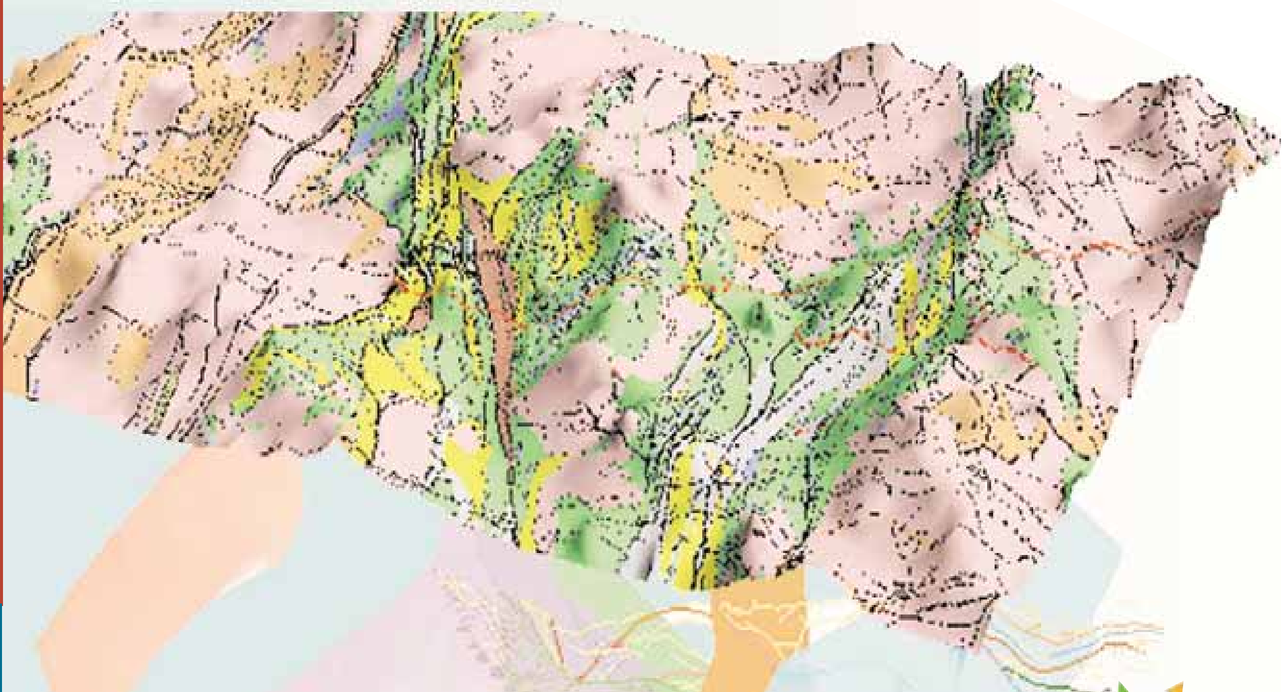
Record 2002/18

GEOSCIENCE Australia

Geology, geochronology and geophysics of the north eastern Yilgarn Craton, with an emphasis on the Leonora-Laverton transect area

Proceedings of the papers presented at an industry workshop held in Perth, 20 June, 2002

Edited by K.F. Cassidy



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Geoscience Australia
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Geology, geochronology and geophysics of the north eastern Yilgarn Craton, with an emphasis on the Leonora-Laverton transect area

Forward

Geoscience Australia (GA) and the Geological Survey of Western Australia (GSWA), in conjunction with the Predictive Mineral Discovery Cooperative Research Centre (*pmd**CRC) hosted an industry workshop on 20th June 2002 in Perth, Western Australia. The North Eastern Yilgarn Workshop focussed on presentation of results from the GA Norseman-Wiluna Synthesis and GSWA East Yilgarn projects, as well as the release of deep seismic reflection data acquired as part of the 2001 Northern Yilgarn seismic survey.

North Eastern Yilgarn Geology

The GA Norseman-Wiluna Synthesis and GSWA East Yilgarn projects undertook integrated geoscience studies in the north eastern Yilgarn Craton, with an emphasis on the Leonora-Laverton transect area, including:

- development of Phase 3 of the East Yilgarn Geoscience Dataset based on 1:100,000 geological mapping
- acquisition of additional regional gravity data over the Leonora-Laverton transect area
- acquisition of SHRIMP U-Pb geochronological data in the north eastern Yilgarn
- development of a solid geology map of the Leonora-Laverton transect area
- development of a three-dimensional model of the Leonora-Laverton transect area integrating outcrop and solid geology, geochronology, potential field modelling and time-space studies.

The new data help improve our understanding of the geodynamic framework of the north eastern Yilgarn Craton by providing constraints on the three-dimensional geometry of the region, specifically the Leonora-Laverton transect area, as well as constraints on the timing of magmatic, tectonic and metallogenic events. In combination, these constraints may allow identification of possible relationships between geodynamic events and formation of world-class mineralising systems, thereby furthering development of conceptual and predictive exploration models.

2001 Northern Yilgarn seismic survey

GA and GSWA, through the *pmd**CRC, acquired 432 km of deep seismic reflection data in the north eastern Yilgarn Craton and onto the western margin of the Officer Basin, as part of the 2001 Northern Yilgarn seismic survey. Data were acquired along the 380 km 01AGSNY1 transect from just west of Leonora to east of Lake Yeo, and along the 52 km 01AGSNY3 transect from Lake Yeo north east into the Officer Basin. The data, processed by GA officers within the *pmd**CRC, were released to help provide information on the three-dimensional geometry of the north eastern Yilgarn Craton and the western margin of the Officer Basin.

An earlier version of this Record was prepared as a special volume for the North Eastern Yilgarn Workshop, and handed out to participants of that workshop under separate cover.

Kevin Cassidy
Geoscience Australia

Contents

Aeromagnetic interpretation of the Yilgarn Craton with an emphasis on the north eastern Yilgarn

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Introduction

Transported cover and weathering are extensive on the Yilgarn Craton with the result that regional geological models are poorly constrained. Aeromagnetic data are little influenced by this thin regolith and their interpretation provides a continuous model of the Archaean bedrock.

This study is largely based on the interpretation of 1500 to 400 m line-spaced aeromagnetic data from the National Airborne Geophysical Database of Geoscience Australia. The 400 m data were acquired in joint projects with the Geological Survey of Western Australia over the central and northeastern Yilgarn Craton. The project also drew on 200 to 400 m line-spaced data, for the Menzies to Norseman region, provided by Fugro Airborne Surveys Pty Ltd, and 250 m line spaced data for the Western Kalgoorlie Sheet provided by De Beers Australia Exploration Ltd/ Pitt Research Pty Ltd. Interpretation was undertaken at 1:250 000 scale.

Five regionally distributed geophysical map units, and eight province-sized domains composed of these units, have been defined for the Yilgarn Craton. The geophysical map units include gneiss-migmatite-granite[1] , banded gneiss, granite plutons, sinuous gneiss, and greenstone. Granitic rocks are inferred to dominate the first three units, whereas a wide variety of lithologies are thought to give rise to well-developed compositional banding in greenstone and sinuous gneiss. Sinuous gneiss is not present in the northeastern Yilgarn Craton and is not discussed further.

Geophysical map units

Extensive regions of low to moderately magnetised gneiss-migmatite-granite (Agmg; Fig. 1) constitute more than 45 percent by area of the Yilgarn Carton. Within these regions, interpreted internal boundaries are sparse to rare. Compositional banding is also rare, and where present, is not generally aligned with regional trends. Abundant normal or remanently magnetised dykes and poorly magnetised faults are the most evident features in these regions. Gneiss-migmatite-granite surrounds examples of all other units. Greenstone is commonly in apparent concordant contact with the margins of gneiss-migmatite-granite and metamorphosed to amphibolite grade (Binns et al., 1976). Lower grades of metamorphism are recorded further from the contacts in the larger greenstone belts (Binns et al., 1976).

Moderately- to highly-magnetised banded gneiss (Agn; Fig. 1) is widespread and is particularly abundant in the central and northeast parts of the Yilgarn Craton. Banded gneiss occurs in elongate

[1] Granite is used here as a general term to indicate felsic intrusive rocks.

belts up to 150 km in length and 5-15 km in width, in and along the margins of gneiss-migmatite-granite regions. Both internal compositional banding and elongation of the belts grossly parallel adjacent regional shear zones, e.g., adjacent to the Ballard Shear. Banded gneiss encloses sparse but locally common greenstone pendants and amphibolite of uncertain origin. Contacts of banded gneiss with greenstone are sharp, however, boundaries with adjacent gneiss-migmatite-granite are irregular and poorly resolved.

Circular to elongate granite plutons (Ag; Fig. 1) intrude all other mapped units. Plutons show a wide range of magnetisation, from low to high. Although most are evenly magnetised, some are zoned e.g., Monument monzogranite. Granite plutons are unevenly distributed across the Yilgarn Craton with high abundances in the southern Murchison domain (M in Fig. 2), and within the greenstones of the Norseman – Wiluna Belt of the Eastern Goldfields domain (NW in Fig. 2). In several locations granite intrusions are clustered and aligned with regional trends, e.g., south east of Leonora.

Greenstone occurs in irregularly distributed, elongate belts that account for more than 20 percent the Yilgarn Craton. Most greenstone is poorly magnetised and component lithologies, including mafic and felsic volcanic rocks, are not readily discriminated by aeromagnetic data. The belts also contain highly-magnetised banded iron-formation and ultramafic rocks which provide some information on the internal structure of the belts.

The interpretation also maps the distribution of other features including dykes, granite and gneiss domes, layered intrusions, small intrusions of unknown composition, compositional layering, shear zones, and faults.

Shear zones and Faults

The extent and form of poorly magnetised shear zones and faults within similarly magnetised greenstone is difficult to determine from aeromagnetic data. Shear zones and faults are, however, well delineated in moderately magnetised gneiss-migmatite-granite regions. Their form in this felsic crust is inferred to provide a model for related structures in the greenstone belts.

Shear zones are the largest structures, commonly exceeding 100 km in length and over 1 km in width. They consist of overlapping, *en echelon* lineaments or distended ‘S’form curvilineaments. Where measured (Koolyanobbing and De La Poer shear zones), apparent lateral movement on shears is in the order of 30 to 50 km. Deformation of associated felsic crust is inferred to have occurred in the brittle-ductile transition. By comparison, faults are generally less than 50 km in length and occur as discrete to anastomosing zones less than 300 m in width. Apparent lateral movement on faults is generally less than 5 km and inferred to have dislocated brittle crust. Where coincident, faults overprint and, hence, postdate movement on the shear zones.

Accretion models developed to explain crustal growth require craton-crossing faults as terrane boundaries (e.g., Myers, 1995). There are a number of difficulties with such interpretations. Firstly there is no evidence in the aeromagnetic data for craton scale faults. Some of the proposed terrane boundaries do not correspond with discrete faults but with structural corridors, e.g., the Ida lineament. Finally, some bounding faults coincide with shear zones across which the crust can be correlated, e.g., the Koolyanobbing lineament.

Geophysical domains

The Yilgarn Craton is subdivided into eight geophysical domains (Narryer, Murchison, Toodyay-Lake Grace, South West, Southern Cross, Yeelirrie, Lake Johnston, and Eastern Goldfields domains; Fig. 2), each of which contains at least two of the geophysical map units. Boundaries between the domains coincide with abrupt changes in average magnetisation, anomaly variability

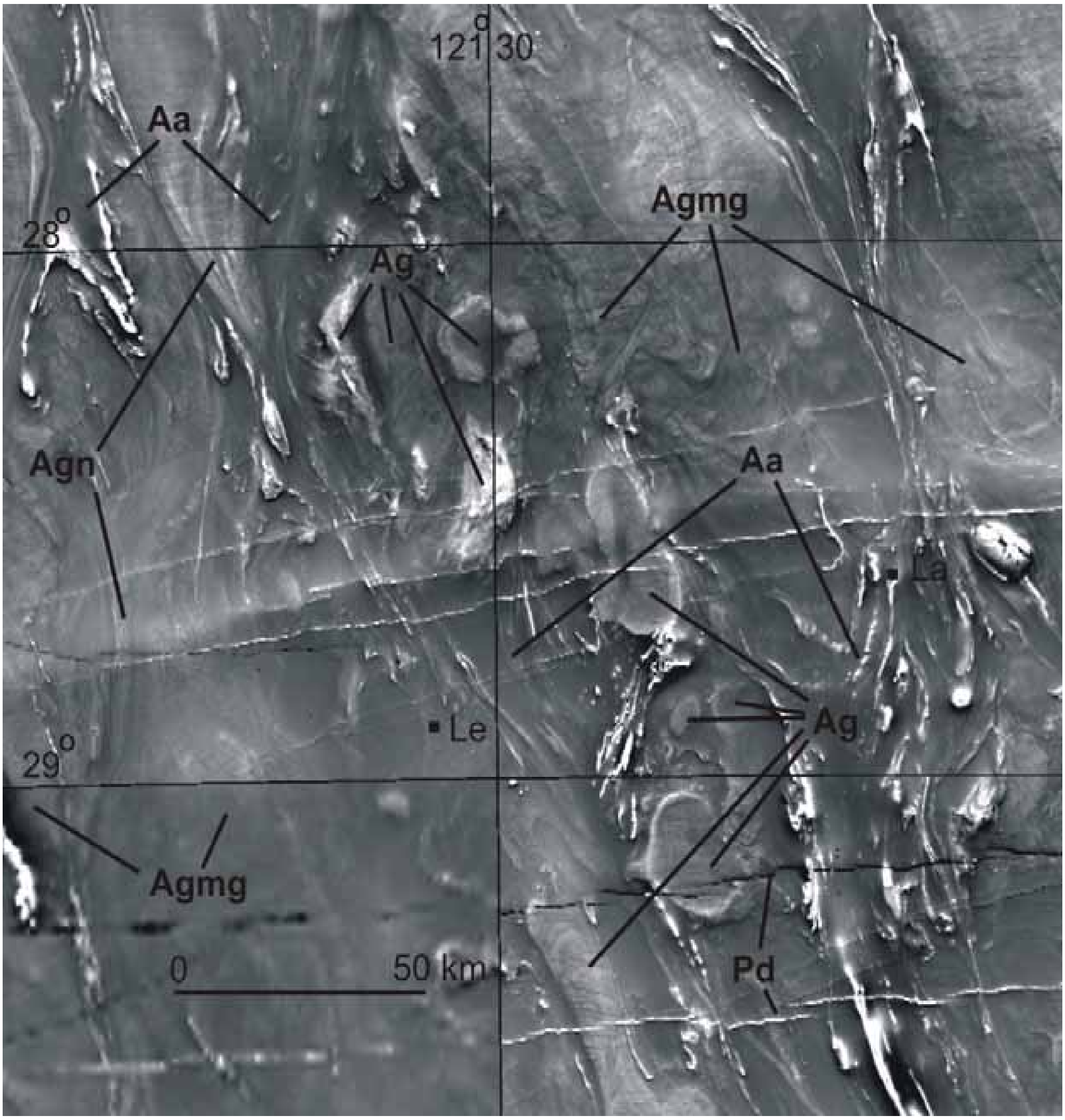

Figure 1 Total magnetic intensity image of the Leonora - Edjudina area of the Eastern Goldfieds domain – black to white represents low to high magnetisation. Geophysical map units are labelled Agmg = gneiss-migmatite-granite, Agn = banded gneiss, Ag =Granite, and Aa = greenstone. Dykes are labelled 'Pd'. Leonora (Le) and Laverton (La) are also located

and orientation, and or geophysical map units, i.e., with inferred changes in crustal composition. Two of the domains, the Murchison and Eastern Goldfields domains, approximate the area of similarly named Provinces of Gee et al. (1981). In the current interpretation, however, the Murchison domain extends to the western boundary of the Craton separating crust in the southwest from that in the northwest (cf. Western Gneiss Terrain). Furthermore, the central Craton area can be subdivided into four domains based on average magnetisation of granitic crust, abundance of gneiss, and structural trends in gneiss and greenstone (cf. Southern Cross Province). Only aspects of the Yeelirrie and Eastern Goldfields domains will be discussed below.

The northeast Yilgarn Craton is largely the one geophysical domain, the Eastern Goldfields domain, but also includes, to the west, the north-trending Yeelirrie domain. The latter is composed of moderate- to highly-magnetised gneiss-migmatite-granite with subordinate banded gneiss and banded iron-'rich' greenstone, both of which are aligned with north-northwest and north-northeast shears.

The Eastern Goldfields domain can be subdivided into two main components, the Norseman-Wiluna Belt (Gee, 1979) in the western half, characterised by abundant greenstone, and to the east, the felsic dominated crust of the eastern gneiss sub-domain.

Greenstone accounts for nearly 50 percent of the Norseman – Wiluna Belt. Structural trends within the greenstones are largely aligned with north-northwest and north trending shear zones. The Belt also includes three sub-domains composed largely of gneiss-migmatite-granite and banded gneiss, the Yandal, Ballard and Laverton sub-domains (Williams & Whitaker, 1993). These sub-domains have grossly similar characteristics being of low to moderate magnetisation with few internal boundaries and granite plutons. The sub-domains may be related crust that is in sheared contact at depth but are separated by greenstone at the surface. Greenstone is in apparent concordant contact with the boundaries of these sub-domains. Highly magnetised banded iron formation is much less abundant than in greenstone belts of the Yeelirrie domain to the west.

The eastern gneiss sub-domain is largely composed of moderately magnetised, undivided gneiss-migmatite-granite with some banded gneiss, and small greenstone remnants spatially associated with widely spaced shear zones. Abundant granite and gneiss domes, interpreted from 200 and 400 m line-spaced aeromagnetic data, occur along the margin of, and immediately to the east of the Norseman-Wiluna Belt. An east–west elongate zone of sinuously deformed granitic gneiss truncates the north-northwest trending Jasper Hills greenstone belt in the northwest of the Minigwal Sheet. In addition, gneiss-granite domes disrupt several shear zones in this region. This suggests that the region did not experience the D_3 strike slip deformation observed in the Norseman Wiluna Belt (Swager, 1995), or that the observed domes and cross-cutting gneiss reflect a later deformation event.

Within the Norseman-Wiluna Belt, interconnecting north-northwest- and north-trending shear zones define deformed rhomb-shaped areas of granite and greenstone. Collectively, the structures of the belt are thought to comprise a craton-scale shear zone approximately 200 km in width, with less deformed crust to the east and west.

The 2001 seismic reflection lines 01AGS-NY1 and 01AGS-NY3 traversed most of the Eastern Goldfields domain from Leonora in the west, east, to within eighty km of the eastern boundary of the Yilgarn Craton. From the aeromagnetic interpretation, the seismic lines sampled Archaean crust with contrasting characteristics. In the west, the line 01AGS-NY1traverses part of the Norseman-Wiluna Belt with abundant shear zones and greenstone, and to the east, the eastern gneiss sub-domain with sparse shear zones and a much lower abundance of greenstone. The eastern seismic line, 01AGS-NY3, parallels for ~50 km to the northwest, the northeast-trending boundary of the Yilgarn Craton with Albany-Fraser Province. Northeast-trending lineaments in this area are inferred to be faults. These structures possibly resulted from tectonic interaction between the Yilgarn Craton and the Albany-Fraser Province during the Proterozoic.

Acknowledgements

Fugro Airborne Surveys Pty Ltd and De Beers Australia Exploration Ltd/Pitt Research Pty Ltd are gratefully acknowledged for providing access to their respective multi-client data covering the Menzes to Norseman area. This report has benefited from reviews by Kevin Cassidy and David Champion and is published with the permission of the Chief Executive Officer, Geoscience Australia. This report is a contribution to the GA-GSWA Norseman-Wiluna Synthesis Project, and is GeoCat number 40395.

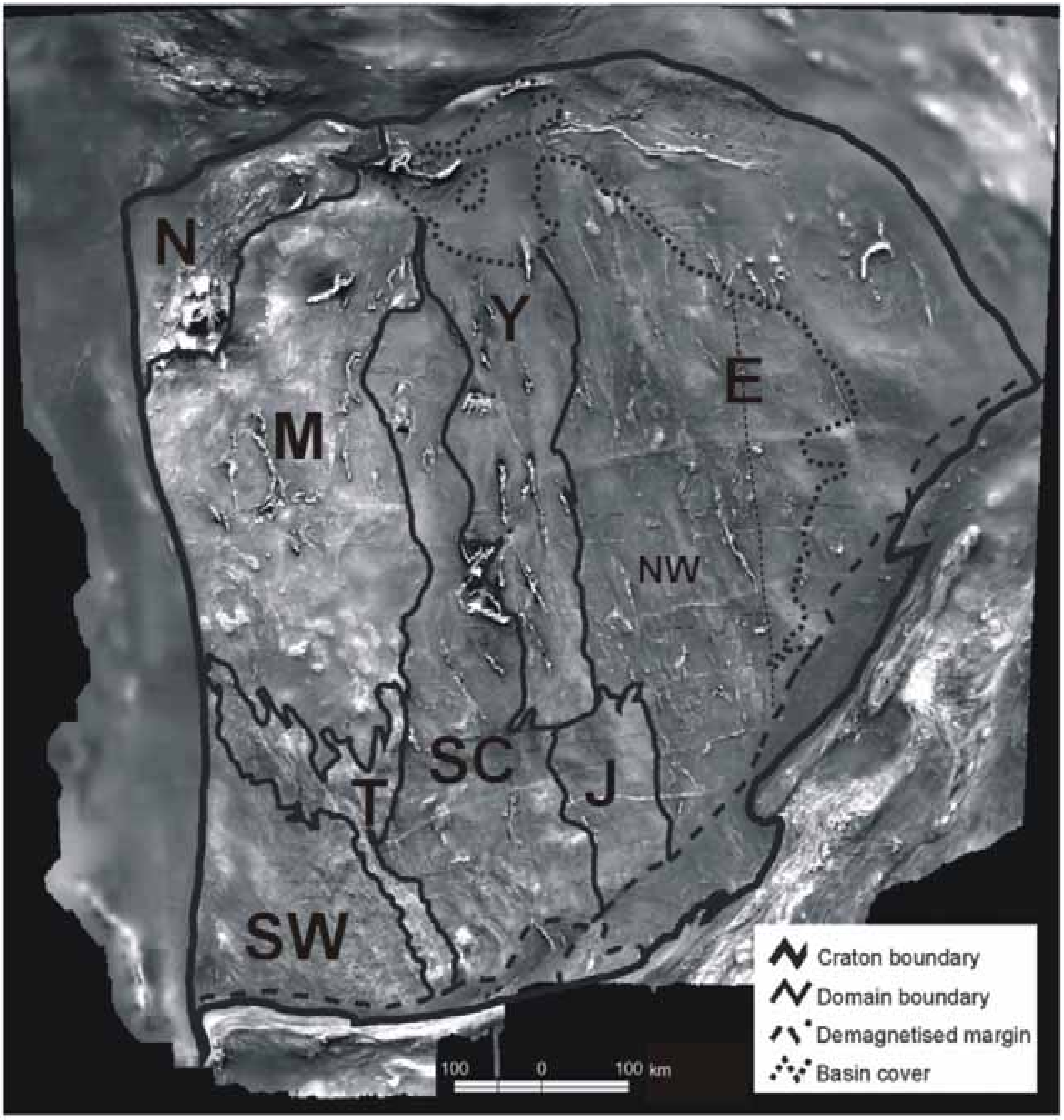

Figure 2 Total magnetic intensity image of the Yilgarn Craton – black to white represents low to high magnetisation. Geophysical domains are labelled N = Narryer, M = Murchison, T = Toodyay-Lake Grace, SW = Southwest, SC = Southern Cross, Y = Yeelirrie, J = Lake Johnston, E = Eastern Goldfields. NW in the west of the Eastern Goldfields domain correlates approximately with the Norseman-Wiluna Belt of Gee et al. (1981)

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Outcrop geology in the Leonora-Laverton transect area from the East Yilgarn Geoscience Database

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Introduction

The 430 km long 2001 Northern Yilgarn seismic survey extends eastward from Leonora across the Eastern Goldfields Granite–Greenstone Terrane of the Yilgarn Craton on to the western margin of the Phanerozoic Gunbarrel Basin (Fig. 1). The western 220 km of the traverse lies within the Leonora-Laverton area of the East Yilgarn Geoscience Database, a seamless digital compilation of the fifty six 1:100 000–scale geological maps produced under the National Geoscience Mapping Accord. The Leonora–Laverton transect area has some of the most extensive exposure of Archaean greenstones in the Eastern Goldfields, but due to the complexity of faulting and folding of the diverse lithostratigraphic packages of the region, geological relationships remain largely unresolved. Interpretation of the seismic line in conjunction with other geophysical data will contribute greatly to understanding the geology of the area in three dimensions, but any detailed interpretation of the lithostratigraphy and original tectonic setting requires structural, petrographic, and geochronological data that are only available from outcrop studies.

The recently completed Phase 3 of the East Yilgarn Geoscience Database has normalised and collated the eighteen 1:100 000–scale map sheets from the central Eastern Goldfields produced by Geoscience Australia (17 sheets) and the Geological Survey of Western Australia (1 sheet). Of approximately 49 000 km^2 covered, outcrop amounts to only 13% of the area , of which 8% is granitoid and 5% greenstone. There are 127 Archaean rock types , represented by approximately 9000 polygons. More than 8000 measurements of bedding, foliation, lineation, and fold axes, made at some 4300 localities, have been collated. Mineral occurrence and tenement information are also included in the digital database. The database is valuable as it provides lithological and structural information that must be used as the basis of any regional interpreted bedrock geology map, especially in constructing feasible cross-sections.

Geology of the greenstone belts and tectonic zones

Within the Leonora-Laverton transect area, mapped supracrustal assemblages may be divided into five or more greenstone belts or tectonic zones based on differences in lithostratigraphic characteristics, and intensity of deformation within areas bounded by regional scale faults. A summary of the main characteristics of these subdivisions, from west to east, follows.

Substantial komatiitic and basaltic sequences are present in the Agnew–Wiluna greenstone belt. The former include thick ultramafic cumulates at Mount Clifford and Marshall Pool in which deformation is relatively limited and primary rock textures are well preserved, despite pervasive serpentinisation. The southern part of the greenstone belt, where the seismic traverse commenced, is attenuated between the Sons of Gwalia and Mount George Shear Zones (Fig. 2).

The arcuate Sons of Gwalia Shear Zone separates the supracrustal rocks from the Raeside Batholith, and dips radially away from the batholith with a mineral lineation that tends to plunge down-dip (Williams, 1998). Normal movement towards the north relative to the present orientation of the shear suggests an extensional environment, not necessarily related to emplacement of the granitoid, for D_1 (Passchier, 1994). The eastern boundary of the Agnew-Wiluna greenstone belt is the Mount George Shear Zone, characterized in outcrop by strong shear and the formation of chert bands with relict mylonitic fabrics. Passchier (1994) found evidence of repeated reactivation and inferred a possible initial D_1 origin.

