).

The timing of gold is not easy to reconcile. Hronsky (1993) suggested that gold was deposited during a retrogressive stage, with temperatures of 325°C (± 50) compared to the peak metamorphic temperatures of 450°C and pressures of 1.5 (± 0.5) kb. This would place the gold in the D_{4b} sinistral or D_5 dextral times. However, Hronsky (1993) showed that gold was deposited in low-strain domains about boudin necks—these boudins developed during the extension (D_3). Lancefield may be a location of more than one gold event. Wallaby and Sunrise Dam are examples in the region where this has also been demonstrated (Miller, 2006).

Locality 11a: View north over the openpit

The main features of this stop are to show the convex-curved outline of the pit that mirrors the shape of the granite in the footwall beneath (Figs 46 and 47). The old mill and headframe base are preserved on a narrow septum transecting the pit. Note the active extension on pre-existing normal faults (down to the east) caused by the underground collapse of the lower workings.

Locality 11b: Extensional shear zone via the northern access ramp of openpit

The access ramp provides a dip and strike section through the extensional shear zone at Lancefield. On the dip section, note the two fabrics (S–C) indicative of east-down D_3 extensional shearing. On the strike section these down-to-the-east shears are best seen by viewing northwards onto joint faces. Also along the strike section, a series of C' planes intersect the exposed C planes and they are revealed as centimetre-wide monoclines (with east-down vergence).

From the strike section look upwards and note that the foliation and outcrop also break out into pronounced S–C fabric at decimetre scales (Fig. 44b). The view is from below and appears sinistral, but geometrically and regionally it should be viewed from above and is therefore dextral. The D_5 dextral shear is also apparent on the faces at the pit floor. When viewed onto the moderately east-dipping rock face (towards you), the S planes dip to the right and the C planes dip to the left. Note also that carbonate slickenlines (D_4) are only developed on these left-dipping C-planes, which cut and smear-out the C' planes of the earlier D_3 extension.

Locality 12: Hanns Camp Syenite (MGA 445094E 6837519N)

Travel through the town of Laverton and drive straight on to the east on the Yamarna White Cliffs road for 11 km. The Hanns Camp Syenite crops out on both sides of the road.

The purpose of visiting this site is to see a regional exposure of granite, although an area this large of syenite is unusual. The pronounced gently dipping foliation likely developed during extension, provides an age constraint on this event and links it to the development of the coeval Wallaby Basin to the west (which is intruded also by syenite).

The Hanns Camp Syenite is located around 5 km east of Laverton. It was emplaced at 2664 ± 2 (Cassidy et al., 2002a), probably during regional extension. Details of the structural history of this site may be found in Blewett et al. (2004b). The syenite has a pronounced gently east-dipping mylonitic foliation (Fig. 48a) with a north-northwest to south-southeast movement direction. Kinematic indicators observed in several thin sections of a fine-grained siliceous phase suggest that movement was extensional, with down-to-the-east and southeast kinematics (Fig. 48b,c). This mylonitic fabric is overprinted by spaced north- and north-northwest-trending D_{4b} sinistral shear zones (Fig. 48e) and open to tight upright folds that developed during ~northwest–southeast contraction (Fig. 48d,f). Later minor D_5 dextral shears reflect a switch to northeast–southwest transtension, with the final event northeast-trending kink bands of the main penetrative foliation (Fig. 48g).

We hope that you enjoyed the trip and that it met with your expectations.

Return to Laverton and the highway back to Leonora and Kalgoorlie, this trip is about a four-hour drive.

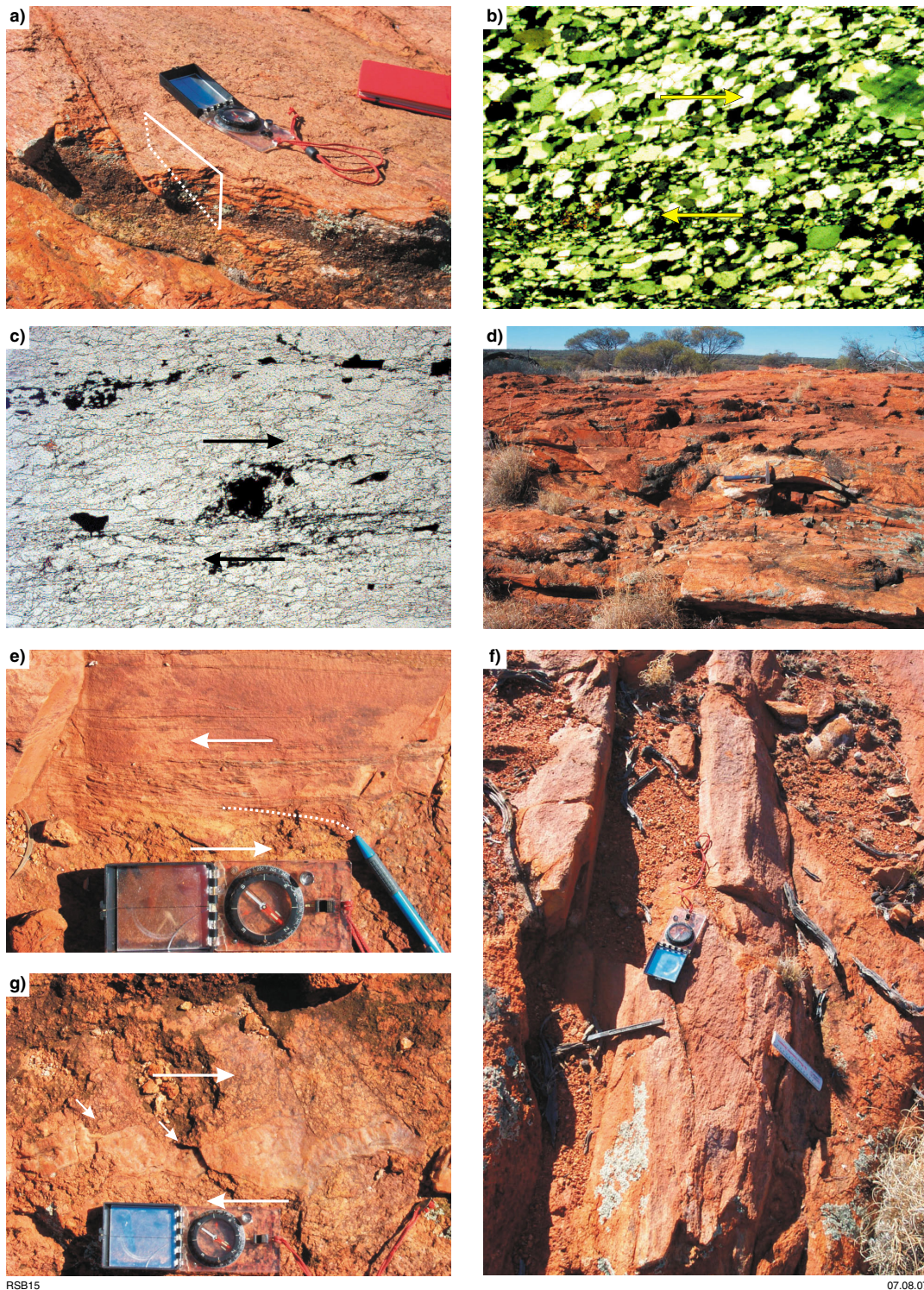


Figure 48. Compilation of structural events of the c. 2665 Ma Hanns Camp Syenite: a) view north-northeast of gently dipping high-strain foliation (extensional) with well-developed southeast-plunging lineation. Box is thin section planes in (b) and (c); b) microphotograph (perpendicular to foliation and parallel to lineation) of down-to-the southeast extensional kinematics (preferred fabric orientation) from within the high-strain foliation in a siliceous phase of the Hanns Camp Syenite; c) microphotograph (perpendicular to foliation and parallel to lineation) of down-to-the-southeast extensional kinematics (S-C) from within the high-strain foliation in a siliceous phase of the Hanns Camp Syenite; d) view north-northwest of open upright F_{4a} folds with a gentle north-northwesterly plunge; e) north-northwesterly trending, steeply dipping S_{4b} sinistral shear. Inferred σ_1 was likely oriented northwest-southeast to west-northwest-east-southeast during this event; f) view north-northwest of tight upright F_{4a} folds. Note ruler and chisel defining the folded S_3 surface over the F_{4a} hinge; f) bookshelf boudinage of quartz vein associated with north-trending D_5 dextral shear

Acknowledgements

We would like to acknowledge the following companies for access to their ground and their support of this field trip:

A1 Minerals: King of Creation

Barrick: New Holland, Sunrise Birthday and Jupiter

Metex: Lancefield

Navigator Resources: Mertondale

St Barbara: Tarmoola, Gwalia and Victor Well

Regal Resources: Yunndaga.

This project has been a rewarding and challenging experience for both of us. We would like to thank the sponsors for their ongoing commitment to the *pmd**CRC and the Y1-P763 project. Special mention to:

- Trevor Beardsmore (Barrick) who provided his excellent reports on Mount Morgans and Lawlers, and was a constant source of encouragement for our work.
- John Beeson (ex-Placer) who accompanied us in the field in the Laverton district and we welcomed his contributions.
- Simon Apps (Barrick) who provided support at Lawlers and smoothed our way underground at New Holland. Barrick also provided field support while we were based at Lawlers.
- Cees Swager (ex-AngloGold Ashanti) who provided advice on the direction of our research and was always receptive to novel ideas.
- Phung Nguyen (Goldfields Agnew) who provided permission and access to the Agnew pits.
- Bob Love (SOG now St Barbara) who provided access to the Leonora deposits, especially Tarmoola and Gwalia openpits.
- Bruce Groenewald, Sarah Jones and Charlotte Hall (GSWA) who were always available for discussion.
- The GSWA are gratefully acknowledged for providing their 4WD vehicle and fuel support for our field work over three seasons, and also their safety back up systems (especially Brain Moore at Carlisle base, and Wayne Hitchcock at Kalgoorlie). Without their help this work could not have been accomplished.

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