The Malcolm greenstone belt is bounded to the west by the Mount George Shear Zone and to the east by the western edge of the Keith Kilkenny Tectonic Zone, the Glenorn Shear Zone. The greenstone belt is broadest some 40 km south of the seismic line where it wraps around major granitoid bodies. It joins the Kurnalpi domain of the southern Eastern Goldfields through an extension to the southeast (Groenewald et al., 2000). The Malcolm greenstones are characterized by the predominance of felsic volcanic rocks with subordinate basaltic and sedimentary rocks. Three volcanic complexes are present: the bimodal Melita Complex comprising rhyolitic to dacitic rocks interlayered with pillow basalts and mafic hyaloclastites (Brown et al., 2001); the Teutonic Bore Complex comprising strongly deformed interbedded andesite, pillow basalt, silicic volcaniclastic rocks and rhyolite lava (Brown et al., 2001); the Jeedamya Complex, a silicic calc-alkaline complex, in which rhyolitic to rhyodacitic are predominant (Witt, 1994). SHRIMP U-Pb zircon ages of 2692 ± 4 have been obtained for the Teutonic Bore Complex Ma (Nelson, 1995) and 2681 ± 4 Ma for the Jeedamya Complex of (Nelson, 1996).

The least deformed rocks of the belt are in the Melita and Jeedamya complexes. Other more highly deformed areas, particularly north of Leonora, commonly contain sedimentary rocks with subordinate silicic volcanic rocks, but exposure is typically poor.

Aeromagnetic anomalies clearly outline the Keith–Kilkenny Tectonic Zone as a lineament 300 km in length. In the central Eastern Goldfields, the western and eastern limits of the tectonic zone are respectively the Glenorn and Kilkenny Faults. The Keith–Kilkenny Tectonic Zone coincides with the 3 to 8 km wide polymictic conglomerate and immature sandstone outcrops of the Pig Well Graben, and mafic and ultramafic L-S tectonites can be seen near the seismic traverse in subcrop beneath the conglomerates.

The Murrin greenstone belt, lying between the Keith-Kilkenny Tectonic Zone and the Celia Tectonic Zone to the east (Fig. 2), has lithostratigraphic sequences at least 10 km thick consisting predominantly of andesitic, mafic and ultramafic volcanic and intrusive rocks, with lesser proportions of felsic volcaniclastic and volcanic rocks, siltstone, and sandstone. In the western part of the Murrin greenstone belt, the Benalla Anticline, a large south plunging fold, has the andesitic volcanic and associated epiclastic rocks of the Welcome Well Complex in the core, overlain by several thousand metres of basalts with minor felsic volcanogenic interlayers, and an uppermost sandstone unit. These basalts are repeated on the western limb of the Rio Tinto Syncline to the east, followed upward by komatiitic basalts, then the major layered komatiite flow field with several hundred metres of ultramafic and mafic cumulate rocks (Hill et al., 2001). This komatiitic unit extends further east to form the Kilkenny Syncline, and northeast to the Murrin Murrin Ni mine, where it has weathered to form economic lateritic Ni-Co deposits. The large north northeast trending D_2 folds are disrupted by northerly and north northwesterly trending D_3 shear zones.

The Celia Tectonic Zone, 8 to 10 km wide, lies between the Claypan and Safari Faults and separates the Murrin and Laverton greenstone belts (Fig. 2). The main lithologies within this zone are strongly sheared felsic volcanic rock types, sediments and BIF.

The Laverton greenstone belt has extensive areas of komatiitic and basaltic rocks, felsic volcanic and volcaniclastic rocks, and sedimentary packages of siltstone and sandstone that

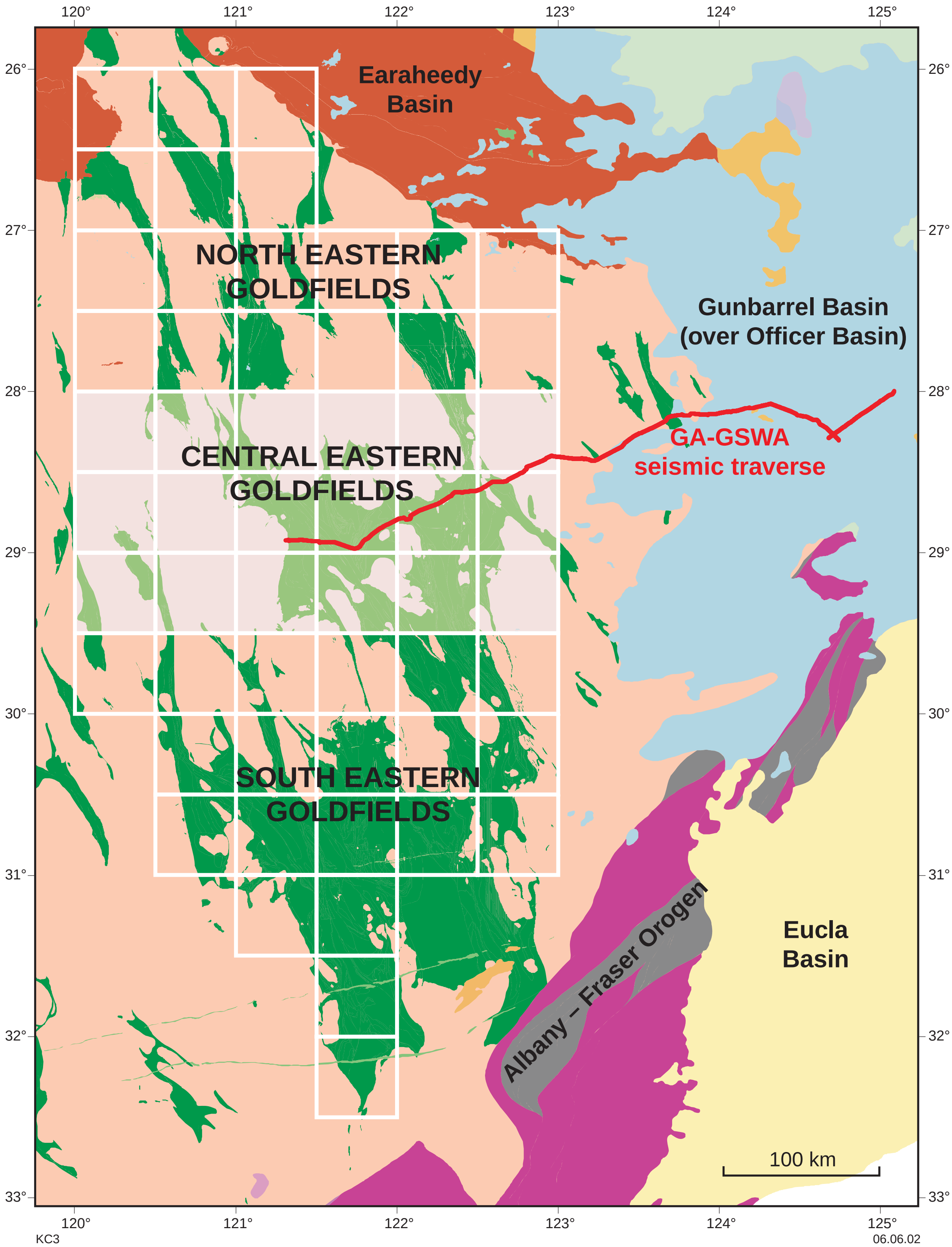
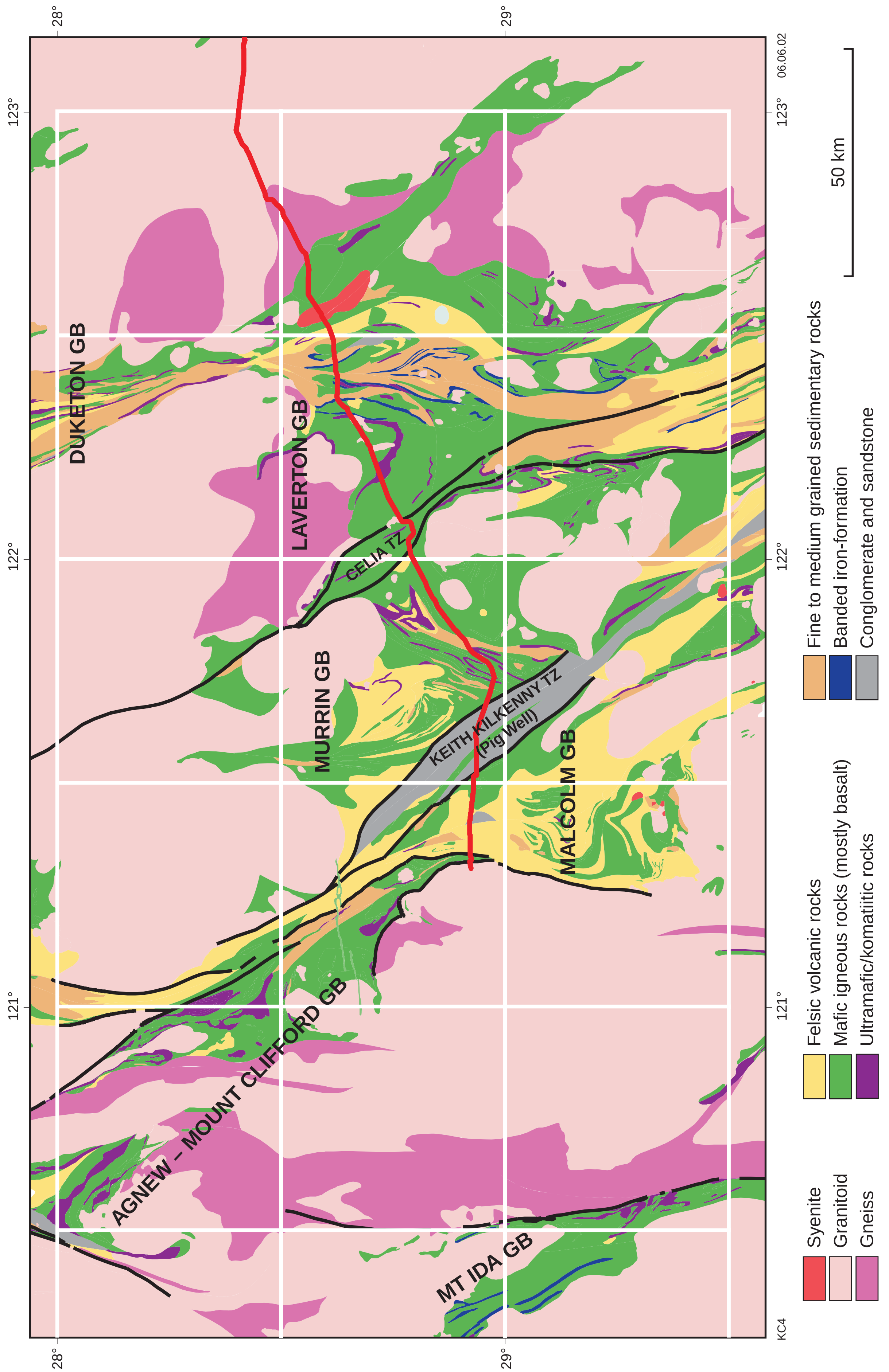


Figure 1 **Location of the 2001 Northern Yilgarn seismic survey in the Eastern Goldfields Granite-Greenstone Terrane and Officer/Gunbarrel Basin. The extent of the 3 stages of the East Yilgarn Geoscience Database are shown**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KEITH KILKENNY TZ
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MALCOLM GB
AGNEW – MOUNT CLIFFORD GB
MT IDA GB
Syenite
Granitoid
Gneiss
Felsic volcanic rocks
Mafic igneous rocks (mostly basalt)
Ultramafic/komatiitic rocks
Fine to medium grained sedimentary rocks
Banded iron-formation
Conglomerate and sandstone

host banded iron-formation units. These rocks form the regional scale Margaret Anticline in the west, dominated by mafic rocks, while to the east and south felsic volcanogenic rocks, sedimentary rocks, and associated BIF are more dominant, although outcrop is poor. Variations in outcrop lithology are considerable, with siltstone, sandstone, felsic volcanic and volcaniclastic rocks, and ultramafic rocks all locally important. The major lithological contrast with greenstone belts west of the Celia Tectonic Zone is the abundance of BIF in the Laverton greenstone belt. The Laverton greenstone belt hosts unusual intrusions such as the 50 km^2 Diorite Hill layered noritic complex, the 25 km^2 Hanns Camp porphyritic syenite (the largest syenitic intrusive of the Eastern Goldfields Granite–Greenstone Terrane), and the 10 km^2 Mount Weld Carbonatite, present in the subsurface south of Laverton.

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Figure 2 ***(opposite)*** **The greenstone belts and tectonic zones in Phase 3 of the East Yilgarn Geoscience Database (Painter et al., in press) traversed by the 2001 Northern Yilgarn seismic survey**

Granites in the Leonora-Laverton transect area, northeastern Yilgarn Craton

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Introduction

Granites in the Leonora-Laverton transect area (LLT), provide a cross section through the eastern Yilgarn Craton, encompassing the western half of the Eastern Goldfields Province (EGP) and the eastern quarter of the Southern Cross Province (SCP; Fig. 1). More importantly, the granites[1] comprise greater than 60 percent of the total surface area and, as such, knowledge of their petrogenesis and geochronology provide strong constraints on crustal growth models as well as on the thermal and tectonic history of the region.

Champion & Sheraton (1993), studying the granites in the Leonora-Laverton region recognised five main granite groups (Table 1). More recent work (Champion, 1997; Champion & Sheraton, 1997; Champion & Cassidy, 1998), covering the whole of the northern Eastern Goldfields, comprising the northern EGP and the northwestern part of the SCP, has confirmed and extended these granite groups (Fig. 1). This latter work has proceeded simultaneously with the acquisition of SHRIMP U-Pb geochronology (Nelson, 1995-2000; Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep) and Sm-Nd isotopic data (Champion & Sheraton, 1997) for granites of the northern Eastern Goldfields, for all granite groups, such that the combination of this data is now providing an overall framework for the development of the region.

Previous classifications

Granite classifications in the EGP have previously been based on both granite and structural characteristics, notably gneiss, pre-folding and post-folding (Bettenay, 1977; Witt & Swager, 1989; Champion & Sheraton, 1993; Witt & Davy, 1997). Subsequent work by Champion & Sheraton (1997), largely supported by new geochronological data, showed that there was not a simple relationship between structural history and age, probably largely reflecting either diachronous deformation, unrecognised deformations and/or strain partitioning. Accordingly, Champion & Sheraton (1997) and Champion (1997) classified the eastern Yilgarn granites primarily on the basis of geochemistry and petrography. Additional geochronology (e.g., Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep), have further refined the data, showing that granites of very similar geochemistry do indeed exhibit both a range of ages and a variety of structural states (Table 1).

Granite Groups

Champion & Sheraton (1997), following Champion & Sheraton (1993), subdivided the granites

[1] Granite is used as a general term for felsic intrusive rocks ranging in composition from quartz diorite to syenogranite.

of the eastern Yilgarn into two major (High-Ca and Low-Ca) and three minor (Mafic, High-HFSE and Syenitic) geochemical groups (Table 1); relationships with previous classification schemes are given in Champion (1997). All types are present within the transect area (Figs 1,2,3).

The bulk of the granites within the transect area are mineralogically similar, with over 70 percent being biotite-bearing granodiorites, trondhjemites or monzogranites. Differences between groups are evident, however, and include differing ferromagnesian minerals and accessory phases, amongst others (Table 1). Granites from all groups exhibit a range of deformation and metamorphic fabrics (Table 1), although most banded and/or migmatitic gneisses fall into the High-Ca group. Conversely, the Low-Ca and Syenitic group members are, in general, the least deformed.

The High-Ca and Low-Ca groups are the most dominant in the LLT, comprising over 60 percent and 20 percent, respectively, of the total granites (Figs 1, 3). Both groups occur within and external to the greenstone belts, although the Low-Ca group granites are largely restricted to the larger granite masses between greenstone belts (Figs 1, 3). The High-HFSE (High-Field-Strength Element; Fig. 1, 3b) and Mafic granites (Fig. 2b) and Syenites (Fig. 2a) form minor components of the LLT, together constituting 10-20 percent of the total granites. They are mostly restricted to either within, or marginal to, the greenstone belts. The High-HFSE granites appear to be confined to a younger NNW-trending zone from Kookynie up to Teutonic Bore and further north (Malcolm Domain[2]), and an apparently older broader NNW zone in the Minara-Yundramindra area (southern Murrin to Merolia domains) and extending further south (Figs 1, 3b). Granites of both zones are commonly associated with coeval, and possibly comagmatic, felsic volcanic rocks (Hallberg & Giles, 1986; Brown et al., 2002), as part of bimodal (western zone) or calc-alkaline-dominated sequences (eastern zone) (Morris & Witt, 1997; Brown et al., 2002). The Syenitic granites form generally small, lithologically and texturally diverse bodies within the LLT, their distribution apparently broadly associated with the larger faults (Smithies & Champion, 1999; Fig. 2a). The Mafic Group is also lithologically diverse (Table 1). These granites are commonly more mafic than those of the other groups, and include a number of intrusives, both within the LLT, e.g., the Granny Smith and Lawlers plutons, and elsewhere in the east Yilgarn, e.g., Liberty, Porphyry, Kanowna-Belle that are closely spatially associated with mineralisation (Champion & Cassidy, 1998). Notably, however, both Syenitic, e.g., Jupiter

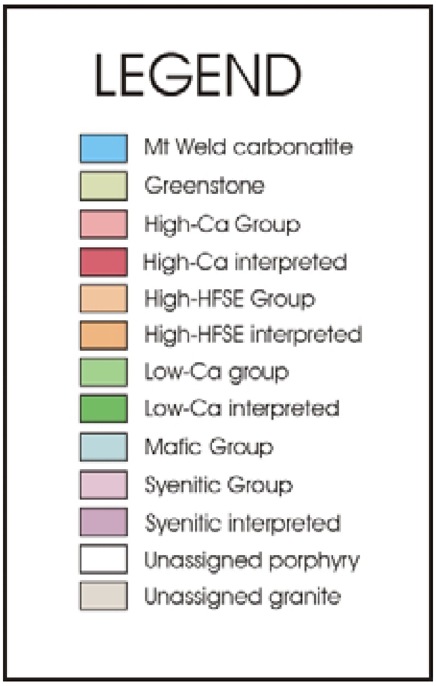


Figure 1 ***(opposite)*** **Distribution of granite groups within the Leonora-Laverton transect area, northeastern Yilgarn Craton. Granite distribution modified from Champion & Sheraton (1997)**

[2] Refer to Cassidy et al. (this volume) for domain locations and boundaries.

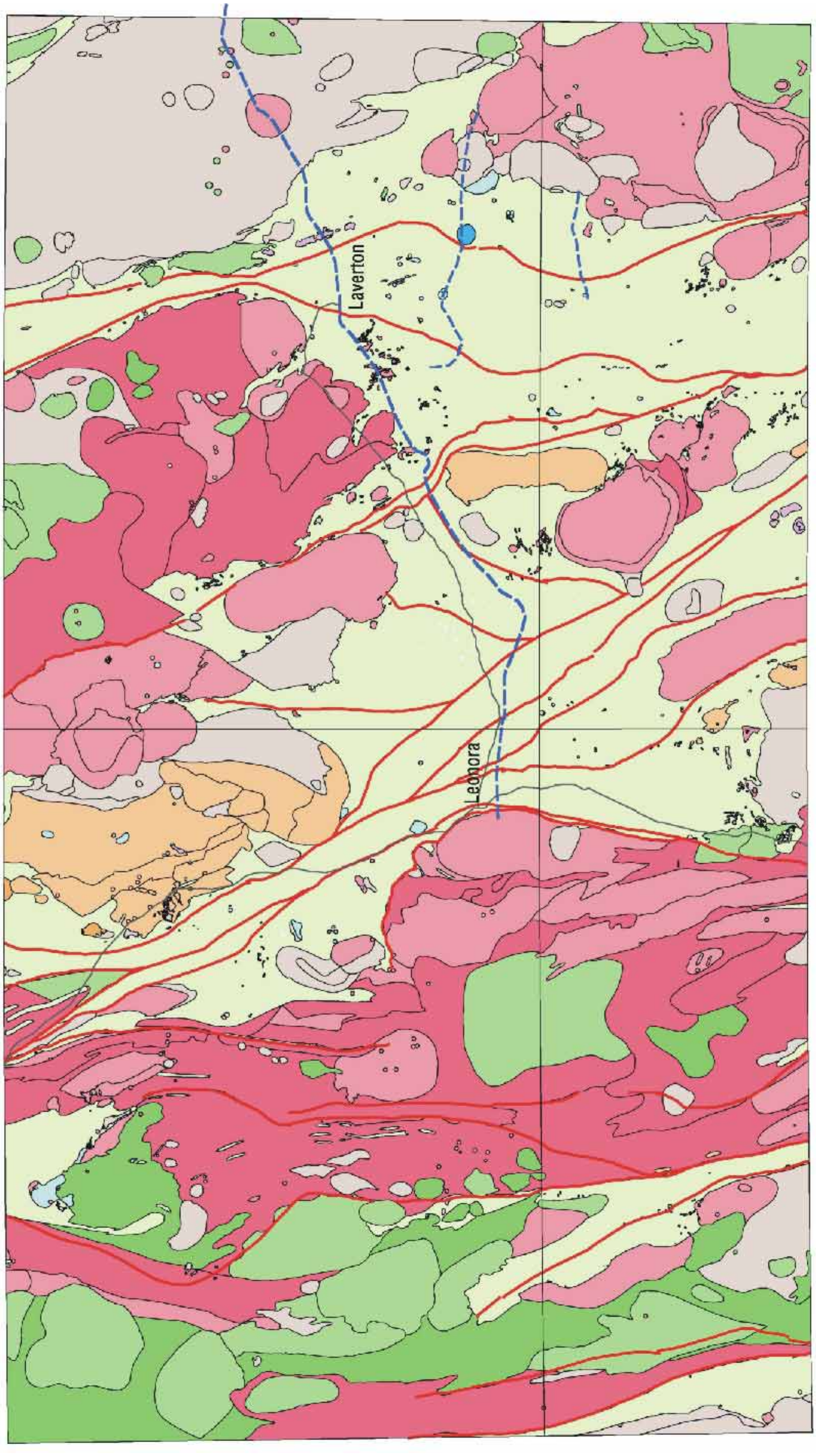

Laverton
Leonora

Table 1 Characteristics of the main granite groups in the Leonora-Laverton transect area (modified from Champion, 1997)

Group (examples)	**Distribution**	**Field characteristics**	**Feldspar-quartz** mineralogy	**Fe-Mg minerals and** accessories	**Geochemistry**	**εNd**
High-Ca (Trump, Tarmoola, Ballard gneiss)	internal & external	often strongly deformed to gneissic. In the EGP can be strongly feldspar porphyritic	**plagioclase dominant often with common zoning or patchy cores**	biotite-bearing, minor amphibole; some allanite or titanite	**high Na_2O, low Th, LREE, Zr**	90%: +0.15 to +2.4 10%: -2.0 to +0.15
Low-Ca (Mt Boreas)	internal & external	commonly mildly deformed at best but can be locally strongly deformed. Also forms small pods to plutons in external gneisses; often have post-tectonic look	**common K-feldspar**, plagioclase typically unzoned	biotite-bearing, amphibole very rare; **mafic compositions rich in allanite and titanite (to 3%); fluorite commonly present**	**high K_2O, low Na_2O, high Rb, Th, LREE, Zr**	pronounced zoning from east (+2.0) to west (-4.5)
High-HFSE (Kookynie)	appear to be all internal or marginal to greenstone belts	variably deformed, commonly spatially associated with volcanic rocks and volcanic complexes; **geographically restricted to north-south zone from S of Kookynie to N of Wiluna**	mostly very felsic, i.e., quartz and feldspar rich	despite felsic nature can have either biotite and/or amphibole. The presence of amphibole in a very felsic rock is diagnostic of this group	**distinctive combination of high FeO*, MgO, TiO_2, Y, Zr with low Rb, Pb, Sr, Al_2O_3**	-0.95 to +2.8
Mafic (Granny Smith, Lawlers)	appear to be all internal or marginal to greenstone belts	variably deformed, **distinctive dark-looking granites**	mostly plagioclase dominant (over K-feldspar); plagioclase has common zoning, often oscillatory	**common to abundant amphibole ± biotite ± pyroxene**. Biotite may be relatively common in clans with high-LILE contents, e.g. Granny Smith clan	**low SiO_2 contents (55-70+%)**, moderate to high Ni, Vr, MgO	+0.9 to +2.6
Syenitic (Jupiter, McAuliffe Well; Hanns Camp)	appear to be all internal or marginal to greenstone belts	commonly undeformed; **commonly very distinctive red granites with green pyroxene** (or amphiboles); often have haematitic or altered look	**K-feldspar-rich, with little or no quartz**	**common green pyroxene (locally amphibole) and adundant titanite**; notably ferromags are only locally strongly abundant; i.e. mostly low pyroxene/feldspar ratio	**high total alkalis ($Na_2O + K_2O$) 10-12%**; commonly low MgO, FeO*, TiO_2	+0.8 to +2.3

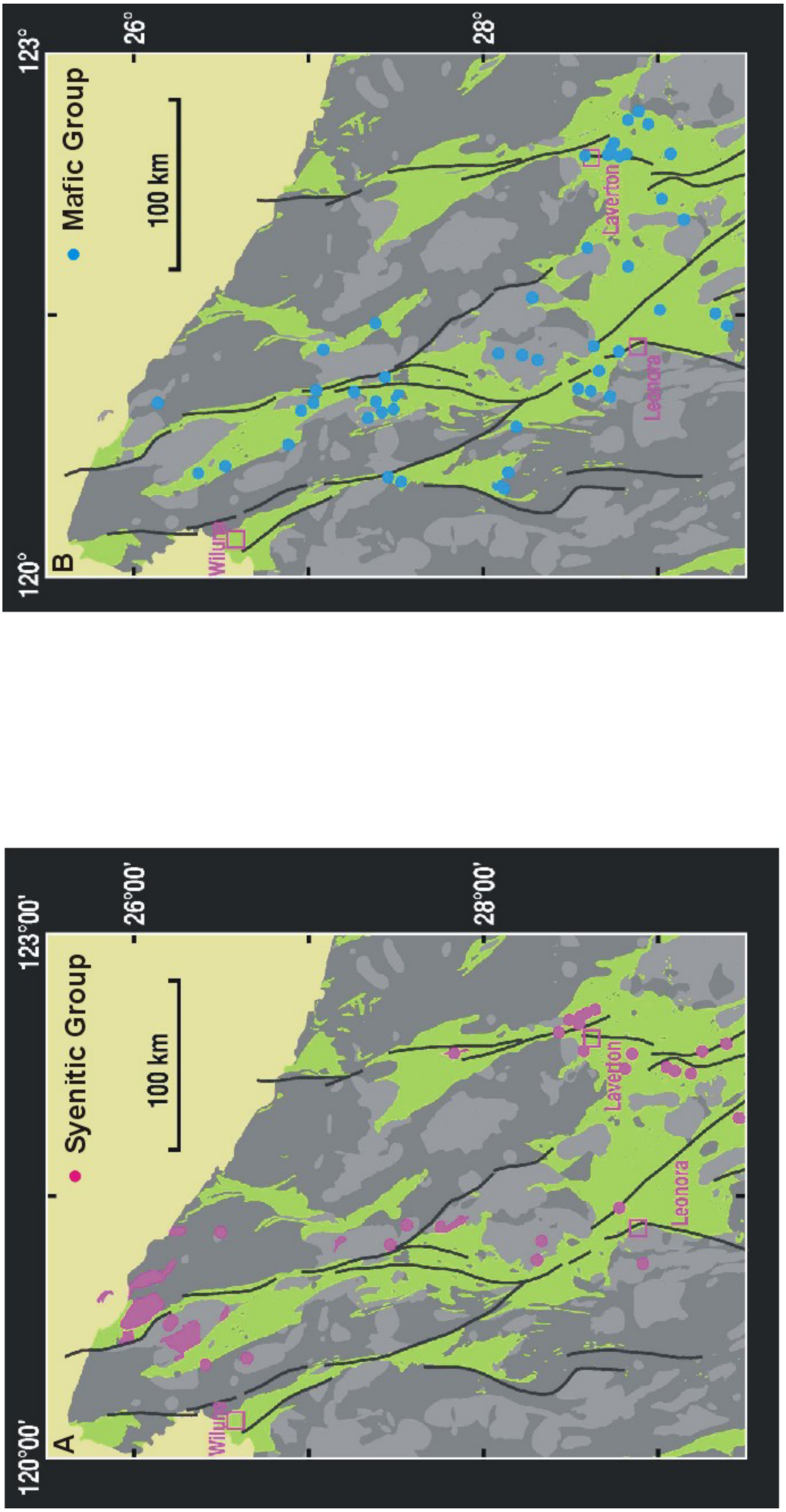


Figure 2 Distribution of the Syenitic (a) and Mafic (b) granite groups within the north-eastern Yilgarn region

and Wallaby, and High-Ca, e.g., Tarmoola, granites within the LLT are also spatially associated with Au mineralisation.

Geochronology

U-Pb zircon geochronology of granites (Hill et al., 1992; Nelson, 1995-2000; Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep) within both the eastern Yilgarn have increased markedly within the last 5 to 10 years. This is particularly true for the LLT (Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep; see Cassidy et al., this volume; Figs 3-4). All available public domain data for the eastern Yilgarn indicate an apparent continuum in magmatism between 2.72 and 2.63 Ga with a pronounced peak between 2.68 and 2.65 Ga (Fig. 4). Although most data are for the High-Ca and Mafic groups, it is evident that all groups span a range of ages. More importantly, however, the growing geochronological database now clearly confirm distinct periods of specific granite magmatism, for example, the Low-Ca granites are late in the magmatic sequence with ages between 2.655 and 2.63 Ga (Fig. 4). Such temporal groupings are also clearly evident within the data for the LLT. The earliest magmatism in the LLT is the High-Ca magmatism in the Agnew-Mt Clifford domain, dated at ca. 2810-2760 Ma (Fig. 3a). The oldest widespread magmatism occurs within the eastern third of the LLT (Murrin to Merolia domains), comprising 2.72 to 2.70 Ga High-HFSE and Mafic group granites (e.g., Cassidy et al., this volume; Fig. 3b). The High-HFSE magmatism appears to broadly young to the west with 2.695 to 2.68 Ga High-HFSE magmatism around the Teutonic Bore and Kookynie regions (Black et al., 2002; Fig. 3b), equivalent in age to felsic volcanic rocks of similar chemistry (Brown et al., 2002). Widespread High-Ca magmatism appears to largely post date the High-HFSE magmatism, with ages of 2.682 to 2.66 Ga across the LTT (Fig. 3a, 4). Notably, there appears to be little difference in timing of the High-Ca magmatism across the region. Around ca. 2.665 Ga, localised Mafic and Syenitic magmatism occurred (Fig. 3b). Within the LLT, there is an apparent hiatus in magmatism, between 2.66 and 2.655 Ga, before the onset of widespread Low-Ca and Syenitic magmatism; this hiatus is not as marked outside of the LLT (Fig. 4). Low-Ca magmatism occurs over a 20 Ma time frame across the whole LLT, although there is an indication in the data that there may actually be two peaks in this magmatism, at ca. 2650 and ca. 2640 (Fig. 4).

Champion (1997), on the basis of available data at the time, suggested that EGP granites were contemporaneous with, or postdated, greenstone formation at 2.72 Ga and younger (Nelson, 1997b; Krapez et al., 2000). While this has not changed in principle, it is now recognised that both older (>2.72 Ga) granites and greenstone are present locally within the LLT and the eastern Yilgarn. Evidence for old (>2.73 Ga) granites include 2.81 High-Ca gneisses at Twin Hills, 2.76 Ga High-Ca granites in the Raeside granite complex (west of Leonora; Black et al., 2002), 2.77 Ga migmatite at Mt Dennis (Dunphy et al., in prep), >2.8 Ga High-Ca granitic gneiss east of Laverton, outside the LLT (Black et al., 2002), and 2.738 Ga high-HFSE? gneisses, north of Leinster (Nelson, 1997a). Older greenstone sequences include the 2.736 Ga Kathleen Valley Gabbro (Black et al., 2002); a maximum depositional age of 2.86 Ga from a highly-deformed conglomerate in the Dingo Range greenstone belt (Dunphy et al., in prep); and a minimum age of 2.755 Ga for mineralisation in the Tower Hill deposit near Leonora (Witt et al., 2001).

As well as the presence of older granites, the younger (post 2.72 Ga) granites (and volcanic rocks) contain evidence of various amounts of inheritance (Hill et al., 1992; Nelson, 1995-2000; Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep), ranging in ages to from 2.69 Ga to greater than 2.9 Ga. Importantly this includes a number of well determined inherited ages, of ca 2.81 Ga, recorded from the Agnew-Mt Clifford domain (i.e., the Kalgoorlie terrane; Fig 3a), including: a High-Ca granite south-east of Lawlers (Black et al., 2002); and migmatitic and gneissic High-Ca components in the Wilbah gneiss (Dunphy et al., in prep), as well as 2.77 to 2.8 Ga inheritance in High-Ca granites in the Merolia domain (Fig. 3a) and further to the east; all clearly indicating the presence of crust of this age within the LLT.

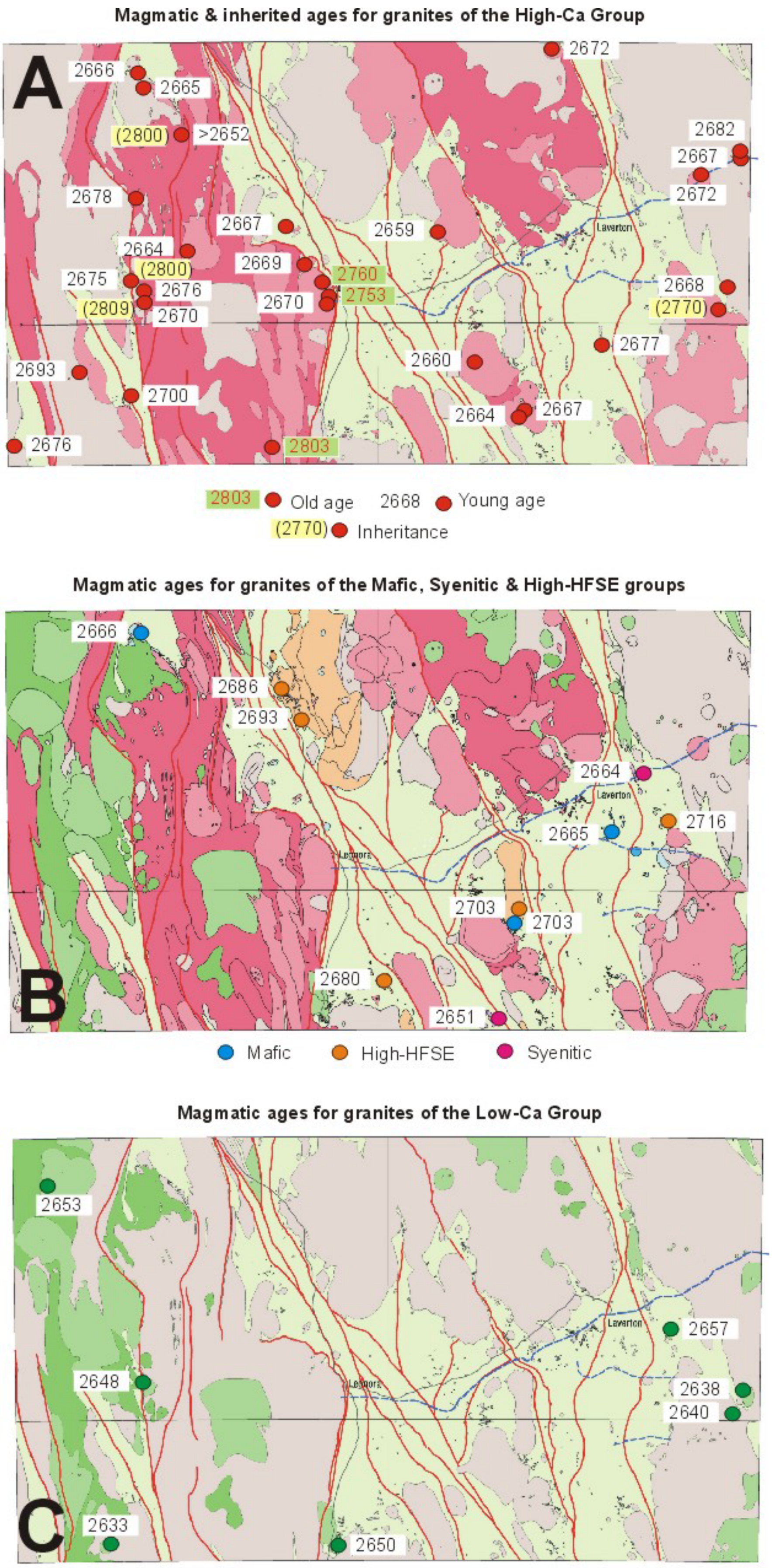


Figure 3 **Geochronological data for granite groups within the Leonora-Laverton transect area: a) Magmatic and inherited ages for the High-Ca Group; b) Magmatic ages for the High-HFSE, Mafic and Syenitic groups; c) Magmatic ages for the Low-Ca Group**

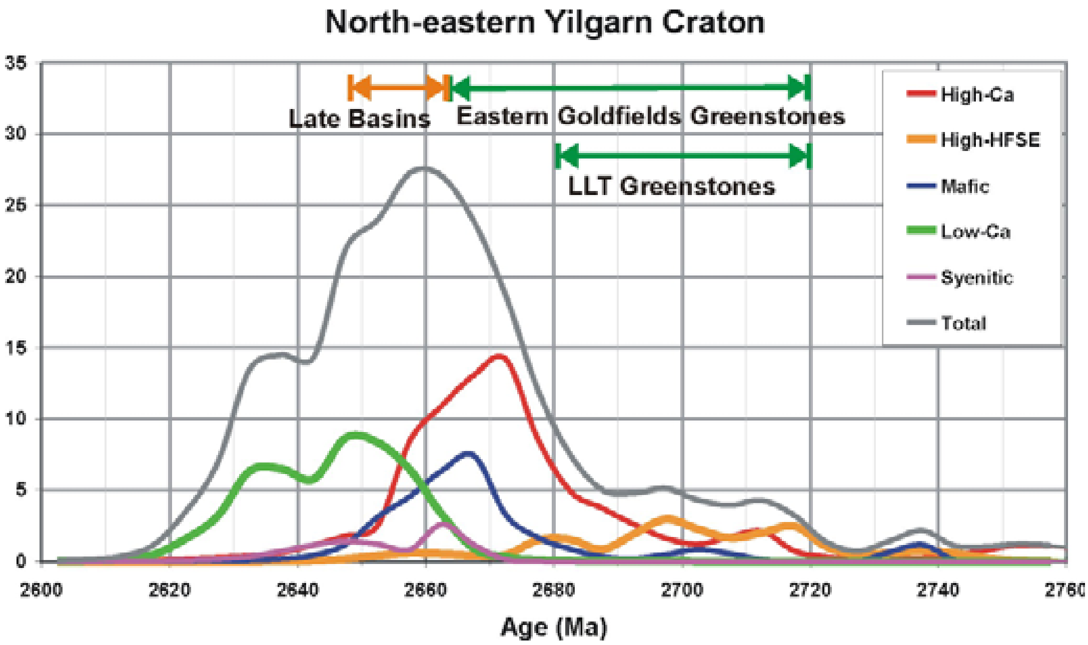


Figure 4 Statistical distribution of granite ages in the north-eastern Yilgarn Craton. Also shown are ages of greenstone within the Leonora-Laverton transect area (LLT) and the Eastern Goldfields Province, and interpreted ages of the late sedimentary basins. Data sources listed in text

Geochemistry

Champion & Sheraton (1997), and Champion (1997) described the geochemistry of about 1000 samples of the northeastern Yilgarn granites. The following is summarised from that work and additional unpublished work; most emphasis is placed on the granites of the LLT.

High-Ca Group

The High-Ca granites comprise sodic trondhjemite, granodiorite and granite characterised by a moderate silica range (68-77% SiO_2), high Al_2O_3 (^{3}15% at 70% SiO_2), moderate to high Na_2O, and (low to) moderate LILE (K_2O, Rb, Pb, Th, U, LREE) and HFSE (HREE, Y, Nb, Zr) (Figs 5-8). All exhibit negative Nb, P and Ti anomalies on primitive mantle-normalised (PM-N) multi-element plots. Rb/Sr ratios are consistently low (mostly <0.5), while most are LREE-enriched with strongly fractionated REE patterns. In detail, the High-Ca group defines a quasi-continuous range in LILE and Zr contents, which can be arbitrarily divided into 2 end-member subgroups, i.e., low-LILE and High-LILE (Fig. 5). Notably, a similar divide can also be used to discriminate between the high-LILE and low-LILE suites of the Mafic group (Champion & Cassidy, 1998). Importantly, available geochronological data suggests that the high-LILE members of both groups are the younger members of each group.

Members of the High-Ca group are dominantly Y-depleted (Y<10 ppm), although they do extend to Y-undepleted compositions (10-25 ppm Y; Fig. 8), the latter mostly, but not exclusively, confined to the High-LILE subgroup. Yttrium contents show an inverse relationship with Eu/Eu*[3] with Y contents <7 ppm having no or positive Eu anomalies (Fig. 8). The High-Ca granites share many common features with typical Archaean Tonalite-Trondhjemite-Granodiorite (TTG) suites (Martin, 1994), though the High-Ca granites are, in general, more felsic, have higher LILE contents and lack the more mafic end-members found in most TTG suites. Champion &

[3] Eu/Eu* = chondrite-normalised Eu divided by half the sum of normalised Sm and Gd; FeO* = total Fe as FeO; mg* = 100 molecular Mg/(Mg+Fe); HREE = heavy Rare Earth Elements, LREE = light Rare Earth Elements.

Smithies (2001) placed the High-Ca granites into a transitional TTG grouping.

Geochemical discrimination between the High-Ca and other groups is mostly straightforward. Most difficulty occurs with the more siliceous members of the Low-LILE subgroup of the Mafic group whose compositions strongly converge with that of the High-Ca group (see below; Figs 5-8).

Low-Ca Group

The Low-Ca group (68-76% SiO_2), comprises potassic granite and lesser granodiorite, characterised by high LILE (K_2O, Rb, Pb, Th, U) and HFSE (LREE, HREE, Y, Zr) contents (Figs 5-7). In particular, elements such as Zr, La and Ce, are strongly enriched, particularly in the more mafic end-members (Fig. 6). While there is some variability in the LILE and HFSE contents between granite suites within the group, the variation is not as pronounced as that observed in the High-Ca group (Fig. 5). The majority of the Low-Ca granites have moderate to high Y (and HREE) contents (10-30 ppm), but do include a minor subgroup which are lower in Y (<10 ppm). Therefore, like the High-Ca group, the Low-Ca group also includes both Y-undepleted and Y-depleted granites, although, unlike the High-Ca group, all are Sr-depleted, i.e., have (low to) moderate Sr contents and negative Eu anomalies (Fig. 8). Systematic geochemical trends, e.g., increasing Rb (Fig. 7), Rb/Sr, Rb/Ba with increasing SiO_2, and decreasing K/Rb, suggest that crystal fractionation was significantly more important than in the High-Ca granites. Relative to the High-Ca group the Low-Ca granites have lower Al_2O_3, MgO, CaO, Na_2O and Sr, and higher TiO_2, K_2O, Rb, Pb, Th, U, LREE, HREE, Y, and Zr contents, for a given SiO_2 content (Figs 5-7).

High-HFSE granites

The High-HFSE group granites are characterised by high SiO_2 (>70%), with low Al_2O_3, like the Low-Ca group, but CaO, Na_2O, and K_2O contents and K/Na ratios more like those in the High-Ca group. For a given silica content they have elevated to significantly higher TiO_2, total FeO, MgO, P_2O_5, Y, Zr, and Nb, relative to other eastern Yilgarn granites (Figs 5-8), characteristics suggesting an A-type affinity. Notably, LILE contents, especially Rb and Pb (Fig. 7), are generally moderate to low; the low Pb contents, in particular, being a distinctive characteristic of the High-HFSE granites, the only other granites showing this feature being a couple of Low-LILE High-Ca suites. All High-HFSE granites are strongly Sr-depleted (low Sr and moderate to large negative Eu anomalies) and Y-undepleted (Fig. 8), and exhibit marked negative Nb, Ti and P anomalies on PM-N multi-element plots.

Syenitic Group

The geochemistry of the Syenitic group and its members has been recently described in detail by Smithies & Champion (1999). Members of the group (50-73% SiO_2) are clearly distinguished by their high total alkalis (Na_2O+K_2O > 10%), high K_2O, and variable to high LILE (Figs 5-8). They are locally peralkaline and have generally lower MgO, total Fe and mg numbers than other eastern Yilgarn granites (Figs 6-7). Many elements show considerable scatter, even within individual plutons, reflecting both obvious and cryptic lithological heterogeneity. Despite the variability, their Zr, Y, and Nb contents (Fig. 6), and Ga/Al ratios suggest that the Syenites are A-type in character (Collins et al., 1982). Smithies & Champion (1999) showed that Nb content and Nb/Y ratios within the syenites decreased across the EGP from east to west. Similar east to west variation includes increasing Na_2O, K/Rb, and decreasing Rb, Ba, Rb/Sr, K_2O, K/Ba, although these trends are partly complicated by the strong Ba and Sr enrichment observed in the Syenites and other granites, e.g., High-Ca, Mafic, around the Kambalda region (e.g., Perring & Rock, 1991; Smithies & Champion, 1999). All syenites show marked Nb depletion on PM-N multi-element plots.

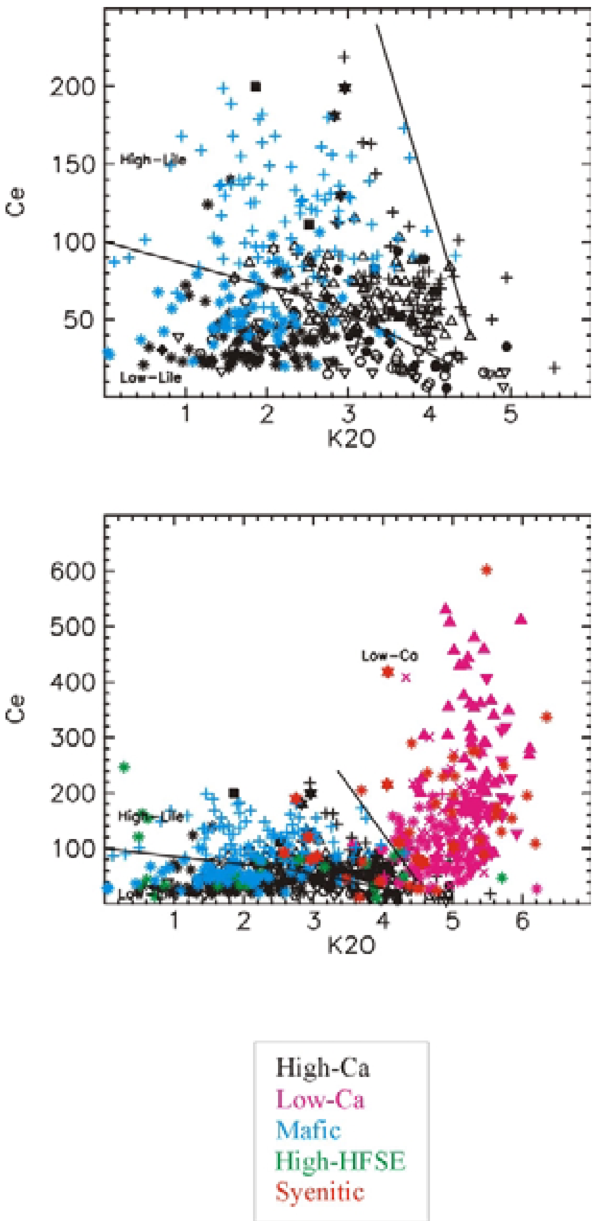


Figure 5 Ce versus K_2O plots for granite groups of the northeastern Yilgarn. Fields for High-LILE and Low-LILE (modified from Champion and Cassidy, 1998), demonstrate the range of LILE contents within the High-Ca and Mafic groups. Compare with the high LILE contents of the Low-Ca and Syenitic group. Note different scales of x and y axes. Oxides are in wt%, elements in ppm for Figures 5 to 8

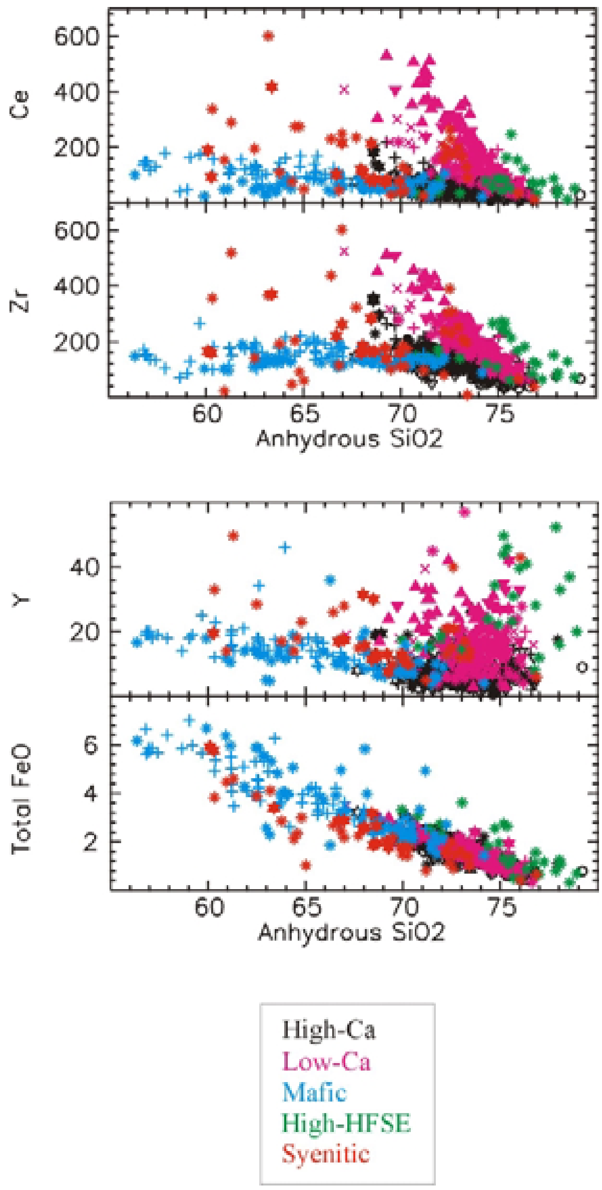


Figure 6 Total FeO, Y, Zr and Ce versus anhydrous SiO_2 plots for granite groups of the northeastern Yilgarn. Note the elevated levels of these elements for the Low-Ca and High-HFSE granites

Mafic Granites

Champion & Sheraton (1997) and Champion (1997), originally defined the Mafic group as a variety of granite suites and supersuites largely characterised by their lower silica contents (55-70%) and variable LILE and LREE content. Differences between granite suites in the group include large variations in LILE and the LREE, particularly K_2O, Sr, Ba, Th, U, Pb, La and Ce, whereas the HFSE, (Y and to a lesser extent Zr), contents are similar (Figs 6-8). These differences led Champion & Cassidy (1998) to subdivide the Mafic group into two broad end member types, namely High-LILE and Low-LILE (Fig. 5). An important feature of this subdivision is that the high LILE and LREE character of the High-LILE subgroup persists for even the most mafic end-members, clearly indicating fundamental differences between the two types. The geochronological data suggests that the High-LILE subgroup is largely ca 2665 Ma and younger (Nelson, 1995-2000; Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep). Despite these differences, however, the Mafic granites are dominantly Sr-undepleted or slightly depleted, with Eu/Eu* between 1.0 and 0.9 for all units despite the large range in Sr contents (Fig. 8). Similarly, Eu/Eu* shows no variation with increasing SiO_2, unlike Y which decreases, from Y-undepleted (20 ppm) to Y-depleted (<8 ppm; Fig. 6). All Mafic granites show strong negative Nb, and Ti anomalies on PM-N multi-element plots. REE vary from strongly to moderately fractionated, reflecting the different LREE contents between suites. Another important feature of the Mafic group, especially the High-LILE subgroup, is the tendency towards high mg numbers (70 to 45; Fig. 7), Ni (to 150) and Cr (to 300+; Fig. 7), which coupled with moderate silica (>57% SiO_2), and the elevated LILE (medium- to high-K), indicates that these units have affinities with the sanukitoid/high-Mg diorite (Shirey & Hanson, 1984; Smithies & Champion, 2000) class of granites, i.e., granites closely related to subduction tectonics.

At higher silica contents the Mafic granites, particularly those with lower LILE contents, trend towards compositions similar to the High-Ca granites (Figs 6, 7), and it is not clear whether there is any genetic relationship between the two granite groups. Although, the two groups show only limited compositional overlap in silica content (between ~68 and 69 wt%), element trends

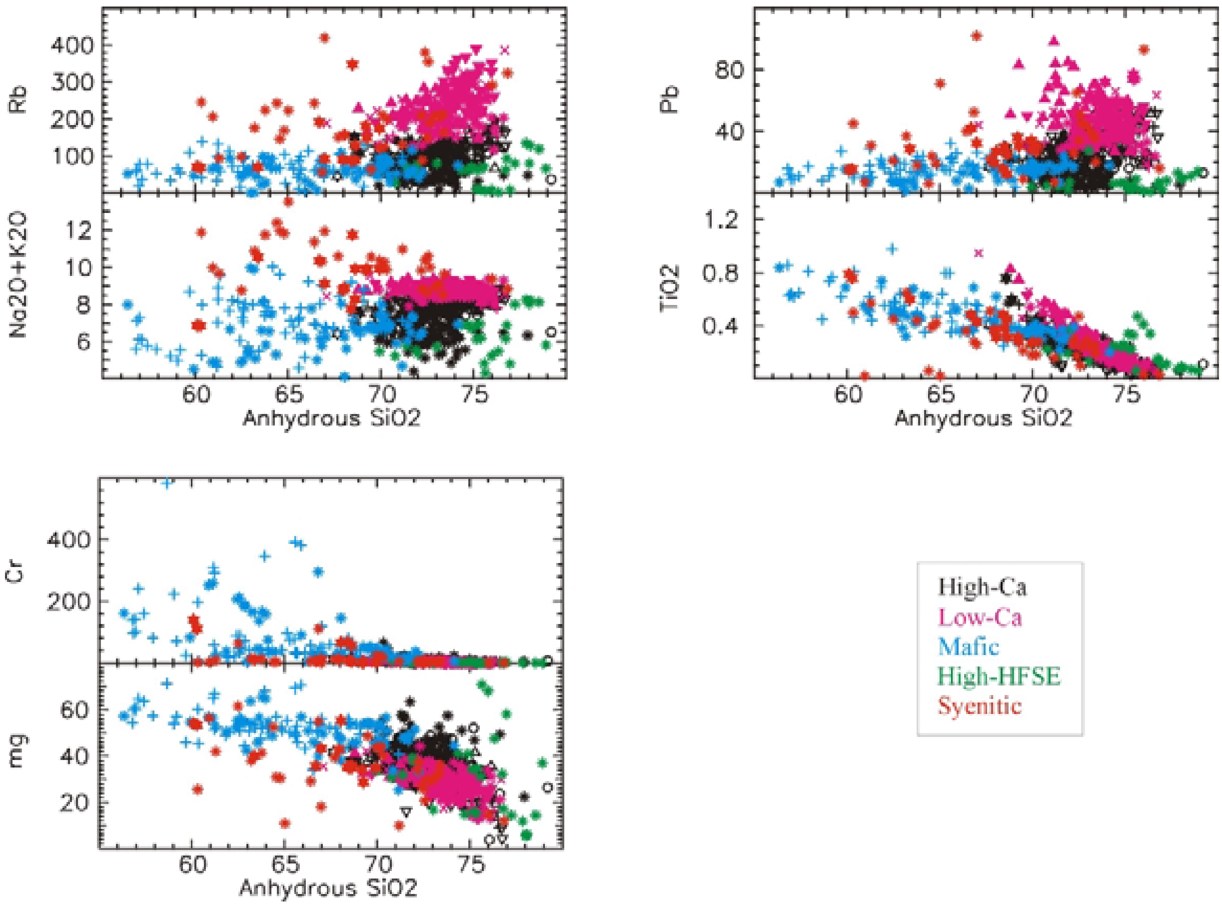


Figure 7 TiO_2, Pb, Na_2O+K_2O, Rb, mg* and Cr versus anhydrous SiO_2 plots for granite groups of the northeastern Yilgarn. Note the elevated mg* and Cr for the Mafic group, the high TiO_2 and low Pb and Rb for the High-HFSE group, the high Na_2O+K_2O for the Syenitic group, and the high Rb for the Low-Ca group

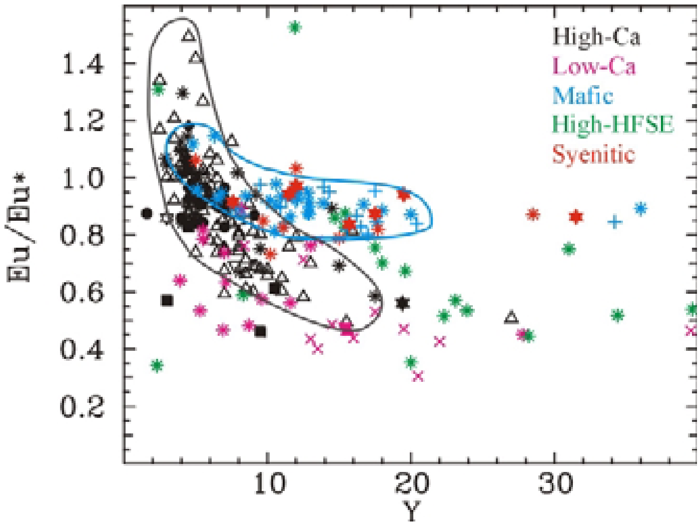


Figure 8 Eu/Eu* versus Y for granite groups of the northeastern Yilgarn. Values of Eu/Eu* <1.0 indicate negative Eu anomaly. Note divergent trends (circled) for High-Ca and Mafic groups

between the groups are largely continuous, albeit often with a marked inflection (e.g., mg* or TiO_2 vs SiO_2; Fig. 7). As such, it is possible that, at least some of, the Mafic granites may be related to the High-Ca group, although a significant mineralogical change during either partial melting or fractional crystallisation would be required to explain the inflections. It is also evident, however, that subsets of each group are clearly distinct (e.g., Zr vs SiO_2, Fig. 6; Na_2O+K_2O vs SiO_2, Fig. 7; Eu/Eu* vs Y, Fig. 8).

Sm-Nd Isotopes

Champion & Sheraton (1997) reported on an extensive database of Sm-Nd isotope analyses of granites from the northeastern Yilgarn. Minor additional data collected since 1997 (GA, unpublished data) has expanded this data set but not significantly changed earlier interpretations (Table 1, Fig. 9). ε_{Nd} values for the High-Ca granites fall over a moderate range from –2.0 to +2.4 (38 analyses), although 90% fall between +0.15 and +2.4 (Fig. 9a). This narrower range, although greater than analytical error (±0.5 epsilon unit), constrains the High-Ca granites to have formed from a generally isotopically uniform source (±1 epsilon unit). Depleted-mantle model ages (two-stage models) cluster strongly around 2.8 to 2.9 Ga, and overlap with inherited zircon ages, especially in the Agnew-Mt Clifford domain. There is, however, a small subset (~10% of data) of High-Ca granites, in the LLT and surrounding region, with more evolved ε_{Nd}, e.g., -1.3 for gneiss south-west of Lawlers. These appear to occur within the eastern part of the LLT (Laverton & Merolia domains) and their north and south extensions, and within the Agnew-Mt Clifford domain. Inherited zircon data (see above) shows older crust (ca. 2.8 Ga and older?) exists within the latter region; the inference from the Sm-Nd isotopic data is that older crust is probably also present within the Laverton and Merolia domains. ε_{Nd} data for the Mafic (0.9 to 2.6) and Syenitic granites (0.8 to 2.3) form very tight groupings with total variation less than ±1 epsilon unit (Fig. 9a). These values overlap the bulk of the High-Ca group, clearly showing that a large component of the source rocks for these three groups must be relatively young, i.e., a significant part of the crust in the northeastern Yilgarn was produced between 2.9 and 2.65 Ga, either via one or two stage growth.

Champion & Sheraton (1997) showed that the Low-Ca granites exhibit a pronounced polarity spanning six ε_{Nd} units, from primitive in the east (2.0), to evolved (-4.5), west of the Ida lineament, in the SCP. Additional infill data (GA unpublished) has not modified this interpretation but does show that more isotopically primitive Low-Ca granites are not confined to the east, extending across the LLT (Figs 9b,c). Depleted-mantle models ages vary from similar to the High-Ca

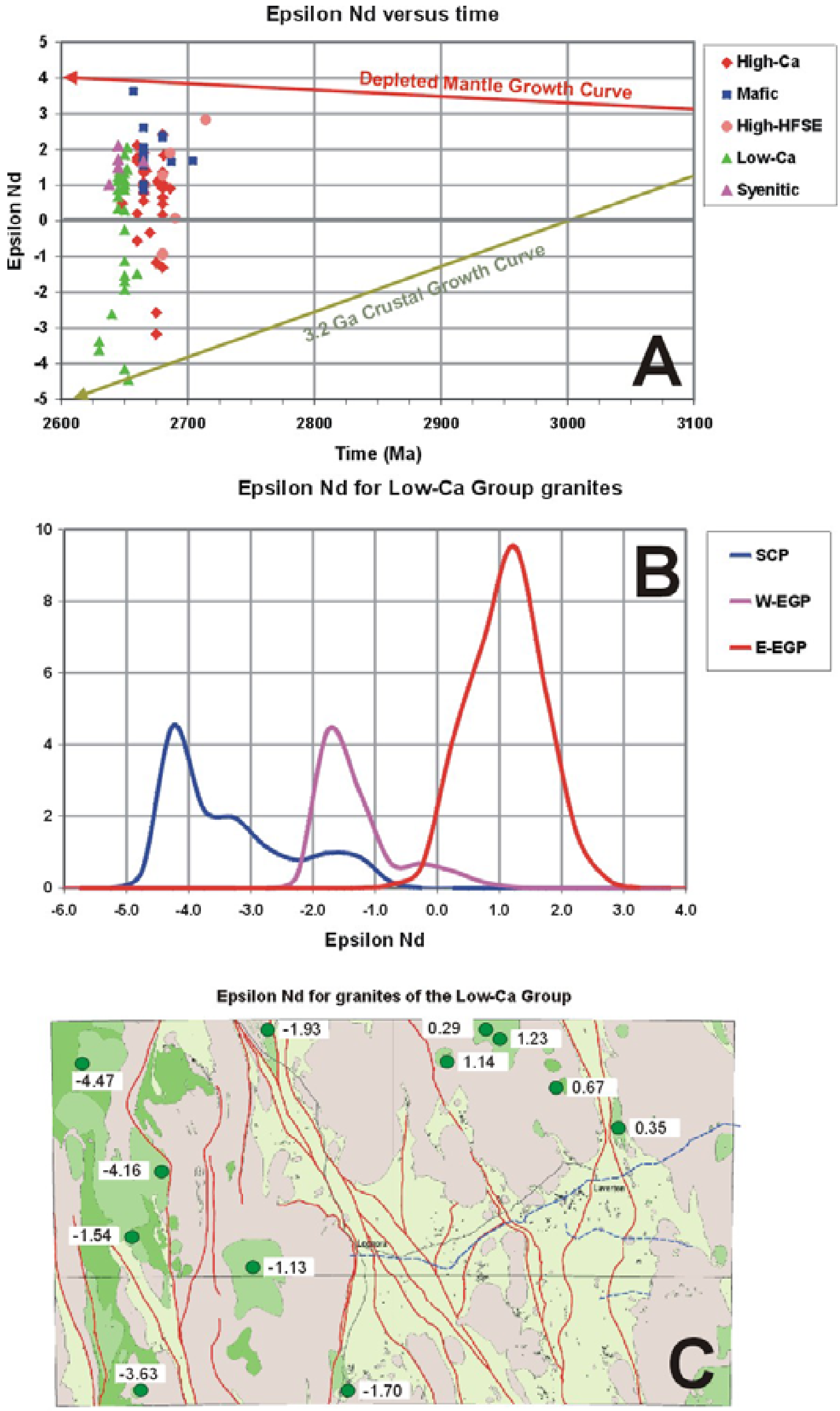


Figure 9 Sm-Nd isotopic data for granite groups in the north-eastern Yilgarn Craton: a) ε_{Nd} versus time plot for all granite groups; b) statistical distribution of ε_{Nd} for Low-Ca granites in the Southern Cross Province (SCP), western Eastern Goldfields Province (W-EGP), and the eastern EGP (E-EGP); c) ε_{Nd} data for Low-Ca granites in the Leonora-Laverton transect area. Data sources: Champion & Sheraton (1997), GA (unpublished data)

group (2.9-2.8 Ga), in the east, to significantly older in the west (>3.1 Ga). Although this trend is explicable in a number of ways, e.g., the Low-Ca source rocks become progressively younger to the east, the data provide good evidence for the presence of old continental crust, particularly in the western half of the LLT (Fig. 9b). Although, it is difficult to tightly constrain source ages from Sm-Nd data alone, the presence of not uncommon 2.8 Ga inheritance in the High-Ca granites, coupled with the observation that the High-Ca granites are significantly more isotopically primitive than the Low-Ca granites, would suggest that source ages for the latter are not younger than 2.8 Ga in the Agnew-Mt Clifford domain, i.e., the Low-Ca granites are sampling crust significantly older than 2.8 Ga in this region. Data for the High-HFSE granites (-0.95 to +1.9 for the Malcolm domain, and +2.8 (one value only) for the Murrin domain show that they broadly mirror the Low-Ca group trend.

Petrogenesis

The general geochemical characteristics of the High-Ca group indicate derivation from a mostly mafic LILE-poor source, probably broadly basaltic in composition. The observed range in the LILE contents within the group, however, suggests a more complex process, strongly implying the involvement of at least two components, either as a simple heterogeneous source (basaltic to quartz dioritic in composition), or by some other process (assimilation of pre-existing crust, magma-mixing, etc). Importantly, the very similar ε_{Nd} signatures for the majority of the High-Ca group granites in the northeastern Yilgarn provides some constraints to this argument. For example, the generally much more evolved ε_{Nd} of the Low-Ca group, especially within the Leonora region (Fig. 9c), indicate that no significant component of the Low-Ca source was involved in the generation of the High-Ca granites. Conversely, the similar isotopic signatures observed in the Mafic granites (Low- and High-LILE), and, to a lesser extent the Syenites (Fig. 9a), suggest some possible relationship. In this regard the temporal and isotopic equivalence of the high-LILE High-Ca and high-LILE Mafic subgroups may indicate some commonality of process in their respective genesis.

Apart from higher LILE contents, the geochemistry of the dominantly low-Y High-Ca granites bears a strong resemblance to TTG suites common in Archaean terranes elsewhere. As for TTGs in general, the Sr-undepleted, Y-depleted nature of the majority of the High-Ca granites indicate derivation at pressures great enough to stabilise garnet and destabilise plagioclase (>10 kbars) (e.g., Barker & Arth, 1976; Martin, 1994, Rapp et al., 1991), either deep within a thickened crust (>35-50 km) (e.g., Rudnick, 1995), or from melting of a subducting slab (e.g., Martin, 1986; Martin & Moyen, 2002; Fig. 10b). It is difficult to unequivocally prove either model, as both models are feasible (see discussion in Champion & Sheraton, 1997), and not necessarily mutually exclusive, as shown by Smithies (2000) and Smithies et al. (2002). The presence of inherited zircons, the variable range in Sr and Y contents to Sr-depleted and Y-undepleted compositions, the lack of granites with high mg*, and the Sm-Nd isotopic data, suggest either a thickened crust source, or slab-melts strongly modified by crustal assimilation and accompanying fractionation (Fig. 10). Notably, if the High-Ca granites were largely derived by melting within thickened crust then part of the crust must have since delaminated (e.g., Smithies & Champion, 1999), as the seismic evidence from the southern EGP (Drummond et al., 1993), indicates that the present-day eastern Yilgarn crust is too thin (<40 km) and too felsic. Regardless of model used, the data indicate that an older crustal component is required.

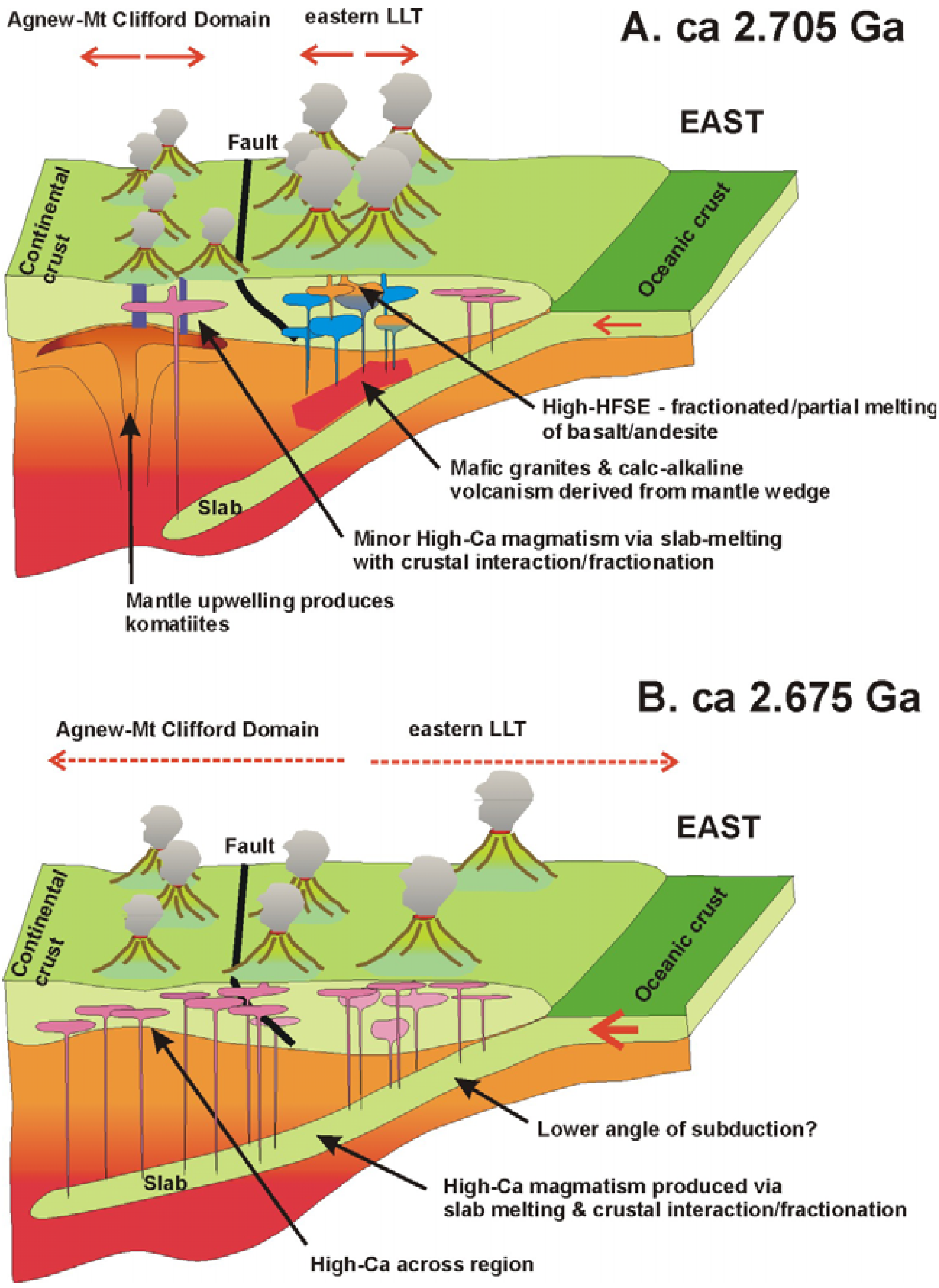
The geochemical and Sm-Nd isotopic data for the Low-Ca granites indicate derivation from an, at least moderately, potassic and LILE-rich crustal source, i.e., they represent reworked crust (Fig. 10d). Champion & Sheraton (1993, 1997) suggested that an appropriate source would be one comprised of less-siliceous Archaean TTG suite rocks, i.e., tonalitic rocks, consistent with experimental evidence (Skjerlie & Johnston, 1992). Notably, the low CaO in the Low-Ca granites and the very minor occurrence (at most) of amphibole in the granites, indicate partial melting was largely via dehydration melting driven by biotite breakdown, i.e., either small volume melts or from a source with only minor amphibole. Further, the high levels of the HFSEs, in particular Zr, in the Low-Ca granites, suggest high temperature melting, consistent with a generally water-poor (i.e., limited amphibole) source. The largely Y-undepleted, Sr-depleted nature of the Low-Ca granites suggests they were generated at moderate crustal levels (mostly <35 km). Finally, the geochemical and Sm-Nd isotopic data suggest that the northeastern Yilgarn is composed of crust of broadly tonalitic composition that was generated over several hundred millions of years, from possibly >3.0 Ga in the SCP to ca. 2.8 Ga or younger in the east. Unlike the High-Ca granites, the variation in LILE, in particular, and the HFSE, within the Low-Ca granites can mostly be explained by changes in the percentage of partial melt, although variations in source compositions may have contributed.

Champion & Sheraton (1997), and Champion (1997), suggested that the High-HFSE group granites were crustally-derived melts from an intermediate to more siliceous source, the latter hypothesis based on the decoupled LILE, in particular high Ba but low to moderate Rb, and especially low Pb, which together argue against both small degrees of partial melting and any extensive crystal fractionation. The Sr-depleted, Y-undepleted nature of the group, strongly infer generation at only moderate crustal pressures, i.e., <10 kbars (<35 km thick), i.e., consistent with a crustal source. Similarly, as discussed by Champion & Sheraton (1997), the Sm-Nd isotope data indicate, at least locally, significant involvement of pre-existing crustal rocks in the generation of the High-HFSE granites.

As noted earlier, the High-HFSE granites are commonly associated with felsic volcanic centres, often within a bimodal association (Morris & Witt, 1997; Brown et al., 2002). This association raises the possibility that the High-HFSE granites (and probably felsic volcanic rocks) may, in fact, represent variably crustally-contaminated, fractionated tholeiitic magmas (Fig. 10a). In this scenario, the elevated FeO*, Zr, Y, HREE and low LILE (especially K_2O, Rb, Pb) in the granites, is consistent with, but not as extreme, i.e., generally lower and higher levels, respectively, as those observed in fractionated tholeiites, for example the felsic phase of the Kathleen Valley Gabbro has ~6 wt% FeO*, >400 ppm Zr, with <0.5 wt% K_2O, at ~72 wt% SiO_2. The variable LILE component would, therefore, in this model represent crustal contamination/assimilation. Alternatively, it is possible that, like the Iceland rhyolites (Gunnarsson et al., 1998) which have somewhat similar (though more extreme) geochemical characteristics (e.g., elevated FeO*, LREE, Zr, Y, low Rb), the High-HFSE granites may represent partial melting of a broadly tholeiitic source (Fig 10a), more akin to the early models of Champion & Sheraton (1997) and Champion (1997). It is noted that both models are consistent with the inferred high temperatures considered a feature of A-type magmatism (King et al., 2001).

Although the petrogenesis of the Syenitic group has been described in some detail by Johnson (1991) and Smithies & Champion (1999), the relative contributions of mantle versus crustal components is equivocal; this is a general problem for many quartz-normative syenites like those in the EGP. Smithies & Champion (1999) suggested that features such as the lack of associated mafic rocks, the presence of quartz, the mostly high LILE contents, the presence of some inherited? zircons, and the presence of strong negative Nb and Ti anomalies, all a dominantly crustal origin. A similar conclusion was reached by Johnson (1991), although it is difficult to rule out a dominantly metasomatised mantle origin with a significant crustal contribution. This may particularly be the case for the 2.665 Ga syenites (e.g., Hanns Camp syenite, west of Laverton) which are contemporaneous with interpreted subduction-related high-LILE Mafic granites (e.g., Granny Smith Granodiorite). Similarly, it could be speculated that the apparent systematic regional variations observed in the syenites, although mostly younger, may reflect metasomatic changes related to this earlier subduction.

As indicated by Champion (1997), the source of the Mafic group granites is largely equivocal, with evidence for both crustal and mantle-derived contributions (e.g., Foden et al., 1984; Witt & Swager, 1989). Clearly the variation in the LILE and LREE, evident in even the most mafic end-members, requires at least two separate components. Champion (1997) suggested two such


Agnew-Mt Clifford Domain
eastern LLT
A. ca 2.705 Ga
EAST
Fault
Continental crust
Oceanic crust
Slab
High-HFSE - fractionated/partial melting of basalt/andesite
Mafic granites & calc-alkaline volcanism derived from mantle wedge
Minor High-Ca magmatism via slab-melting with crustal interaction/fractionation
Mantle upwelling produces komatiites
B. ca 2.675 Ga
Agnew-Mt Clifford Domain
eastern LLT
EAST
Fault
Continental crust
Oceanic crust
Slab
Lower angle of subduction?
High-Ca magmatism produced via slab melting & crustal interaction/fractionation
High-Ca across region

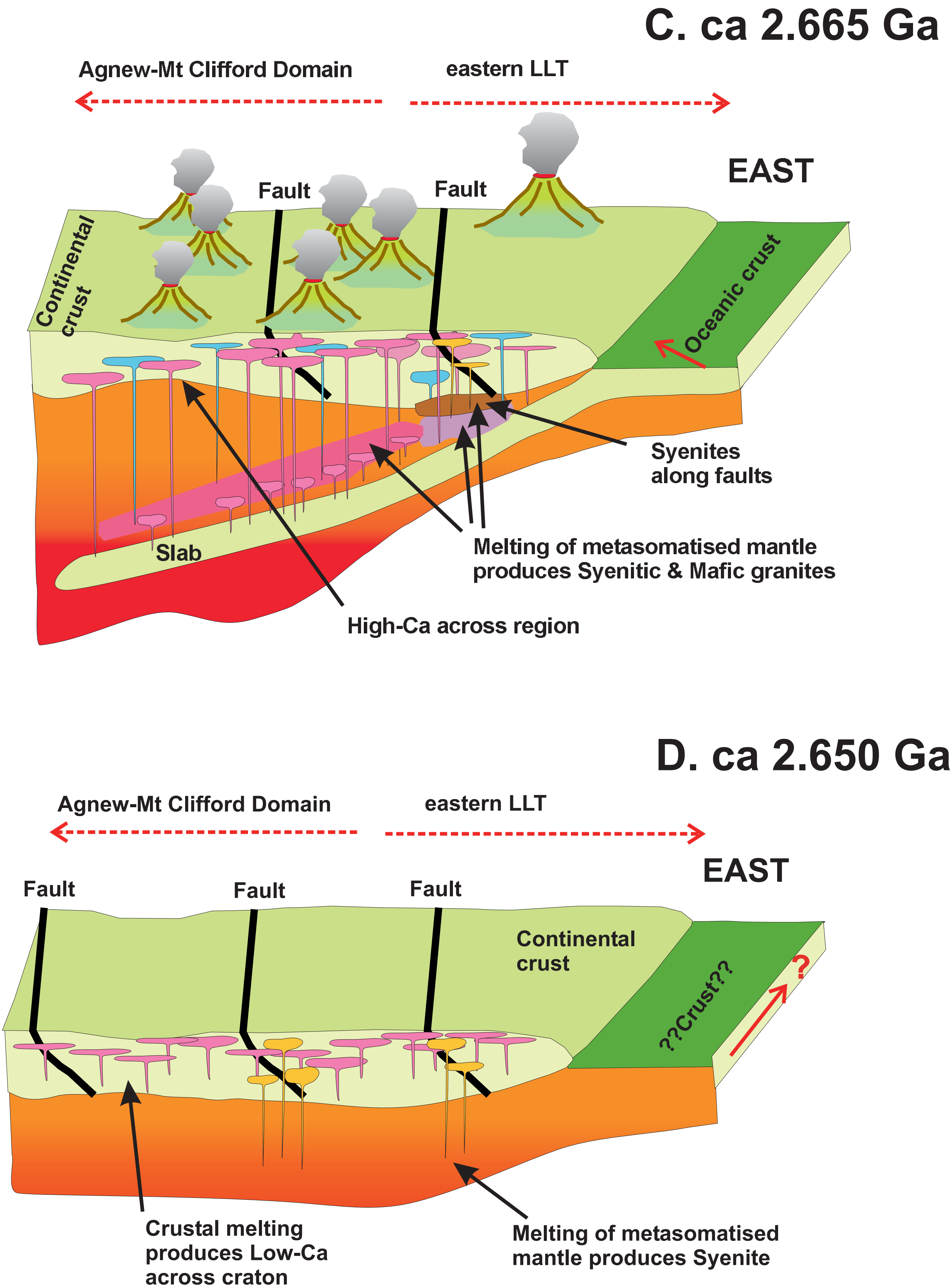


Figure 10 Speculative petrogenetic and tectonic models for formation of granite magmatism over four time periods in the Leonora-Laverton transect area

sources, namely a mafic 'basaltic' source, similar to that proposed for the High-Ca granites, and a more mafic, mantle-derived, LILE-rich source component. This model is broadly similar to those proposed for sanukitoids/high-Mg diorites, a class of granites characterised by the combination of elevated LILE and high mg*, Ni and Cr (e.g., Shirey & Hanson, 1984; Smithies & Champion, 2000), thought to represent the interaction between slab melts (i.e., TTG) and the mantle wedge or later remelting of slab-melt modified mantle (e.g., Smithies & Champion, 2000). The characteristics of the High-LILE Mafic subgroup, in particular, are consistent with the sanukitoid classification and suggests a similar process may have been operative for the formation of these granites (Fig. 10c). Alternatively, the overlap of ages for many of the High-LILE Mafic granites, around 2665 Ma, with some Syenitic group magmatism, may also indicate a possible relationship between the latter and at least part of, the LILE and LREE enrichment in the former.

Tectonic environment

It is evident that all previous tectonic models require some modification to take into account recent geochronological data (e.g., Krapez et al., 2000; Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep). The geochronological and isotopic data for the LLT clearly show evidence for some early greenstone and granite formation prior to 2.76 Ga (possibly ca 2.81 Ga), at least in the Agnew-Mt Clifford domain, and probably also in the Laverton and Merolia domains (see Cassidy et al., this volume), although little else is known about these older rocks. The data for the LLT also show changing magmatism over time, from early High-HFSE and Mafic (with minor High-Ca) ca 2.72 to 2.68 Ga, to voluminous High-Ca and lesser Mafic (and Syenitic) ca. 2.685-2.66 Ga, followed by widespread Low-Ca and lesser Syenitic magmatism (2.655-2.63 Ga). These changing magmatic patterns must also reflect minor or major changes in tectonic environment, especially the High-Ca to Low-Ca transition.

The High-HFSE granites appear to have formed in direct response to localised tectonic events, such as extension and/or rifting, (e.g., Hallberg & Giles, 1986). The spread of ages in both granite types suggests this rifting/extension occurred repeatedly through time, though may perhaps have become younger from east to west (Cassidy et al., this volume). The ages of the High-HFSE group (2.72-2.68 Ga) overlaps largely with ages for greenstone deposition (e.g., Nelson, 1997b; Krapez et al., 2000; Cassidy et al., this volume), and, hence basin formation (Krapez et al., 2000), as would be expected given the close spatial, temporal, and, at least locally, genetic, relationship between the High-HFSE granites and volcanic rocks (e.g., at Kookynie). This basin-forming environment is at least partly consistent with the inferred rifting/extensional setting for the High-HFSE granites. In this regard, it is possible that much of the pre-2.675 Ga greenstones may have formed in one or more basin environments (Krapez et al., 2000), perhaps partly in response to mantle plume activity at around 2.705 Ga (Nelson, 1997b), given that some form of mantle plume or mantle upwelling would appear to be necessary to explain the komatiitic volcanism (Campbell & Hill, 1988; Fig. 10a). The main difficulty with this scenario is the presence within the LLT of calc-alkaline (broadly andesitic) volcanism both older and younger than the regional komatiitic volcanism (Nelson, 1997b; Morris & Witt, 1997; Brown et al., 2002) which appear to require environments more akin to modern back-arc regions (as suggested by Brown et al., 2002), or perhaps an environment where plume-related mafic-ultramafic volcanism is imposed on an arc/back-arc region, as proposed by Wyman (2001).

The change over, around ca. 2.685-2.68 Ga, from High-HFSE, Mafic and intermediate to felsic extrusive magmatism (i.e., bimodal and calc-alkaline) to voluminous High-Ca magmatism (Figs 10a,b) must reflect some change in the configuration or style of convergent tectonics, given that all are apparently subduction-related. One solution may be something as simple as a change in the angle of subduction, from a typical modern angle (30-60%, e.g., Tatsumi & Eggins, 1998), with associated calc-alkaline magmatism (i.e., melting within the mantle wedge) to shallow plate subduction with associated slab-melting (e.g., Gutscher et al., 2000a, b), production of

TTG-like magmatism (High-Ca) and sanukitoid (High-LILE Mafic) magmatism at ca. 2.665 Ga. This would also have the effect of widening the associated volcanic arc (to explain the east-west distribution of the High-Ca granites across the LLT), and perhaps explaining the westerly position of the largely-coeval Black Flag Beds (Nelson, 1997b; Morris & Witt, 1997; Krapez et al., 2000). An alternative scenario is that this period may correspond to a time of terrane amalgamation, perhaps even of docking between the Southern Cross and Eastern Goldfields Provinces. This accretion/amalgamation event may correspond to the apparent unconformity, documented by Krapez et al. (2000), between their Spargoville and Black Flag formations, within the Black Flag Group. It is noted, however, that the LILE-rich geochemistry of the High-Ca granites is inconsistent with the EGP being produced by the amalgamation of a number of small, primitive island-arc-like, tectonic plates as has been proposed for the Abitibi subprovince (Jackson et al., 1994), where granites have LILE-poor compositions consistent with a juvenile source (Feng & Kerrich, 1992). This, however, does not negate accretion of larger more continental-type terranes. Another speculative idea is that this period may, perhaps, equate with the waning of effects of the postulated 2.705 Ga mantle plume.

All the proposed models are clearly speculative and equivocal, although some form of subduction environment appears to be required (e.g., Champion & Sheraton, 1997; Morris & Witt, 1997; Nelson, 1997b). This is also consistent with the presence of sanukitoid-like High-LILE Mafic magmatism at this time. The recent recognition of syenitic magmatism around 2665 Ma, within the LLT (e.g., Black et al., 2002), and to the north (Nelson, 1999), however, must reflect some form of rifting and/or local extension, or perhaps slab break-up. The association of this magmatism, therefore, with voluminous High-Ca, and common sanukitoid-like Mafic magmatism suggests a behind-arc or perhaps back-arc environment at this time (Fig. 10c). The simplest model for the Low-Ca granites, is generation from moderately dry tonalitic (or more felsic) pre-existing crust in an extensional environment with an elevated geothermal gradient. This is clearly contrary to the general scenario for the High-Ca granites, indicating not only distinct source rocks, but distinct sites of granite generation for the two granite types, as also indicated by the Sm-Nd isotopic data (Champion & Sheraton, 1997). These differences are even more significant when the age distributions of the two granites groups are taken into consideration, i.e., the observed change from voluminous dominantly High-Ca magmatism to less voluminous, but very widespread, dominantly Low-Ca magmatism, around 2655 Ma. This changeover in magmatism clearly suggests some significant change in tectonic environment or style around this time, and may indicate a change from an arc-related environment to one dominated by extension or post-tectonic relaxation, i.e., some mechanism produced a change in the thermal regime, that not only increased the thermal gradient (to allow generation of Low-Ca granites) but effectively turned off production of High-Ca granites (Figs 10c,d). This change is also consistent with the recent data of Krapez et al. (2000) which shows that the late basin formation (e.g., Kurrawang, Jones Creek) post dates 2661 Ma, and hence, major deformation, or at least one phase of such (see Cassidy et al., this volume), was younger again. In the model advanced here, this would place (one phase? of) compressive deformation (= D_2) at ca 2660-2650 Ma, younger than previously suggested but not as young as that interpreted by Krapez et al. (2000).

The exact nature of this tectonic transition is largely dependent on the origin of the High-Ca granites, which as described earlier, is not straight-forward. If the High-Ca granites were generated by partial melting in thickened crust, then melting shifted to higher crustal-levels (the site of Low-Ca generation), with the thickened lower crust (High-Ca source) either somehow insulated from further melting or, more likely, given the seismic evidence (e.g., Drummond et al., 1993), removed. In this regard, Smithies & Champion (1999) suggested that this ca 2655 Ma thermal event may have resulted from lower-crustal delamination following crustal thickening during the main D_2 shortening deformation. These authors further speculated that this event represented an additional tectonothermal event in the eastern Yilgarn Craton, contemporaneous with lower-middle crustal high-grade metamorphism and regional Au mineralisation (e.g., Kent et al. 1996). If, however, the High-Ca granites were largely generated by slab-melting, then the change over to Low-Ca (and syenitic) magmatism may simply reflect some form of wide-scale extension, perhaps not unlike that presently operating in the Basin and Range province in the western United States, although with some differences, e.g., apparent lack of contemporaneous felsic volcanism.

The isotopic data for the crustal-derived Low-Ca granites indicate the presence of old continental crust in the Southern Cross Province, and progressively younger crust to the east. The transition across the region is either gradational (i.e., a number of discrete crustal blocks = terranes or perhaps lateral crustal growth by roll back), or, perhaps, a mixture of 2 end-members. The geochemistry of the Low-Ca source rocks and, hence the crustal blocks, is most probably similar to typical TTG suites found in other Archaean terranes; the LLT crust, therefore, as sampled by the Low-Ca granites, may have been produced by arc-related lateral growth (3.1 Ga and younger), and/or amalgamation of a number of smaller plates (before 2.66), prior to reworking (at 2.655 to 2.63 Ga) to produce the Low-Ca group granites. On the other hand, the volumetrically dominant granites of the High-Ca group appear to have derived by partial-melting of a largely mafic source at high pressures, either by a single stage, (e.g., slab-melting), or two-stage process, (e.g., thickened mafic crust; Champion & Sheraton, 1997). The timing of this crustal growth is model dependent and may have occurred at any time from several hundred million years earlier, up to the time of formation of the High-Ca group (2.69 - 2.64 Ga), although it is noted that the geochemical, inherited zircon and some of the Sm-Nd isotopic data, requires some input from pre-existing continental crust. Indeed, Cassidy et al. (this volume) have suggested that the period between 2.81-2.77 Ga was the major crust forming event in the EGP, with the younger sequences, including felsic-intermediate and mafic-ultramafic volcanism, superimposed on this substrate.

As indicated by Champion (1997) and Smithies and Champion (1999), alkaline and sub-alkaline rocks such as those in the Syenitic group are good indicators of regions undergoing, at least local, extension, or an anorogenic (post-tectonic) environment. The timing and locations, therefore, of members of the Syenitic group provide some constraints on the tectonic evolution of the EGP. In this sense, the 2650 to 2640 Ma syenites, reinforce the inferences deduced from the Low-Ca magmatism, i.e., there is a significant change in tectonic environment in the period 2660 to 2655 Ma, from voluminous, possibly arc-related, High-Ca magmatism, to ‘post-tectonic’, or extensional, Low-Ca and Syenitic magmatism (Figs 10c, d).

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Geochronological constraints on the Leonora-Laverton transect area, north eastern Yilgarn Craton

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Introduction

The Leonora-Laverton transect area is an important metallogenic region within the north eastern Yilgarn Craton and contains a variety of mineral systems, including orogenic Au, magmatic Cu-Ni-sulfide and lateritic Ni-Co, VHMS Cu-Zn and possibly intrusion-related Mo-Au mineralisation. In recent years, the region has been the centre of mineral exploration that has led to the discovery of several major gold deposits (Sunrise-Cleo, Wallaby, Thunderbox) and development of the 'world-class' Murrin Murrin lateritic Ni deposit.

The transect area has been the subject of geological and geophysical studies by Geoscience Australia and the Geological Survey of Western Australia over the past 10 years or so, primarily geological mapping (1:100,000 and 1:250,000 outcrop and solid geology: see Painter et al., in press, for details), acquisition of regional aeromagnetic and gravity datasets, and the recent acquisition of a deep seismic reflection profile (Jones et al., this volume). The development of a three-dimensional model for the region (Blewett et al., this volume) is the culmination of these studies, and has important implications for geodynamic models for the eastern Yilgarn and models for development of the various mineral systems.

In addition to the studies outlined above, a major component has been the acquisition of SHRIMP U–Pb geochronological data on a variety of lithologies throughout the region (Fletcher et al., 2001; Black et al., 2002; Dunphy et al., in prep). Much of this new data is the product of a Geoscience Australia-Curtin University of Technology collaborative research agreement that has resulted in over 50 new age determinations in the eastern Yilgarn Craton, primarily in the transect area. The combination of these new and existing data has provided improved age constraints, and permitted the development of an improved geological framework for the region.

This report summarises available geochronological constraints for the transect area. The data confirm the inferred stratigraphic relations of Hallberg (1985) that suggest that the supracrustal sequences that form the bulk of the greenstone belts between Leonora and Laverton are as old as, or older than, the Kambalda mafic-ultramafic stratigraphy, suggesting that this region has a different depositional history to that in the Kalgoorlie Terrane. Much of the new geochronological data are for granitoids and gneiss that form >60% by area of the transect region (Fig.1). The data clearly demonstrate a felsic magmatic event throughout the transect area prior to ENE-WSW-directed thrusting and folding, with emplacement of some granitoids after this major deformation event. There is also evidence, in several places (e.g., Twin Hills, Mt Dennis), for early granitoid-gneiss that may be basement to the greenstone sequences.

Geochronological constraints across the transect area

The transect area predominantly covers the Eastern Goldfields Province (EGP), but also incorporates granitoids and the easternmost greenstone belts of the Southern Cross Province (SCP). The boundary of the EGP with the SCP is inferred to correspond to the Ida Shear in the Ballard-Mount Mason region and the Waroonga Shear in the Agnew region. Between these regions the boundary is ambiguous, but it is inferred to traverse north-south through a zone now largely obscured by later granitoids (Whitaker, this volume). Alternatively, the boundary may pass through greenstones in the western limb of the Kurrajong Anticline and then north-northwest through a zone occupied by sparsely exposed granitoids (S. Wyche, pers. comm. 2002).

The transect area has been divided into a number of litho-structural ‘sectors’ and ‘tectonic zones’ (Gower, 1976; Hallberg, 1985) and ‘greenstone belts’ (Hallberg, 1985; Griffin, 1990; Painter et al., in press; Groenewald, this volume). The subdivision of Hallberg (1985) recognised coherent sectors of granitoid-greenstone terrain separated by zones of structural discontinuity from a few kilometres to over 60 km in width marked by ductile deformation, alkaline magmatism and late siliciclastc sedimentary basins. The geochronological data are discussed from west to east using a number of ‘domains’ (Fig. 1) that largely overlap with the subdivisions of Hallberg (1985) and Painter et al. (in press). The major difference between the domains used in this report and the greenstone belts of Painter et al. (in press), is that we combine the Malcolm greenstone belt and Kilkenny tectonic zone to form the Malcolm domain, combine the Murrin greenstone belt and Celia tectonic zone to form the Murrin domain and subdivide the Laverton greenstone belt into the Laverton and Merolia domains. The Murrin domain and most of the Laverton domain form the Murrin-Margaret sector of Hallberg (1985).

The domains are bounded by major faults and shear zones (Whitaker et al., this volume). Most of these deep-penetrating structures are high-strain zones that trend north-northwest. As discussed by Blewett et al. (this volume), the domain-bounding structures may separate different lithostratigraphic packages and/or may have been initiated as basin-bounding faults with a prolonged history (Hallberg, 1985).

The studies of Fletcher et al. (2001), Black et al. (2002) and Dunphy et al. (in prep.) have resulted in a significant increase in available geochronology for the transect area. In combination with existing data (Pidgeon & Wilde, 1990; Hill et al., 1992; Nelson, 1995, 1996, 1997a, 1998, 2000, 2002; Fletcher et al., 1998; Ojala et al., 1997, Barley et al., 1998; Brown et al., 2002), there are now SHRIMP U–Pb zircon geochronological data for over 60 samples in the transect area (Figs 1-3). The majority of these are for granitoids and gneiss, with data available for 13 supracrustal samples. Discussion of the geochronological constraints on the granitoids uses the granitoid classification scheme of Champion & Sheraton (1997) and Champion & Cassidy (this volume).

SCP domain

The SCP domain is dominated by granitoids and gneisses, but also includes the small Illaara and Mount Ida greenstone belts (Painter et al., in press). There are very few constraints on the ages of the greenstone successions in this domain (Fig. 1). An age of 3304 ± 8 Ma for a metasandstone unit from the Illaara greenstone belt (Nelson, 2000) provides a maximum depositional age for the lower part of this greenstone belt. This is similar to the age of metasandstone and quartzite units in other thin greenstone belts along the eastern edge of the SCP (Nelson, 2000; Riganti et al., 2002).

The Mount Ida greenstone belt, as recognised by Griffin (1990), comprises an eastern and a western segment. The eastern segment contains mafic to ultramafic volcanic and intrusive rocks and is interpreted by Groenewald et al. (2000) to form part of the Kalgoorlie greenstones as defined by Swager (1997) and Krapez et al. (2000). The western part is dominated by tholeiitic

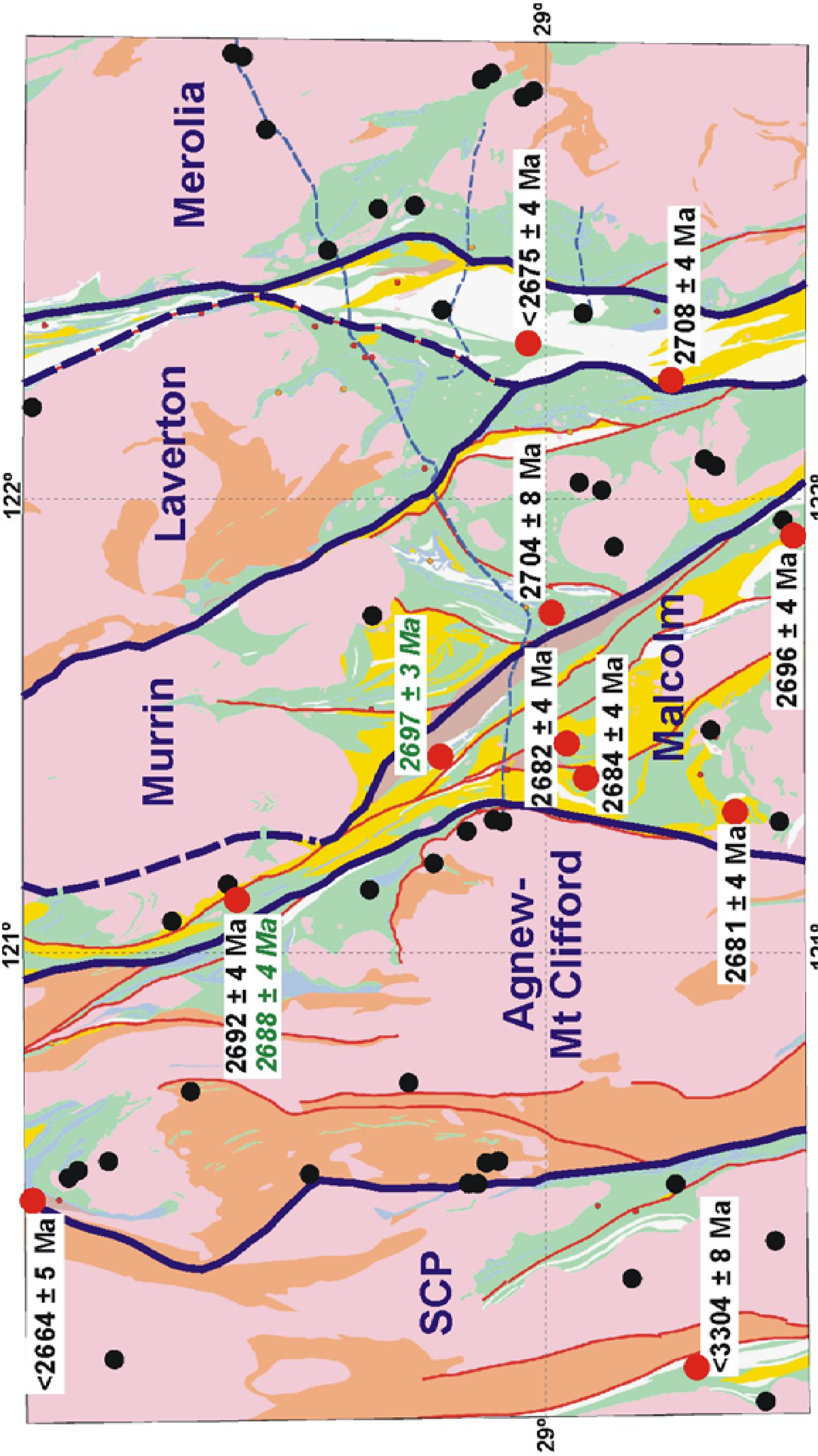

Figure 1 Geochronological constraints on supracrustal rocks (red circles) in the Leonora-Laverton transect area. Domain names and boundaries are also shown

basalt with banded-iron formation (BIF) units and is thought to form part of the SCP (Wyche, 1999). A quartz-feldspar porphyry dyke in the eastern part of the belt has an age of 2700 ± 9 Ma (Nelson, 2002) and provides a minimum depositional age for the greenstone succession.

Geochronological data have been obtained for a number of High-Ca and Low-Ca granitoids in this domain (Figs 2-3). High-Ca granitoids have SHRIMP U–Pb zircon ages of 2693 ± 5 for a foliated monzogranite xenolith in a monzogranite pluton (Black et al., 2002) and 2676 ± 5 Ma for the Day Rock granodiorite (Nelson, 2000). In contrast, Low-Ca granitoids are considerably younger with ages of 2653 ± 3 (Wallaby Knob monzogranite) and 2633 ± 2 Ma (Walling Rock monzogranite) (Black et al., 2002). The range of ages for the High-Ca and Low-Ca granitoids is consistent with the range for granitoids in other parts of the SCP (Qiu et al., 1999; Nelson, 2000, 2001).

Agnew-Mt Clifford domain

The Agnew-Mt Clifford domain (Fig. 1) incorporates the Agnew and Mt Clifford greenstone belts (Griffin, 1990; Painter et al., in press). It is bounded on the west by the Waroonga–Ballard shear zone, a mostly north-south striking zone of heterogeneously deformed granitoids, and on the east by the Moriaty–Mount George shear zones (Fig. 1). The domain contains a number of large gold deposits (Emu-Redeemer, Lawlers, Tarmoola, Sons of Gwalia, Bannockburn) as well as a several magmatic Ni (Marriots Prospect, Weebo Bore) and lateritic Ni (Marshall Pool) prospects.

There are no constraints on the age of the greenstone sequences in either the Agnew or Mt Clifford greenstone belts in the Leonora-Laverton transect area, except for minimum ages based on cross-cutting granitoids and the maximum depositional age of the Scotty Creek conglomerate along the western margin of the Agnew greenstone belt. The greenstone sequences in both belts comprise mafic and ultramafic volcanic and intrusive rocks and metasedimentary units (e.g., Vivien metasedimentary sequence in Agnew greenstone belt). These sequences are inferred to be the equivalent of greenstone sequence in the Kalgoorlie region. The ultramafic volcanic and intrusive units at Marshall Pool and Mt Clifford are interpreted to be the time equivalent to Kambalda ultramafic sequence, as well as the mafic-ultramafic sequence at Perseverance and Mt Keith, north of the transect area. A metasandstone unit of the Scotty Creek conglomerate contains a zircon population with a statistically grouped age of 2664 ± 5 Ma (Dunphy et al., in prep), and this is inferred to be the maximum depositional age for the conglomerate. This is similar to the age of metasandstone units in the Jones Creek conglomerate to the north of the transect area (Nelson, 2000; Krapez et al., 2000).

There are a large number of geochronological constraints on granitoids and gneiss in the Agnew-Mt Clifford domain (Figs 2-3). These range from granitic gneisses with ages of ca. 2800 Ma to late mozogranites with ages of ca. 2650 Ma (Fig. 2). Many of these samples are from the multiply deformed granitic gneiss belt along the western edge of the domain, and were sampled to provide geochronological constraints for the various phases in the granitoid complexes. Highly deformed and gneissic High-Ca granitoids have a range of ages from 2687 ± 7 to >2652 ± 8 Ma. Late Low-Ca granitoids have SHRIMP U-B zircon ages of ca. 2650 Ma. In the majority of the High-Ca granitoids, there is a distinct zircon population with an age of ca. 2810–2800 Ma that is interpreted to represent zircon inheritance. At Twin Hills, north of Menzies, a crystallisation age of 2803 ± 8 Ma has been obtained for a High-Ca granitic gneiss (Dunphy et al., in prep), with no indication that the zircon population represents inheritance from a protolith to the gneiss.

The Raeside granitoid complex contains a number of High-Ca granitoids that range in age from 2760 ± 10 Ma for a deformed monzogranite at the Trump deposit (Black et al., 2002), through an undeformed monzogranite at Tower Hill that has an age of 2753 ± 6 Ma (Fletcher et al., 2001), to 2669 ± 7 Ma for the Auckland monzogranite (Black et al., 2002). Variably deformed monzogranite and granodiorite porphyry dykes truncate the greenstone stratigraphy around the

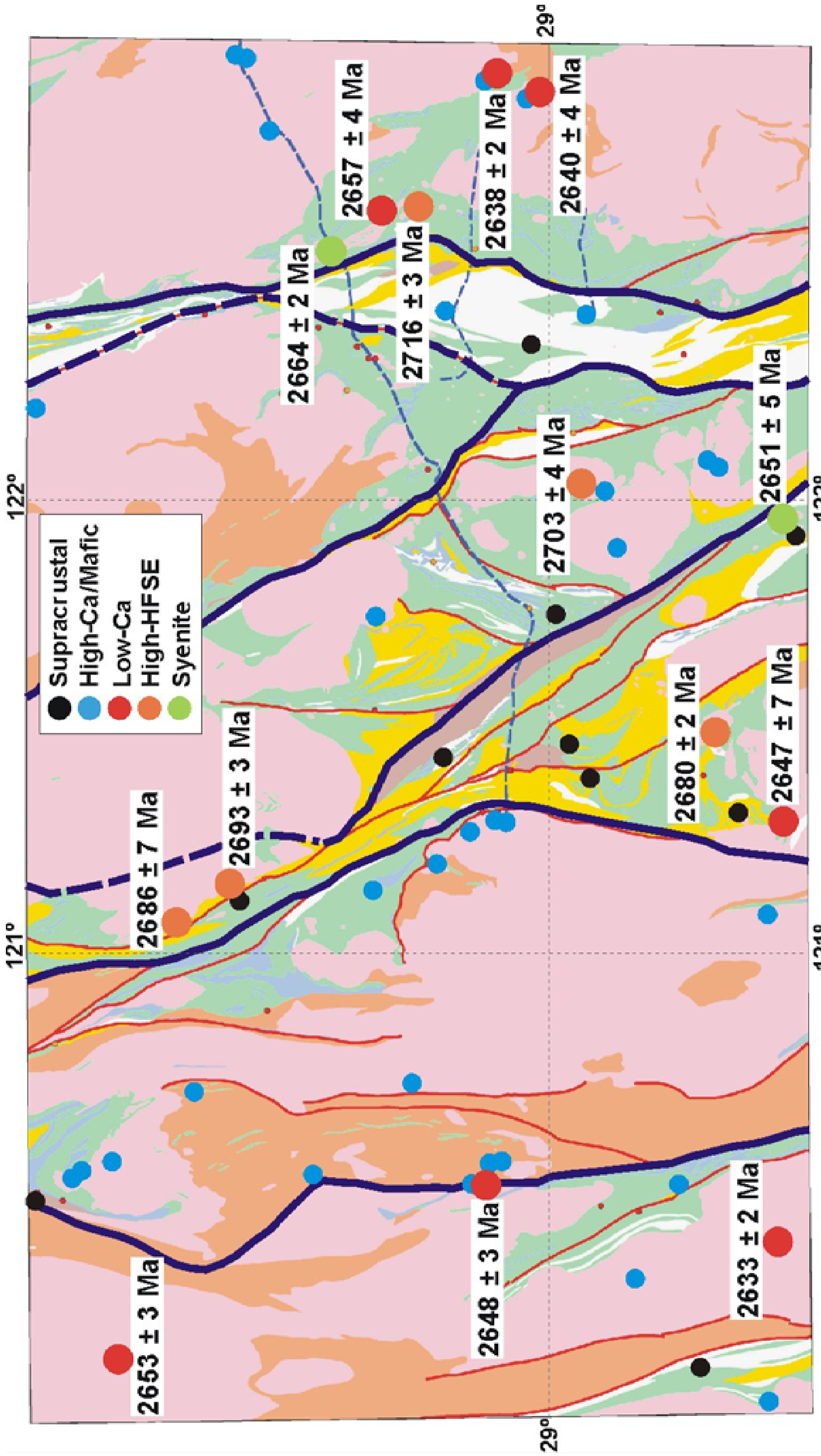

Figure 2 Geochronological constraints on Low-Ca-, High-HFSE and Syenitic granitoids in the Leonora-Laverton transect area. Data sources are listed in the text

Raeside granitoid complex (2670 ± 5 Ma – Tower Hill porphyry dyke: Dunphy et al., in prep; 2677 ± 8 Ma – Tarmoola Mine porphyry dyke: Fletcher et al., 2001). The ca. 2.81–2.76 Ga ages for granitic gneisses in the Agnew-Mt Clifford domain confirms the existence of an older granitic 'basement' for the EGP, as postulated by Archibald et al. (1981).

The Lawlers Tonalite, host to gold mineralisation at the Great Eastern deposit and a member of the Mafic granitoid group, has an age of 2666 ± 3 Ma (Fletcher et al., 1998). Monzogranite dykes and leucogranite that cross-cut the tonalite have an age of 2666 ± 7 Ma (Fletcher et al., 1998). The tonalite contains a sub-horizontal fabric in the upper 30 metres or so of the preserved intrusion. Eisenlohr (1989) and Partington (1987) interpreted the fabric to be related to emplacement of the Lawlers Tonalite and suggested that its emplacement post-dated the regional folding event. In contrast, Platt et al. (1978) suggested that the tonalite was emplaced prior to regional folding. Hammond & Nesbitt (1992) used the area southeast of Lawlers to demonstrate preservation of early deformation fabrics supporting the interpretation of Platt and others.

The Tower Hill, Harbour Lights, and Sons of Gwalia gold deposits in the Leonora district are the subject of renewed interest since relative structural timing evidence and radiometric dating of Mo ± Au-bearing veins suggest an early timing for gold deposition (Witt, 2001; Witt et al., 2001), as well as a possible genetic link with felsic magmatism (Witt, 2001). The Leonora gold deposits are located proximal to the eastern margin of the Raeside granitoid complex and are hosted by the deformed granitoids and adjacent ultramafic schist. Molybdenum ± Au-bearing quartz veins are located subparallel to an intensely developed regional foliation in ultramafic schist oriented parallel to the granitoid contact and are significantly folded, boudinaged, and offset by numerous post-mineralisation deformation events (Witt et al., 2001).

The deformed greenstone sequence at Leonora is inferred to be older than the age interpreted for greentones in the rest of the domain on the basis of Re–Os ages of molybdenite at Tower Hill (Witt et al., 2001). Quartz veins hosting Mo ± Au mineralization have a Re–Os age of ca. 2755 Ma at Tower Hill (Witt et al., 2001), which coincides with phases of felsic magmatism in the Raeside granitoid complex (Fletcher et al., 2001; Black et al., 2002). Early deformational episodes are preserved in the Leonora district, and not preserved elsewhere in the domain (Hammond & Nesbit, 1992; Williams & Whitaker, 1993; Witt, 2001). There are no independent geochronological data, however, on the greenstone sequences or deformation episodes in the Leonora district to demonstrate that they are indeed older than the elsewhere in the domain. Additional studies are required to determine the depositional ages of the greenstones throughout the domain and to determine if a thin belt of older greenstone has been preserved around the Raeside granitoid complex.

Malcolm domain

The Malcolm domain (Fig. 1) corresponds with the Malcolm greenstone belt of Griffin (1990), Painter et al. (in press) and Groenewald (this volume). The domain largely corresponds to the Keith-Kilkenny Tectonic Zone of Hallberg (1985), and the northern part of the Gindalbie terrane (Swager, 1997). The domain is bounded on the west by the Moriaty–Mount George shear zones and on the east by the Kilkenny shear zone. These boundaries differ from those of Painter et al. (in press), who include the Kilkenny Tectonic Zone in the Murrin greenstone belt, whereas this zone is included in the Malcolm domain in this report. Whitaker et al. (this volume) divided the domain along the Melita-Emu fault into east and west sub-domains. The Malcolm domain is also host to the Teutonic Bore VHMS base-metal deposit and is the site of active exploration for further base-metal mineralisation. Several small gold deposits are centred around Kookynie and Niagara in the southern part of the domain.

The greenstone successions in the Malcolm domain are host to three significant bimodal and felsic subalkaline volcanic complexes known as the Jeedamya, Melita and Teutonic Bore complexes (Hallberg, 1985; Witt, 1994; Brown et al., 2002). These volcanic successions are

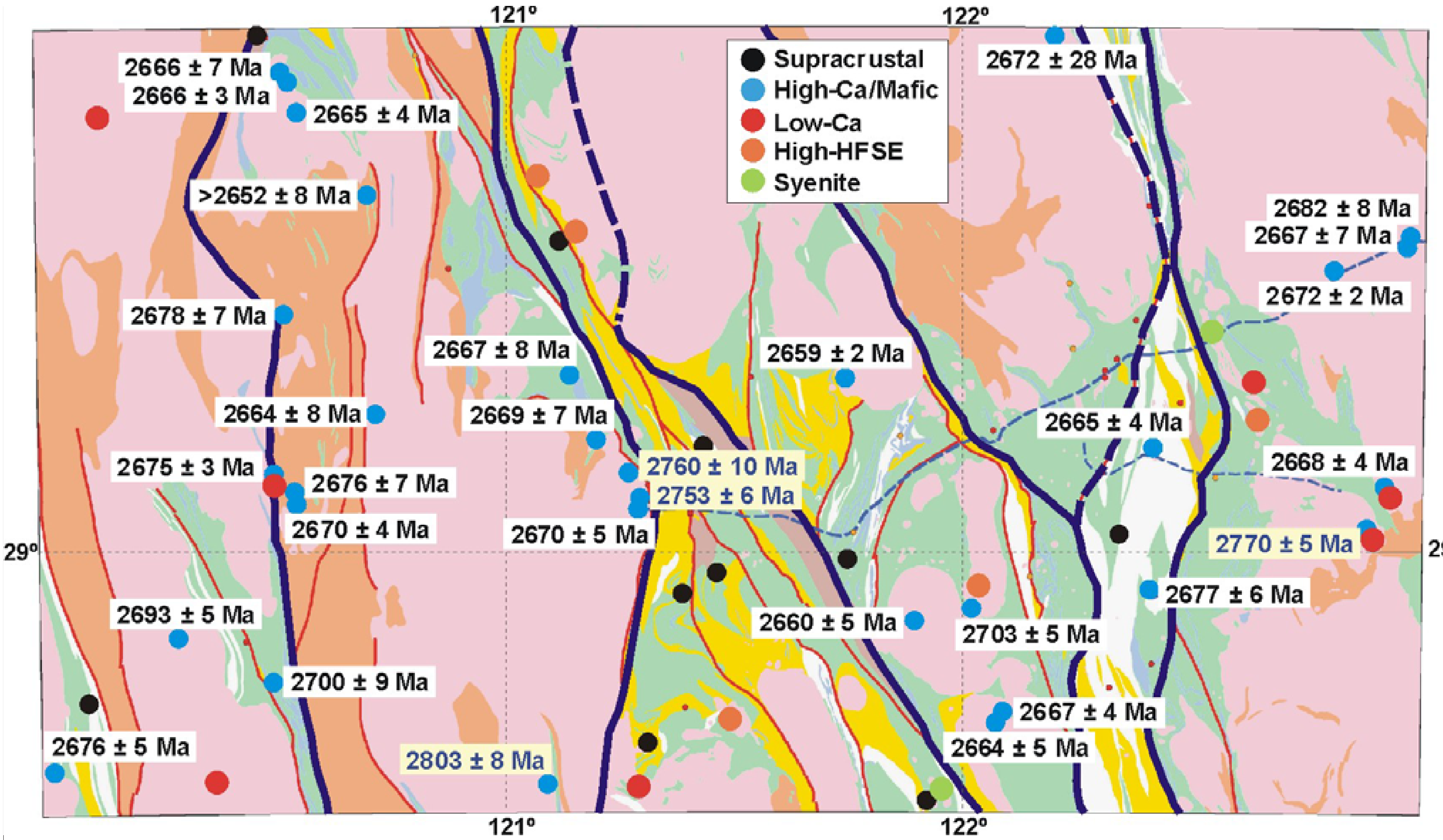

Figure 3 **Geochronological constraints on High-Ca and Mafic granitoids in the Leonora-Laverton transect area. Data sources are listed in the text**

thought to unconformably overlie calc-alkaline andesites and tholeiitic basalts in the Leonora-Laverton area, although the relationship between these two rock associations is unclear (Hallberg, 1985; Rattenbury 1993; Barley et al., 1998; Brown et al., 2002). Lithologies in the eastern part of the domain are similar to those in the adjacent Murrin domain (Association 2 of Hallberg, 1985), whereas the central and western parts are dominated by the bimodal rhyolite-basalt sequences that have not been recognised in other domains in the transect area (Hallberg, 1985). Calc-alkaline intermediate rocks locally form basement (at Teutonic Bore: Hallberg, 1985) to and, hence, probably predate the bimodal volcanic sequences.

There are very good geochronological constraints for the bimodal and felsic subalkaline volcanic complexes in the Malcolm domain (Fig. 1). The oldest felsic volcanic rocks are from the eastern side of the domain and include a SHRIMP U–Pb zircon age of 2696 ± 4 Ma for a felsic volcanogenic sedimentary unit south of the McAuliffe Syenite (Nelson, 1998) and a conventional U–Pb zircon age of 2697 ± 3 Ma for felsic volcanic rocks from near Pig Well (Pidgeon & Wilde, 1990). The Teutonic Bore volcanic complex consists of bimodal rhyolite-basalt volcanism and associated sedimentary successions and has a SHRIMP U–Pb zircon age of 2692 ± 4 Ma (Nelson, 1995) and a conventional U–Pb zircon age of 2688 ± 4 Ma (Pidgeon & Wilde, 1990). The Melita complex is younger and three samples of rhyolite record ages within error of each other (porphyritic rhyolite lava samples have ages of 2682 ± 4 Ma and 2682 ± 4 Ma, spherulitic rhyolite syn-volcanic sill sample has an age of 2684 ± 4 Ma: Brown et al., 2002), and yield a combined weighted mean age of 2682.8 ± 2.4 Ma (Brown et al., 2002). This age is within error of an age of 2681 ± 4 Ma obtained for the Jeedamya rhyolite complex to the south of Melita (Nelson, 1996).

The Pig Well graben (Hallberg, 1985) consists of fine to coarse-grained siliciclastic units that overlie, or are in faulted contact with, other rocks of the Malcolm domain and the adjacent Murrin domain. The graben forms a linear belt along the eastern side of the Malcolm domain that extends southward and probably incorporates the Yilgangi conglomerate. A monzodiorite dyke that intrudes the Yilgangi conglomerate has a SHRIMP U–Pb zircon age of 2662 ± 5 Ma (Nelson, 1996), and provides a minimum age for the siliciclastic unit.

Sub-volcanic granitoids to the bimodal rhyolite-basalt volcanic complexes at Teutonic Bore and Jeedamya have identical ages to volcanic rocks (Fletcher et al., 2001; Black et al., 2002). These granitoids belong to the High-HFSE group of Champion & Cassidy (this volume) and include the Kent syenogranite (2686 ± 7 Ma: Black et al., 2002) and the Alicia syenogranite (2693 ± 3 Ma: Fletcher et al., 2001) near Teutonic Bore, and the Diary monzogranite (2680 ± 2 Ma: Black et al., 2002) near Kookynie (Fig. 2).

The southern part of the domain also contains a number of late granitoids. These include several Low-Ca granitoids, including the Galah Monzogranite, that has an age of 2647 ± 7 Ma (Dunphy et al., in prep), and Carpet Snake Syenogranite (Witt & Davy, 1997) and several other similar granitoids immediately south of the transect area (e.g., Balarky monzogranite). The McAuliffe Well Syenite (2651 ± 5 Ma: Nelson, 1997a) intrudes the greenstone sequence at the southern end of the transect area and is typical of several Syenitic group granitoids in that district (Smithies & Champion, 1999).

Murrin domain

The Murrin domain (Fig. 1) corresponds with the Murrin greenstone belt of Griffin (1990) and includes the Murrin greenstone belt and part of the Celic tectonic zone of Painter et al. (in press). The Murrin domain is bounded by the Kilkenny shear zone on the west and the Celia shear zone on the east and is divided along the Murrin fault into north and south subdomains by Whitaker et al. (this volume). The domain forms the eastern half of the Kurnalpi terrane as defined by Swager (1997). The Celia shear zone joins the Ninnis Fault north and the Claypan shear zone to the south of the transect area. The domain is unusual in that it is intruded by several ovoid to elongate granitoids of various sizes, including the magnetically-zoned Bulla Rocks Monzogranite and Monument monzogranite. A large granitoid-gneiss complex forms most of the northern part of the domain. The world-class Murrin Murrin lateritic Ni-Co deposit and Eucalyptus lateritic Ni-Co prospect are in the Murrin domain, as are minor gold mineralisation at Mertondale and Yundamindera and sedimentary-hosted base-metal mineralisation at Anaconda and Nangaroo.

The regional stratigraphy in the Murrin domain comprises Association 2 of Hallberg (1985) that consists largely of mafic to ultramafic volcanic and intrusive rocks with significant proportions of intermediate volcanic and associated volcaniclastic rocks and lesser felsic volcanic, volcaniclastic and sedimentary units (Hallberg, 1985; Painter et al., in press). Intermediate volcanism is best preserved in the Welcome Well complex, which is dominated by felsic volcaniclastic rocks with subordinate intermediate (andesite) and mafic (tholeiite) volcanic rocks and intruded by dolerite (Giles & Hallberg, 1982; Hallberg, 1985; Brown et al., 2001). There are no age constraints, however, for this volcanic complex.

The Anaconda, Nangaroo and Rio Tinto Cu-Zn deposits are associated with sedimentary rocks of Association 2 (Hallberg, 1985). The Anaconda and Nangaroo mines occur in the same stratigraphic unit on opposite limbs of the Kilkenny syncline; the Rio Tinto deposit lies in a stratigraphically higher unit in the western limb of the Rio Tinto syncline. All three deposits are found within sequences of pyritic-feldspathic graywacke, siltstone and shale, overlain by a sedimentary breccia of variable thickness, with stratabound lenses of massive sulfide within the sedimentary breccia unit. Sediment units are considered to represent a distal, subaqueous facies equivalent to alluvial fan deposits surrounding the Welcome Well andesitic volcanic complex to the north (Hallberg, 1985).

Association 2 contains a number of high-Mg basalt and ultramafic cumulate units, principally in the Kilkenny syncline and adjacent areas and in the western limb of the Eucalyptus anticline. It forms the youngest regionally-defined unit in the domain, and overlies much of the intermediate and felsic volcanic succession (Hallberg, 1985). The ultramafic cumulates are interpreted to be komatiitic in origin and their regolith is host to the Murrin Murrin lateritic Ni-Co deposit (Hill et al., 2001). The best geochronological constraint for this unit is for a prominent quartz-albite unit, locally referred to as a "chert", which forms a laterally continuous horizon around Mount Kilkenny (Fig. 1). The chert lies within a sequence of high-Mg basalts that underlie the Kilkenny layered sill. A revised SHRIMP U–Pb zircon age of 2704 ± 8 Ma has been obtained for the unit (Fig. 4; revision of J.C. Claoué-Long, unpublished data). The simple igneous morphologies with no sign of sedimentary abrasion and a single, predominantly concordant, age cluster are consistent with the interpretation that the chert represents an airfall ash unit within the basalt sequence or the zircons are from an airfall contribution to an interflow sedimentary unit. The unit, therefore, provides a good constraint on the timing of the high-Mg basalt and komatiite units that overlie much of Association 2, and indicate that this mafic-ultramafic sequence is the time equivalent to the mafic-ultramafic sequence at Kambalda and elsewhere in the Kalgoorlie Terrane (Fig. 5; Nelson, 1997b).

The greenstone succession is intruded by a variety of granitoid types (Figs 2-3), including the large Danjo Monzogranite, that belongs to the High-HFSE group of Champion & Sheraton (1997), and rhyolites associated with the bimodal volcanic complexes in the Malcolm domain. The Danjo Monzogranite has a SHRIMP U–Pb zircon age of 2703 ± 4 Ma (Fletcher et al., 2001). On the southern edge of this granitoid, the Maori Queen Tonalite has an age of 2703 ± 5 Ma (Fletcher et al., 2001). The Maori Queen Tonalite is part of the Mafic granitoid group and has geochemistry similar to some of the intermediate volcanic rocks to the southeast at Bore Well. The Danjo Monzogranite and Maori Queen Tonalite may represent sub-volcanic equivalents of Association 2 intermediate and felsic volcanic and volcaniclastic rocks that under- and over-lie the mafic-ultramafic volcanic sequence and may potentially provide an age of this volcanism

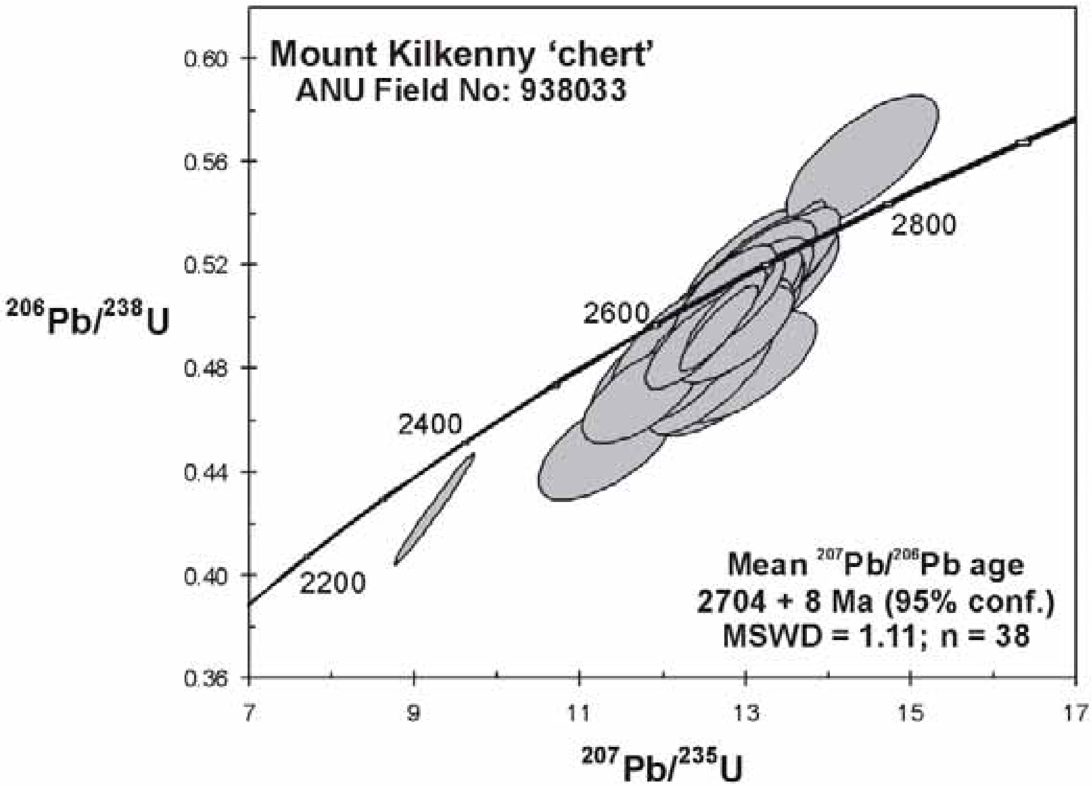

Figure 4 Concordia plot for zircon data from sample ANU Field no 938033: Mount Kilkenny ‘chert’ horizon within basalt stratigraphy underlying Kilkenny layered sill, Murrin domain, Leonora-Laverton transect area (Revision of J.C. Claoué-Long unpublished data)

in the Murrin domain. If this interpretation is correct, the age of intermediate-felsic volcanism is remarkably similar to that of the high-Mg volcanic sequence. A similar complex inter-relationship between felsic and ultramafic magmatism is present in the Boorara domain (Trofimovs et al., 2001), to the south of the transect area.

Several High-Ca granitoids intrude the Murrin domain greenstones, including foliated granodiorites and monzogranites and magnetically-zoned granitoids (Fig. 3). A foliated granodiorite of the Pindinnis granite has an age of 2664 ± 5 Ma (Fletcher et al., 2001). A number of monzogranite dykes intrude the Pindinnis granite at a high angle to the foliation in the host granitoid and do not contain the prominent foliation. One of these dykes northwest of Marloo Well Dykes contains a zircon population with an age of 2667 ± 4 Ma (Fletcher et al., 2001), within error of the age of the host Pindinnis granite. If this age dates the crystallisation of the dyke, it may also provide a maximum age for the foliation in the host granitoid and indicate that host granitoid emplacement, foliation development and dyke emplacement were closely spaced in time. The age of the Pindinnis granite is similar to that for other High-Ca granitoids in other domains, suggesting that the maximum age of this contractional event is likely to be ca. 2665 Ma.

Two magnetically-zoned, High-Ca granitoids intrude the greenstone succession. The Monument Monzogranite has an age of 2659 ± 2 Ma (Fletcher et al., 2001) and the Bulla Rocks Monzogranite has an age of 2660 ± 5 Ma (Black et al., 2002). Both granitoids truncate greenstone sequences that have been folded by the regional ENE-WSW-directed contractional event

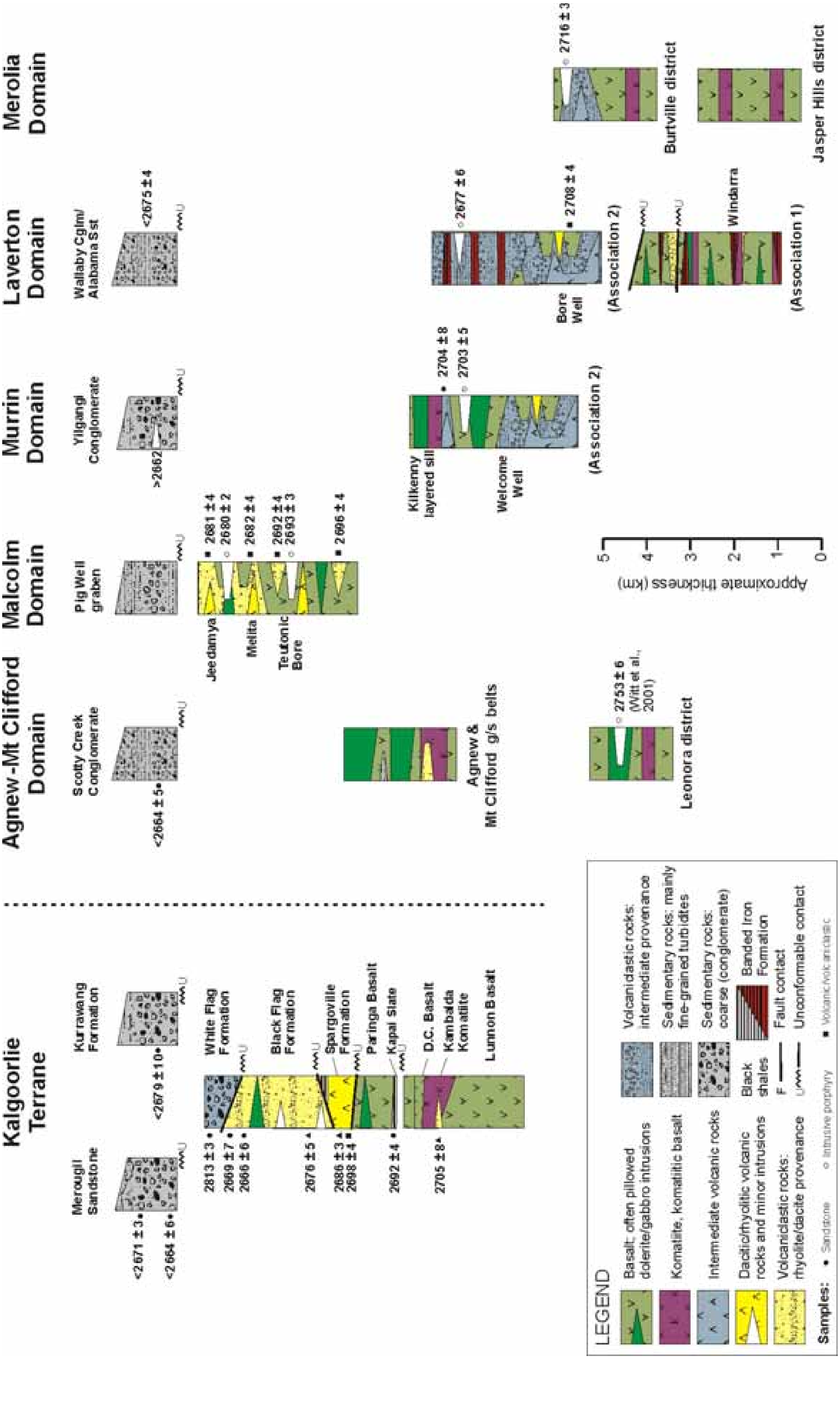

Figure 5 **Simplified stratigraphic relationships in the Leonora-Laverton transect area, and possible stratigraphic relationship with Kalgoorlie Terrane. Geochronological data sources are listed in the text. Modified from Hallberg (1985), Swager (1995), Barley et al. (1998), Krapez et al. (2000), Brown et al. (2001)**

(Whitaker et al., this volume) suggesting that much of this deformation, at least in the Murrin domain, was prior to emplacement of these "late" granitoids. The Bulla Rocks Monzogranite also appears to truncate the Pig Well graben, thereby providing a minimum age for its formation.

Laverton domain

The Laverton domain (Fig.1) is similar to the Margaret greenstone belt of Griffin (1990). The Celia shear zone bounds the domain on the western side, whereas the eastern boundary with the Merolia domain is poorly defined, with the boundary represented by portions of the Cutline and Harold-Pinjin shear zones of Painter et al. (in press). To the north the Laverton domain is equivalent to the Laverton terrane (Myers, 1997) and to the south it corresponds with the Edjudina terrane of Swager (1997). Whitaker et al. (this volume) divided the Laverton domain along the Laverton fault into north and south sub-domains. The domain is highly endowed in gold, with world-class deposits at Sunrise-Cleo and Wallaby and significant gold mineralisation at Lancefield, Whisper-Innuendo, Barnicoat, Granny Smith, Keringal and Red October. The domain also hosts magmatic Cu-Ni sulfide mineralisation at Windarra and South Windarra. The large, Ta-Nb-REE-mineralised, Proterozoic Mt Weld carbonatite complex intrudes close to the eastern boundary of the domain.

The domain can be divided into two sub-domains that approximate the surface position of Hallberg's (1985) Association 1 and Association 2. Association 1 is interpreted to represent a lower lithostratigraphic sequence (Fig. 5), in particular around the Margaret anticline. This region corresponds to the North Laverton sub-domain of Whitaker et al. (this volume). Association 1 comprises a thick mafic-ultramafic volcanic succession with several BIF units. The lower-most part of the stratigraphy is preserved around the Margaret Anticline at Mount Windarra and South Windarra. The magmatic Cu-Ni sulfide mineralisation at Mount Windarra and South Windarra lie at the base of komatiite flows within a deformed ultramafic sequence immediately above the Windarra BIF horizon at the base of Association 1. Three overlapping mineralised komatiite flows have been recongnised at Mount Windarra (Schmulian, 1982). At present, there are no age constraints on this mafic-ultramafic succession.

Association 2 is a calc-alkaline sequence of intermediate volcanic and volcaniclastic rocks and associated rhyolite-dacite rocks, with good exposure at Bore Well and Ida Hill (Hallberg, 1985). The dominantly andesitic complexes in the Murrin and Laverton domains are interpreted to form part of the subalkaline intermediate association of Brown et al. (2001). Associated with the intermediate volcanic centres are subordinate rhyolite-dacite felsic volcanic rocks that are similar in composition to some felsic volcanic rocks (e.g., Jeedamya: Morris & Witt, 1997) associated with the bimodal rhyolite-basalt complexes in the Malcolm domain (Hallberg & Giles 1986). Age constraints on the Association 2 sequences in the Laverton domain (Figs 1, 5) are restricted to an age of 2708 ± 5 Ma for felsic volcanic rocks from Bore Well (Barley et al., 1998) and the Liberty Bore complex (2708 ± 6 Ma: Nelson, 1995) south of the transect area. It is interesting to note that south of the transect area, at Outcamp Bore and Yarri, strongly foliated tonalites have geochemical characteristics indicative of High-HFSE group granitoids and have emplacement ages of ca. 2710 Ma (Nelson, 1997; Black et al., 2002) that are consistent with the age of the andesitic volcanic complexes.

These sequences are unconformably overlain by conglomeritic and fine- to medium-grained sedimentary rocks at Wallaby, Lancefield and Mount Lucky that are interpreted by Brown et al. (2001) as equivalent to the late-stage conglomerates at Jones Creek, Yilgangi, Kurrawang and Penny Dam. Wallaby and Lancefield conglomerates contain well-rounded clasts from a variety of supracrustal and crustal sources, and Mount Lucky preserves a depositional sequence from conglomerate to sandstone to black shale (Brown et al., 2001). At present, there are no age constraints on these late-stage conglomerate units. A sample of medium-grained, graded sandstone from the Alabama prospect, in the southern part of the domain (Fig. 1), contains a complex zircon population, which has a statistically grouped maximum depositional age of 2675 ± 4 Ma (Dunphy et al., in prep). This age is younger than all other supracrustal rocks in the domain, suggests that this sandstone unit may be equivalent to the late siliciclastic sequences and, if so, indicates that they have a maximum depositional age of ca. 2675 Ma in this domain.

The large Mount Boreas granitoid complex comprising High-Ca granitic gneiss, High-Ca foliated and massive monzogranite and granodiorite, and Low-Ca monzogranites dominates the northern part of the Laverton domain. There are only limited age constraints on this granitoid complex (Fig. 3). A high-Ca biotite granite gneiss from Murphy Well, at the northern edge of the transect area, is loosely constrained to a SHRIMP U–Pb zircon age of 2672 ± 28 Ma (Black et al., 2002). However, Low-Ca (ca. 2650–2640 Ma) and High-Ca (2697 ± 6 Ma) granitoids have been dated north of the transect area on the Duketon 1:250,000 sheet (Nelson, 1997).

A number of small Mafic and Syenitic group granitoids intrude the supracrustal successions in the Laverton domain (Fig. 2) . These 'internal' granitoids and porphyry dykes are spatially associated with gold mineralisation at Beasley Creek, Granny Smith, Jubilee, Jupiter, Lancefield, Sunrise-Cleo and Wallaby. Mafic group granitoids have ages of 2665 ± 4 Ma for the Granny Smith Granodiorite (Hill et al., 1992) and 2677 ± 6 Ma for a porphyry dyke in the Sunrise-Cleo deposit (Ojala et al., 1997). There are no age constraints for Syenitic granitoids at Wallaby, Jupiter or Beasley Creek.

Merolia domain

The Merolia domain (Fig. 1) corresponds loosely to the Merolia sector of Hallberg (1985) and the Merolia greenstone belt of Griffin (1990). The southern part of the domain is equivalent to the Linden Terrane of Swager (1997). Supracrustal rocks dominate the western part of the domain, whereas granitoid complexes dominate the eastern part. Mineralisation is limited to minor gold at Burtville.

The supracrustal sequence in the Merolia domain is poorly defined, with mafic-ultramafic sequences dominant. Hallberg (1985) suggested a tentative correlation with Association 2 lithostratigraphy, at least for supracrustral sequences in the southern part of the domain. There are no age constraints on the volcanic stratigraphy in this domain (Figs 1, 5). However, a minimum age for the domain can be inferred from the ages of granitoids intrusive into supracrustal rocks, e.g., at Burtville, a granitoid intrusive into the greenstone succession has an age of 2716 ± 3 Ma (Dunphy et al., in prep). The geochemistry of the intrusion indicates that it likely belongs to the High-HFSE granitoid group, that is closely associated in space and time with rhyolitic rocks of the bimodal basalt-rhyolite association of Hallberg et al. (1993) and Brown et al. (2001).

The domain contains a number of unusual intrusions, including the large Diorite Hill layered mafic complex and the elongate, foliated Hanns Camp syenite. The Hanns Camp syenite has an age of 2664 ± 2 Ma (Black et al., 2002) and is the oldest granitoid of the Syenitic group in the EGP to date (Smithies & Champion, 1999). There is no constraint on the age of the Diorite Hill intrusion.

High-Ca granitoids and gneiss and minor Low-Ca granitoids dominate the eastern half of the Merolia domain (Figs 2-3). High-Ca granitoids have SHRIMP U-Pb zircon ages that are almost in error of one another and range from 2682 ± 8 Ma for pods of granodiorite in a deformed monzogranite at Ivor Rocks (Dunphy et al., in prep), through 2672 ± 2 Ma for a deformed monzogranite in granitic gneiss at Durang (Black et al., 2002), to 2667 ± 7 Ma for a deformed monzogranite at Ivor Rocks (Dunphy et al., in prep). An age of 2770 ± 5 Ma was obtained for a migmatite in the Mt Dennis granitoid complex (Dunphy et al., in prep), and this represents the oldest granitoid so far discovered on the eastern side of the Leonora-Laverton transect area. It is noteworthy that several granitoids in the Merolia domain contain zircon populations with ages of ca. 2780–2770 Ma that are interpreted to represent inheritance from a source similar in age to the Mt Dennis migmatite.

Several Low-Ca granitoids that intrude the High-Ca granitoids and the greenstone sequences have been age dated (Fig. 2). The Low-Ca Meredith Well monzogranite has an age of 2657 ± 4 Ma (Dunphy et al., in prep). This is similar to a late monzogranite phase in the Mt Dennis granitoid complex that has an age of 2650 ± 8 Ma (Dunphy et al., in prep). A monzogranite dyke in a granitic gneiss at Ironstone Point has an age of 2638 ± 2 Ma (Fletcher et al., 2001).

Towards a geological and metallogenic framework

The geochronological constraints can help define discrete mafic and felsic magmatic events in the Leonora-Laverton transect area as well as place absolute timing constraints on some of the major deformation events. Some of the important implications of the geochronology include:

Supracrustal sequences

- The maximum depositional age of 2704 ± 8 Ma obtained on a felsic volcaniclastic chert within the komatiitic sequence in the Murrin domain is similar to the ca. 2705 Ma ages obtained for the komatiite sequences in the Kambalda and Boorara domains of the Kalgoorlie Terrane, the Gindalbie Terrane, and the Jubilee domain of the Kurnapli Terrane south of the transect area (Fig. 5; Claoué-Long et al., 1988; Nelson, 1997b), as well as the Perseverance area north of the transect area (Nelson, 1997b). This is in accord with previous interpretations (e.g., Rattenbury, 1993) that this ultramafic sequence can potentially be used as a marker horizon across the EGP.
- Felsic and intermediate volcanism is apparent above and below the regional komatiite marker horizon (Fig. 5; Hallberg, 1985; Rattenbury, 1993). The intermediate-felsic volcanism and associated sedimentary rocks below the ultramafic marker include the thick sequences at Welcome Well in the Murrin domain, and probably the Bore Well and Ida Hill sequences in the Laverton domain. Available age constraints on these sequences (e.g., Bore Well) are in accord with this interpretation.
- Felsic volcanism and associated sedimentary rocks above the ultramafic marker are dominantly associated with the bimodal basalt-rhyolite volcanic centres, such as those in the Malcolm domain (Teutonic Bore, Melita, Spring Well: Hallberg, 1985; Rattenbury, 1993; Witt, 1994; Brown et al., 2002). These volcanic centres have ages from ca. 2690–2680 Ma (Nelson, 1997b; Brown et al., 2002). Syn-volcanic High-HFSE granitoids are spatially and temporally associated with the bimodal volcanic centres (Champion & Sheraton, 1997; Champion & Cassidy, this volume).
- The geochronological data for the felsic and intermediate volcanism and associated sedimentary rocks and subvolcanic High-HFSE granitoids indicate a decrease in ages from east to west. The ages range from ca. 2715–2710 Ma in the Merolia domain, through ca. 2710–2705 Ma in the Laverton domain and ca. 2705–2700 Ma in the Murrin domain, to ca. 2695–2680 Ma in the Malcolm domain.
- Stratigraphic correlations in the Laverton domain suggest that a mafic-ultramafic volcanic-sedimentary sequence (Association 1 of Hallberg, 1985) lies below the intermediate-felsic sequences of Association 2 (Fig. 5). This suggests that ultramafic units in Association 1 are older than the komatiitic regional marker horizon. Evidence for older greenstone sequences in the EGP are now emerging. A maximum depositional age of ca. 2860 Ma has recently been obtained for a deformed quartz pebble comglomerate unit in the Dingo Range greenstone belt north the transect area (Dunphy et al., in prep). In addition, other inferred older sequences include the ca. 2735 Ma

Kathleen Valley Gabbro (Black et al., 2002), ca. 2770 Ma intermediate dykes in the Wiluna greenstone belt (Dunphy et al., in prep), and ca. 2755 Ma Mo-Au mineralisation in supracrustal sequences at Tower Hill in the Leonora district (Witt et al., 2001). Further work is required to determine the extent and age(s) of these older greenstone sequences.

- In the domains east of the Mount George shear zone, there are no volcano-sedimentary sequences equivalent to the Black Flag Beds (Barley et al., 1998; Krapez et al., 2000; Brown et al., 2001). In the Agnew-Mt Clifford domain, the Vivien metasedimentary sequence may be the time equivalent of the Black Flag Beds, although there are currently no age constraints on this sequence. Further work is required to determine the extent and age(s) of Black Flag-equivalent sequences in the northern EGP.
- The last supracrustal successions in the Leonora-Laverton transect are the late siliciclastic basins (Pig Well-Yilgangi, Jones Creek-Scotty Creek, Wallaby) that are generally associated with domain-bounding structures. Age constraints are available for the Scotty Creek conglomerate ($<2664 \pm 5$ Ma) in the Agnew-Mt Clifford domain, the Yilgangi conglomerate ($>2662 \pm 4$ Ma), and a siliciclastic unit (Alabama sandstone: $<2675 \pm 4$Ma) in the Laverton domain (Fig. 5). In combination, the late siliciclastic basins in the transect area have maximum depositional ages of ca. 2665 or younger. These are consistent with the recent data of Krapez et al. (2000), although they suggest that the siliciclastic units were deposited after 2660 Ma and potentially even younger.

Granitoids

- Granitoids in the Leonora-Laverton transect area were emplaced over an extended time interval from ca. 2.81 to 2.63 Ga, with an apparent continuum from 2.72 to 2.63 Ga, and a pronouced peak at 2.68–2.65 Ga (Champion & Sheraton, 1997; Nelson, 1997b; Fletcher et al., 2001; Dunphy et al., in prep; Black et al., 2002). High-Ca granitoids, derived principally from melting of lower-crust sources or are slab-melts with a significant crustal component, were emplaced from 2810 to 2655 Ma, whereas the mid-crustally-derived Low-Ca granitoids were emplaced from 2655 to 2630 Ma (Champion & Smithies, 2001; Champion & Cassidy, this volume). The minor granitoid groups have the following emplacement ages: High-HFSE (2720–2670 Ma), Mafic (2690–2650 Ma), and Syenitic (2665–2640 Ma; Champion & Sheraton, 1997; Champion & Smithies, 2001). Champion & Smithies (2001) conclude that granitoid types in the eastern Yilgarn Craton show a trend with time to increasingly potassic (higher LILE contents) compositions.
- There is a distinct early High-Ca granitoid episode from ca. 2.81 to ca. 2.75 Ga in the transect area. Circa 2.81–2.80 and 2.76–2.75 Ga granitoids are present in the Agnew-Mt Clifford domain and ca. 2.77–2.75 Ga granitoids in the Merolia domain and further to the east (Black et al. 2002; Dunphy et al., in prep). These High-Ca granitoids dominantly belong to the low-LILE subgroup (Champion & Cassidy, this volume). In addition, many younger granitoids contain evidence of various amounts of inheritance (Hill et al., 1992; Nelson, 1995–2000; Fletcher et al., 2001; Black et al. 2002; Dunphy et al., in prep), ranging in age from >2.9 to only a few m.y. older than the crystallisation age of a specific granitoid. There is, however, evidence of a significant contribution of a 2.81–2.75 Ga inherited component, in particular in granitoids from the Agnew-Mt Clifford and Merolia domains. This inheritance age range overlaps with the range of depleted-mantle model ages obtained from Nd isotopic data (Champion & Sheraton, 1997; Champion & Cassidy, this volume), and is consistent with the 2.81–2.77 Ga

period being a major crust-forming event in the transect area and, in general, the EGP.

- High-HFSE granitoids are present in all domains in the EGP, with exception of the Agnew-Mt Clifford domain. There is a broad decrease in the age of these granitoids from east (2715 Ma in Merolia domain, 2705 Ma in Murrin domain) to the west (2695–2680 Ma in Malcolm domain). As stated above, these ages correspond to the age of felsic volcanism of similar chemistry in each domain (Brown et al., 2002; Champion & Cassidy, this volume).
- Widespread High-Ca granitoid emplacement largely post-dates the High-HFSE magmatism, with ages of ca. 2.68–2.66 Ga across the transect area, with a peak of ca. 2670 Ma (Fig. 3). There appears to be a shift from low-LILE to high-LILE compositions with time (Champion & Cassidy, this volume), although low-LILE members were emplaced throughout this interval. The youngest High-Ca granitoids are the magnetically-zoned ca. 2660 Ma plutons in the Murrin domain, and these appear to reflect a discrete episode of High-LILE magmatism.
- Localised Mafic granitoid emplacement, generally internal into the greenstone successions, occured at ca. 2665 Ma, including the Granny Smith Granodiorite and Lawlers Tonalite. Similar granitoids are present south and north of the transect area and often have spatially associated gold mineralisation. Localised emplacement of Syenitic granitoids (e.g., Hanns Camp Syenite) also occured at this time.
- At ca. 2655 Ma, there was a switch from High-Ca and Mafic granitoids to Low-Ca and Syenitic granitoids. Widespread Low-Ca magmatism occurred from 2655 to 2630 Ma in the transect area, with many Low-Ca granitoids intruded as sheets within the granitoid complexes external to the greenstones, although there are several Low-Ca granitoids in the greenstone successions (e.g., Meredith Well). In combination with data from north and south of the transect area, the emplacement ages of Low-Ca granitoids are consistent with two peaks at ca. 2650 and ca. 2640 Ma. The Syenitic granitoids have ages that range from ca. 2.655 to 2.64 Ga and are restricted spatially to several linear belts (Smithies & Champion, 1999).

Deformation

- The unifying deformation feature of the eastern Yilgarn Craton is the major east-west compressive event that was superimposed on previously deformed cratonic elements. Recent studies in the Leonora-Laverton transect area indicate previously unrecognised complexity in the deformation sequence (e.g., Davis, 2001; Witt et al., 2001; McIntyre & Martyn, 2001). Much of this work suggests additional extensional episodes prior to, during and after the major contractional event. Witt et al. (2001) suggest that, at least in the Leonora district, there is evidence for deformation events that may be associated with an orogenic event at ca. 2.76–2.75 Ga. The new geochronological data recognise an older granitoid event (ca. 2.81–2.75 Ga) and older greenstone sequences (e.g., Dingo Range, Wiluna, ?Leonora), consistent with the increased complexity.
- The major east-west contractional event (D2) resulted in development of regional upright north-northwest-trending folds, and coincided with the uplift of granitoid-core anticlines and development of a pervasive metamorphic foliation (Swager, 1997). Hammond & Nisbet (1992) suggested that the regional antiforms were related to major thrusting, and this view is consistent with the seismic data from Kalgoorlie (Drummond et al., 2000) and the 3D model developed for the transect area (Blewett et al., this volume). The timing of D2 is, however, contentious, with Swager (1997) suggesting ca.

2665 Ma and Krapez et al. (2000) suggesting ca. <2650 Ma.

D2 is considered to mainly post-date development of the late siliciclastic basins (e.g. Kurrawang, Merougil, Penny Dam Sequences) in the southern part of the EGP (Swager, 1997; Krapez et al., 2000), and these basins have maximum depositional ages of ca. 2655 Ma (Krapez et al., 2000). In the transect area, a maximum depositional age of ca. 2665 Ma has been determined for the late siliciclastic basins, and this places a maximum age on D2. In addition, there is evidence from cross-cutting relations that the Bulla Rocks Monzogranite truncates D2 structures and the Pig Well-Yilgangi graben. This granitoid has an age of 2660 ± 5 Ma (Black et al., 2002), consistent with the age of the cross-cutting monzodiorite dyke at Yilgangi, and together they may provide a minimum age for D2 in the Murrin domain, and early deformation along the Kilkenny shear zone.

This age for D2 age in the Murrin domain is older than that indicated by cross-cutting relations in the Kalgoorlie region, south of the transect area. In the Kalgoorlie region, maximum and minimum ages are provided by the emplacement ages of pre-D2 porphyry dykes at Mt Shea (2658 ± 3 Ma: Krapez et al., 2000) and Kanowna Belle (2656 ± 6: Ross et al., 2001) and the age of the post-D2 Liberty Granodiorite (2648 ± 6 Ma: Kent, 1994). In the southern Kalgoorlie region, therefore, D2 is probably constrained to ca. 2655–2650 Ma. In combination with the minimum age indicated for part of the Leonora-Laverton transect area, it appears that there may be more than one episode of D2 across the eastern Yilgarn.

Metallogenic episodes

- The recognition of the regional ultramafic marker unit (ca. 2705 Ma) at the top of Hallberg's (1985) Association 2 in the transect area (Fig. 5), implies that the ultramafic volcanic rocks in Association 1 are older. This suggests that the komatiites at Windarra are older, and implies that there was more than one age of magmatic Cu-Ni-sulfide mineralisation in the EGP.
- As discussed previously by Hallberg (1985), Witt et al. (1996) and Brown et al. (2002), there is a close spatial relationship between VHMS base-metal mineralisation and rhyolitic volcanic rocks associated with bimodal basalt-rhyolite volcanism. Although economic mineralisation has only been discovered at Teutonic Bore, this volcanism is evident throughout the Malcolm domain and may also be present in the other domains of the transect area.
- The recognition of Mo ± Au mineralization spatially and temporally associated with early (ca. 2.76–2.75 Ga) granitoids at Tower Hill (Witt, 2001; Witt et al., 2001), suggests that there was more than one gold-mineralising event in the EGP. This early mineralisation event may be associated with the inferred crust-forming event at 2.81–2.75 Ga, first recognised by this study.
- The main gold mineralization event in the EGP is interpreted to have taken place at 2640 to 2630 Ma, coinciding with, to post-dating, granitoid emplacement and regional peak metamorphism (Groves et al., 2000). If this time interval dates gold mineralisation in the Leonora-Laverton region, the only magmatic event operational at this time was the emplacement of Low-Ca and minor Syenitic granitoids, with all other magmatism earlier. Further studies are needed to confirm this time interval for gold mineralisation, considering the close spatial relationship between gold mineralisation with Mafic granitoids at Granny Smith and Lawlers, High-Ca granitoids at Tarmoola and Syenitic granitoids at Jupiter and Wallaby.

Conclusions

The Leonora-Laverton transect area records multiple episodes of late-Archaean volcanism, plutonism, metamorphism, deformation, and metallogenesis. Constraints from geochronological data support models that suggest that most of the greenstone sequences east of Leonora have a different depositional history to those in the Kalgoorlie Terrane. The new geochronology supports models that suggest that much of the EGP was built upon pre-existing crust, with ages of ca. 2.81 and 2.77 Ga present in the western and eastern parts of the Leonora-Laverton transect area, respectively. Metallogenic events are not restricted to the ca. 2.7 Ga magmatic Ni and 2.64 Ga gold events, as suggested by an older age for mineralisation at Leonora and the potentially older Association 1 stratigraphy in the Laverton domain.

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Leonora-Laverton transect area solid geology

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Solid geology interpretation process

Solid geology was interpreted for eighteen 1:100 000 sheets in the Leonora (all), Laverton (all), Menzies (northeastern), and Edjudina (northern) 1:250 000 sheets. The interpretation integrated 1:100 000 scale outcrop geology, 400 m flight line-spaced aeromagnetic data, and 2 to 4 km spaced gravity data acquired by Geoscience Australia (GA) and Geological Survey of Western Australia (GSWA) under the National Geoscience Mapping Accord and National Geoscience Agreement. Access to 200 m flight line-spaced aeromagnetic data for the Menzies and Edjudina map sheets was also provided by Fugro Airborne Surveys Pty Ltd. The interpretation was undertaken at 1:100 000 scale on images of Total Magnetic Intensity (TMI), 1st vertical derivative of TMI (TMI1vd), TMI1vd with coloured, semi transparent bedrock polygons, and outcrop geology maps. Images of gravity (colour) with TMI1vd (intensity) were also generated at 1:250 000 scale to provide information on dipping contacts, concealed greenstone and granite, and the distribution of dense mafic volcanic rocks verses that of less dense felsic volcanic rocks and sediment in the greenstone pile.

About one third of the area is underlain by poorly magnetised greenstone which is extensively dislocated, and is generally not well subdivided using aeromagnetic data. In these areas, outcrop geology provided the main control while the aeromagnetic and gravity data were used to map the bedrock distribution into regions of cover. The outcrop geology units were generalised for this purpose as many lithological variations are not distinguished in aeromagnetic data. The grouped units included mafic volcanic rocks (Ab), ultramafic rocks (Au), felsic volcanic rocks (Af), sediment (As), dolerite (Aod), gabbro (Aog), chert (Ac), banded iron marker beds (Aci), and late basin sedimentary rocks (Asc).

Areas underlain by granitic rocks in the Leonora-Laverton transect area are moderately magnetised and readily classified using aeromagnetic data. The petrological and geochemical groupings of these rocks are not distinguished in aeromagnetic data. Thus, given the extent of cover, and the dependence on aeromagnetic data to map between outcrops, the regional aeromagnetic classification scheme for granitic rocks of Whitaker (this volume) was used. The relevant units are gneiss-migmatite-granite (Agmg), banded gneiss (Agn), and granite plutons (Ag). These groupings are qualified, where appropriate, using average magnetisation (high, medium, low, and remanent) as a discriminator (Fig. 1).

In general, regions of granite and granite-greenstone contacts were interpreted first, as they were more easily interpreted compared with the areas of widespread greenstone. Particular care was taken to capture those relationships that might be used to infer relative timing e.g., intrusive contacts and dislocations. The general sequence of events for the Archaean includes greenstone formation and subsequent folding, dislocation of the region by major faults or shear zones (tectonic zones), intrusion by granite, deposition of late basin sedimentary rocks, and late minor faulting.

Leonora-Laverton Solid Geology new geological findings

Greenstones

A gross stratigraphic column for the Kalgoorlie region to the south was proposed by Swager et al. (1995). The sequence consists of older mafic volcanic rocks followed sequentially by komatiite, younger mafic volcanic, felsic volcanic, and sedimentary rocks. Komatiite in the Kalgoorlie region has been proposed as a time correlative equivalent of similar rocks exposed in the Leonora-Laverton region (e.g., Rattenbury, 1993; Cassidy et al., this volume), and is dated at ca. 2705 Ma (e.g., Nelson, 1997).

The greenstones of the Leonora-Laverton transect area are largely composed of mafic volcanic rocks (basalts and dolerite/gabbro). Felsic volcanic and sedimentary rocks are locally abundant. The relative rock type abundances in the Leonora-Laverton area contrast with that in the Coolgardie - Kalgoorlie region to the south, where sedimentary and felsic volcanic rocks are together more abundant than mafic volcanic rocks at the surface (Swager & Griffin, 1990).

Ultramafic rocks are widely distributed but comprise only a minor component of the greenstone pile. They are highly magnetised and provide valuable information on the local deformation (folding and dislocation) of the greenstone (Fig. 2). Very highly magnetised Banded Iron Formation (BIF) is also of value for delineating structural trends, however, it has a lower abundance and a more restricted distribution than the ultramafic rocks. BIF is most abundant in sedimentary rocks adjacent to the Laverton shear zone in the east of the area and to a lesser extent in the Welcome Well – Murrin-Murrin region. Dolerite and gabbro intrude mafic volcanic rocks, often adjacent to ultramafic flows, as well as intermediate to felsic volcanic rocks. Although they are widely distributed, the dolerite/gabbro intrusions are rarely discriminated in aeromagnetic data from similarly poorly magnetised host rocks.

Stratigraphic relationships in the Leonora – Laverton transect area are poorly constrained as cover sequences obscures many boundaries, boundaries between rocks with rheology contrasts are commonly tectonised, and there is limited geochronology for most units.

Mafic volcanic rocks followed sequentially by intermediate to felsic volcanic and sedimentary rocks may represent a stratigraphic column of the main rock groups. Ultramafic rocks occur in each of these main rock groups. If the simple column described above is correct then the ultramafic flows occur in different parts of the sequence and must be of different ages. Alternatively, if the ultramafic rocks of the region are coeval, then significant variations in local volcanic events and basin accumulation are evident.

Granite plutons

Granite intrudes all domains, however, pluton-shaped bodies are most common within the greenstone belts. Granite intrusion is commonly clustered and occasionally defines regionally aligned belts (Fig. 1). Intrusion shape is highly variable and includes oval, lenticular and irregular outline forms. Analysis of the gravity and aeromagnetic data indicates that a number of bodies occur as thin sheets overlying greenstone. Several bodies of granite have intruded greenstone prior to deformation with subsequent disruption of abutting greenstone providing apparent sense of movement indicators. Sinistral movement may be inferred on north-northwest trending structures and dextral movement on north trending structures. However, there is some field evidence that sinistral shearing has been overprinted by dextral shearing adjacent to the Ballard

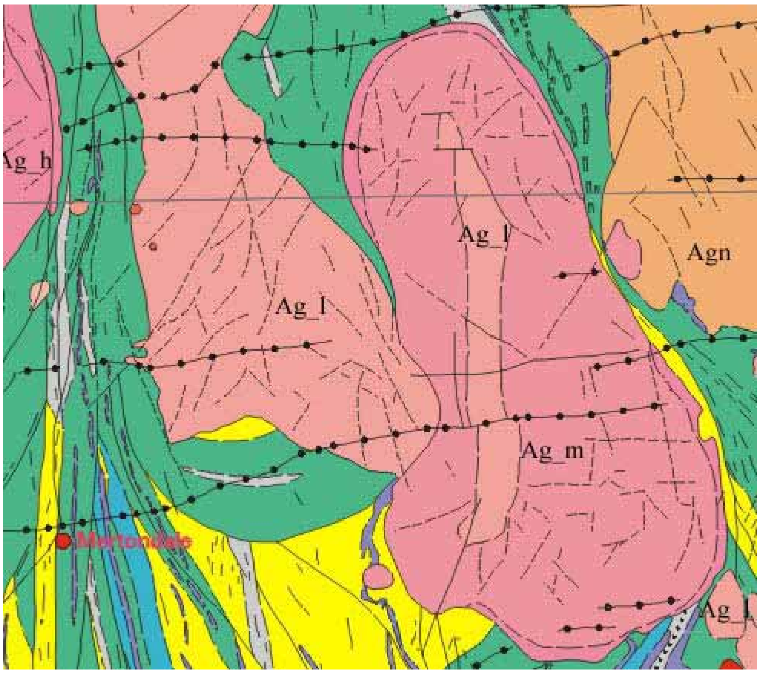

Figure 1 Extract from Leonora-Laverton transect area solid geology showing complexity of granite plutons determined from magnetic discrimination into low-, medium- and high-magnetisation

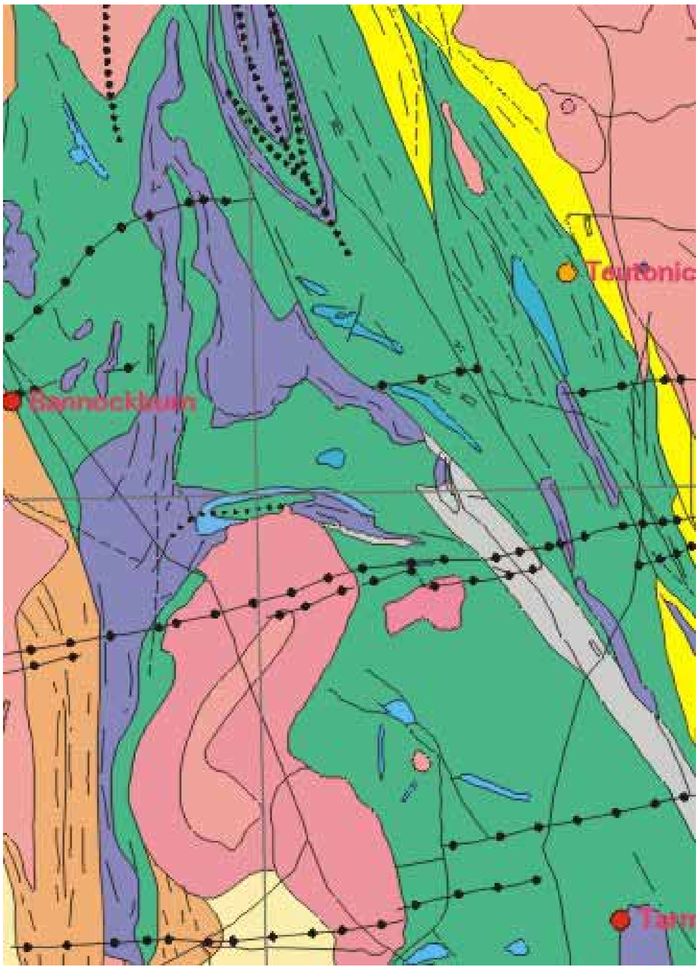

Figure 2 Type II fold interference pattern of komatiite and basalt around Mt Clifford on the Leonora-Laverton transect area solid geology map

shear zone in the west of the area indicating movement may have been complex, and that fabrics have been reactivated and are composite. Some granite has intruded the shear zones and when dated should provide minimum ages for activity on the structures.

Late basins

The late basins are spatially associated with the shear zones (e.g., Jones Creek, Pig Well). They occur as elongate remnants with margins that are largely coincident with faults (Fig. 3). The basins are interpreted to overlie unconformably(?) mafic and felsic volcanic rocks, and older sedimentary rocks in the Mertondale area. Conglomeritic units include sparse porphyry cobbles but rarely include material derived from granite (except for the Jones Creek conglomerate). The late basin sedimentary rocks have been deformed, host a regional cleavage (late D2) and have been sheared by sinistral movements on the major faults.

Gneiss-migmatite-granite domains

Gneiss-migmatite-granite domains comprise the largest component of the solid geology. The domains are moderately magnetised with sparse compositional banding which is not strongly aligned with the regional shear zones. The domains contain extensive belts of banded gneiss of granitic composition. Banded gneiss is moderate to highly magnetised and commonly but not exclusively aligned with adjacent regional shear zones. Greenstone is in apparent concordant, tectonised contact with gneiss-migmatite-granite domains and banded gneiss. The high metamorphic grade of greenstone adjacent and parallel to these contacts is thought to provide evidence of tectonic uplift (through extension) of the gneiss-migmatite-granite domains (Williams & Whitaker, 1993).

Deformation

A characteristic feature of the Eastern Goldfields Province is the pronounced north-northwest structural grain, in which the greenstone sequences are extensively deformed. The structural grain resulted from intense partitioning of strain into high- and low-strain domains (Figs 2–3). In the low-strain domains, open to tight folding of ultramafic rocks is evident in several areas in the Leonora–Laverton transect area with re-folded folds inferred in the Mt Clifford, Welcome Well, Lawlers, and Murrin Murrin areas. Early shear zones are also folded, and these are preserved in the low-strain domains. The high-strain domains are the locus of major faults or shear zones that bound a series of domains and sub-domains (see Blewett et al., this volume). These are zones of intense transposition and dismemberment of greenstone, resulting in parallelism of stratigraphy and earlier structural elements (Fig. 3). Correlation of greenstone sequences across shear zones is poorly constrained due to the lack of suitable marker horizons and effective geochronology. Some sense of relative age of shear zone activity is evident from analysis of the aeromagnetic data. The Murrin shear zone is cut to the southwest and north east by the younger Kilkenny shear zone and Celia shear zone respectively (Fig. 3). The Kilkenny shear zone is in turn cut in the northwest by the Ockerberry-Mount George shear zones, which is inferred to be younger still. Sinistral movement on the shear zones is younger than ca. 2650-2630 Ma, the age of Low-Ca granites (Cassidy et al., this volume).

Late faults of at least three orientations cut all rock types in the transect area. Dislocation on these faults is typically less than a few kilometres (Fig. 4). The east-west oriented fault-set is present throughout the Eastern Goldfields. Consistent sinistral movement of 10s of metres to a few kilometres spaced at 1–2 km intervals must dislocate the northern margin of the craton in excess of 100 km relative to the southern margin. Normal and remanent magnetised dykes intrude many of these late structures.

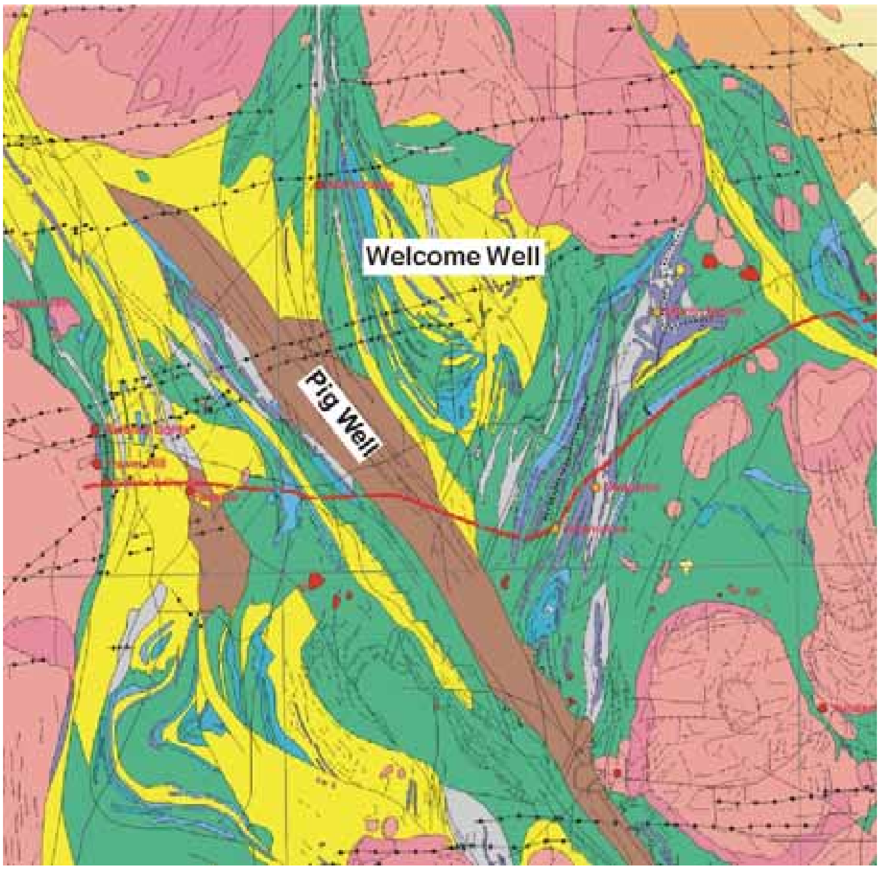

Figure 3 **Pig Well graben developed in high-strain Kilkenny shear zone, transecting Welcome Well and Murrin-Murrin areas at a high angle. Note likely northeast dislocation between the felsic-dominated greenstone in the northwest from mafic/ ultramafic-dominated greenstone in the southeast**

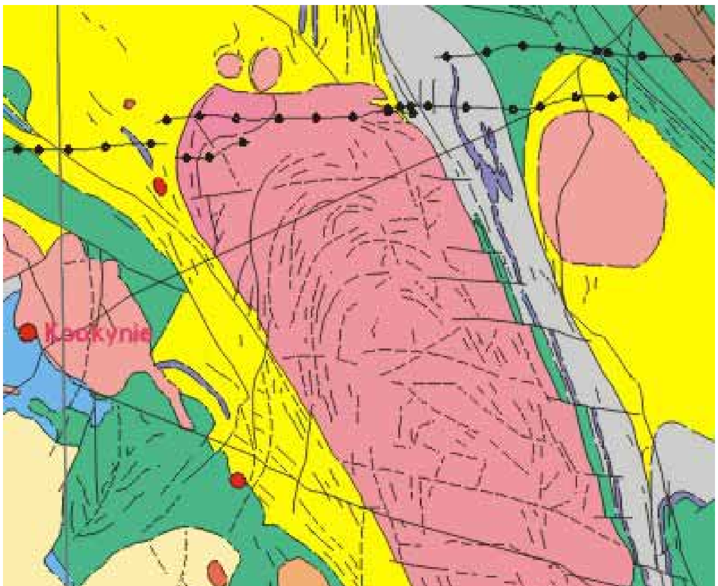

Figure 4 **Latest faults trend east-west (to east of Kookynie) and record small sinistral offsets, e.g., along the northwest trending granite (Ag_m) contact. The accumulated displacement across these numerous faults is likely to be large (see text)**

Time-space analysis of Leonora-Laverton transect area

Geological maps contain an enormous amount of temporal information that can be inferred from simply critically examining the nature of boundary or contact relationships between adjacent polygons. This is especially true of solid geology maps where ‘basement’ or hard rock relationships have been determined. There are, of course, difficulties in unequivocally determining the type of contact between adjacent rock units (polygons) in concealed areas, so any analysis of these contact relationships must be limited by the reliability of the interpretation (map). Establishing a relative age of adjacent units for each polygon boundary is a routine exercise of determining superposition, cut-offs, intrusive relationships, etc. However, taking this analysis further and constructing a map-wide time-space plot so that non-adjacent polygons can be assessed for relative age, needs either a brilliant mind or a software tool!

The Leonora-Laverton transect area is an example of a fairly typical deformed Archaean granite-greenstone terrane. There are a few absolute age determinations (geochronological data) available providing temporal controls on small parts of the region (see Cassidy et al., this volume). However, many areas remain unconstrained in age. This study attempted to establish the relative age relationships for the entire Leonora-Laverton transect area by examining the inherent map patterns explicit in a set of new solid geology maps (Whitaker, 2001; Blewett, 2001).

The process adopted was to examine every polygon systematically and to determine the relative age of each adjacent polygon via the nature of the polygon boundary. All polygons and faults and major fold axes where given a unique label. Each contact relationship was identified, and a syntax of oldest/youngest was ascribed to each polygon boundary, i.e., V1/G1 means greenstone 1 is older than granite 1. The following codes refer to the major rocktypes and structural features that were analysed:

- G - granite and gneiss
- U - ultramafic
- V - undifferentiated greenstone (mostly basalt)
- F - felsic greenstone
- O - dolerite and gabbro
- L - fold axis
- T - fault
- Y - dyke

In some instances relationships were equivocal and the original interpretation (solid geology) was re-examined to see if the relationship could be determined from the magnetic data. Where remaining doubt existed, either a same or equivalent age was given, or a ‘qualified’ decision was made on what was older than what.

Presently there is no suitable tool for managing the huge number of relative age relationships possible in two typical 1:250 000 scale maps. However, Microsoft Project™ was chosen as it does handle time and understands predecessors (read as relative old polygon) from successors (read as relative young polygon), and presents these data in terms of a Gantt chart (Fig. 5). Unfortunately, the time scale is somewhat human biased, and the programme does not want to start in the Archaean. For this ‘project’, the time scale was adjusted to show just a numeric value starting at 1 (the oldest greenstones) and going through until the youngest relationship was determined (the latest cross cutting dykes). Every other relationship fitted in between this.

Each polygon and structural label was added as a ‘task’ and all began with a ‘start date’ of 1. The process then involved systematically transferring all of the oldest/youngest boundary relationships into the project. This process was achieved by linking the oldest to youngest (a drag and drop action) until a complex Gantt chart was produced. The ‘duration’ of all the tasks (units or structural features) was assigned as a single day. The displayed result was a short bar for each unit/structure starting at a particular time from 1 to n (the youngest relationship). These

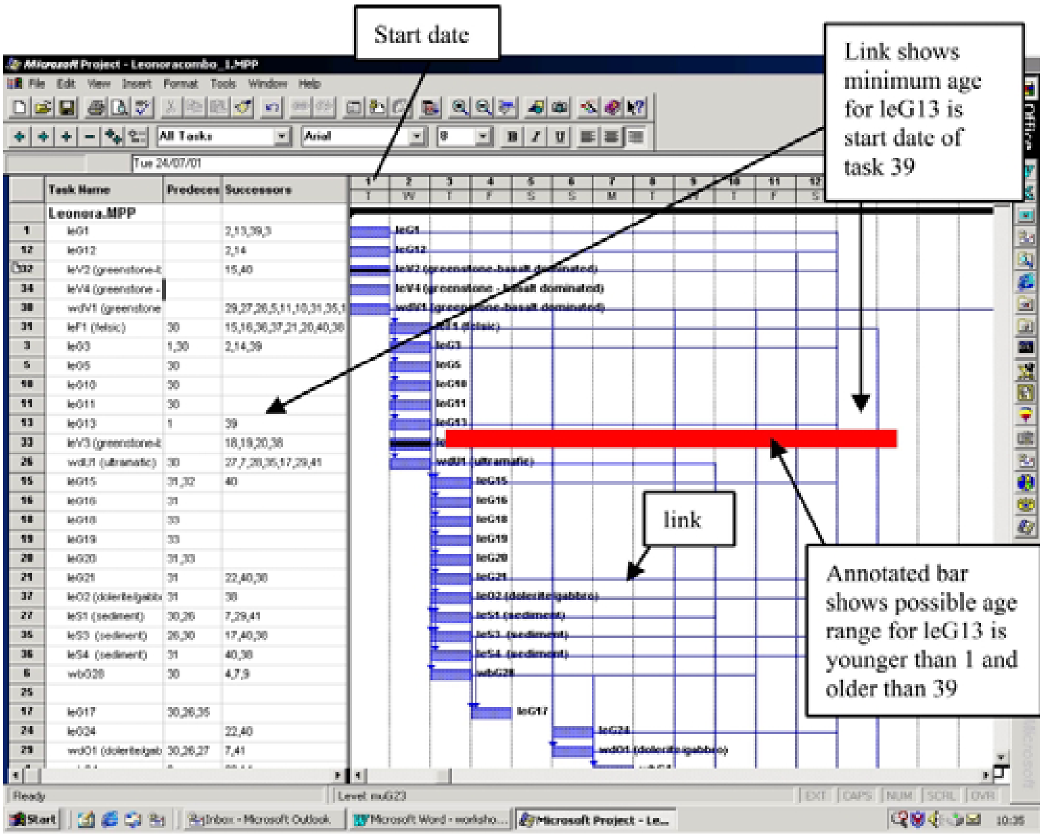

Figure 5 Time-space analysis using Microsoft Project

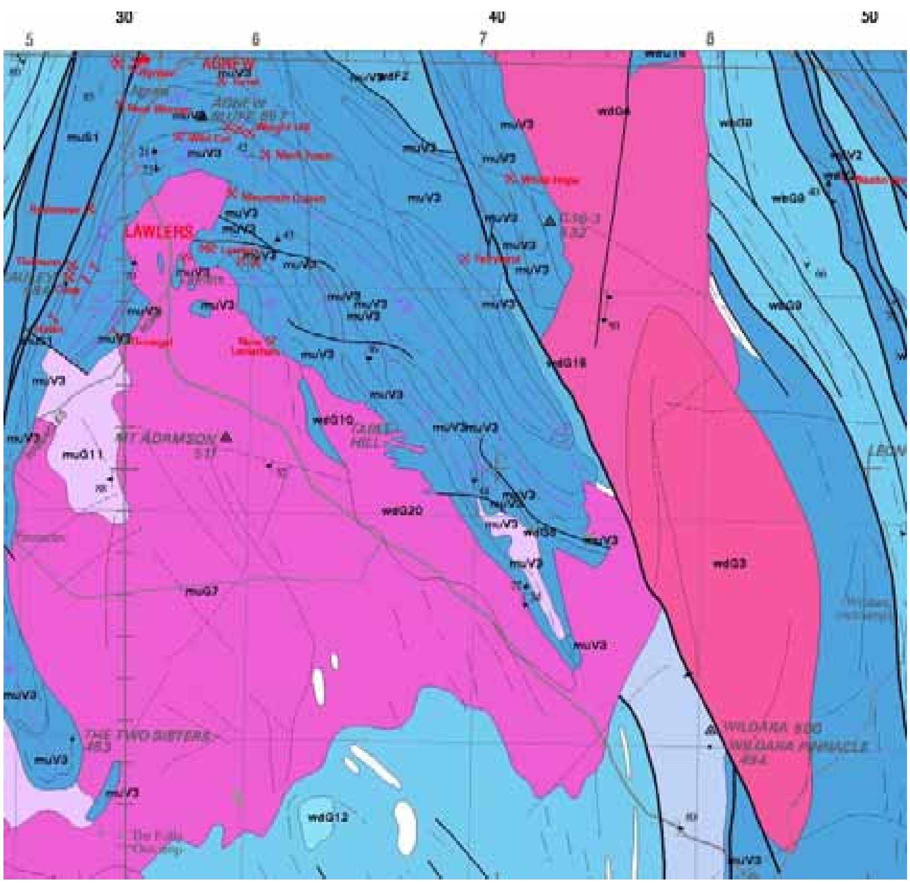

Figure 6 Sample of relative (starting) age of map units from the Lawlers area. Colours are ramped from oldest blue to youngest red. The Leonora map has a total of 20 'events'

bars were joined in time by 'links' (predecessor/successor relationships) that represent the boundary or contact between the units.

Benefits and findings of time-space analysis

Using the time-space analysis we identified a number of errors in the original interpretation of the boundary relationships (solid geology map). These were identified when 'circular logic' of overprinting polygons occurred. For example, following the respective boundaries of a set of nested plutons involving G1, G2, and G3 may be described by G1/G2, G2/G3, G3/G1. In this example, G3 can not be both older and younger than G1. A new inspection of the aeromagnetic data showed an error in the original interpretation that was then revised to remove the logic error and improve the map.

Another way of displaying a time sequence in a project management tool is the use of PERT (Programme Evaluation Review Technique). This technique maps out the critical path, which in a project management sense is the sequence of tasks that must be completed in order to complete the project. In a geological sense it maps the units/structures that have the most connections or links with other units. Therefore understanding the absolute ages in the critical path provides the most constraints on ages for other units/structures. This tool would therefore be a way of targeting sites for geochronology to maximise temporal information.

A method of spatially analysing the time-space relationship is with a map of start dates (Fig. 6). In this example, the Leonora 1:250 000 solid geology polygons were relabelled by a new attribute called start date (a numeric value between 1 and 20 reflecting oldest to youngest). This method of display was not very successful as there are many granite polygons that are poorly constrained and have an early start date (or maximum age). An additional factor is an 'end date' which is determined from the start date of the relatively oldest successor (Fig. 5) In a geological sense we are therefore able to obtain a maximum and a minimum relative age for each unit. The programme, however, does not graphically show the minimum age or end date as the length of the bar (Fig. 5). This bar is the duration that is taken to be a single day or an event. The data must visualised along a spectrum or range between start date and the start date of the oldest successor, and can be viewed by looking at the links. This lack of visualisation was one reason why further work was discontinued.

Future developments on time-space analysis

A more satisfactory arrangement would be to have a module attached to the live GIS solid geology map. A GIS has topology, where the database 'knows' what polygons are on either side of an arc (or polygon boundary). The geologist could systematically evaluate every polygon boundary and major structural feature in terms of relative age on either side of the arc, and be appropriately coded. A syntax could be developed where the oldest unit lies to the to the left of the arc, and coded by the direction of the arc. Alternatively, an arc attribute table could be developed, storing the age of two attributes (left poly and right poly and a value of old or young). The advantage of this system would be a time-space relationship that could be viewed spatially back on the map and as a link on the Gantt chart display (and vice versa). Presently we have to relocate the polygons and the boundaries on a separate window that is not linked. It could be established in the same way as tables are used in Arcview presently. A way of displaying the full range of ages (maximum to minimum) is also required, i.e., not just the short blue duration bar of present, but the red bar separately added (Fig. 5).

Another way to display the age range is to take the XY polygon data and extrude it with a Z value related to the maximum and minimum age (Fig. 7). This would provide a better visual impression of the spatial distribution of the age range information.

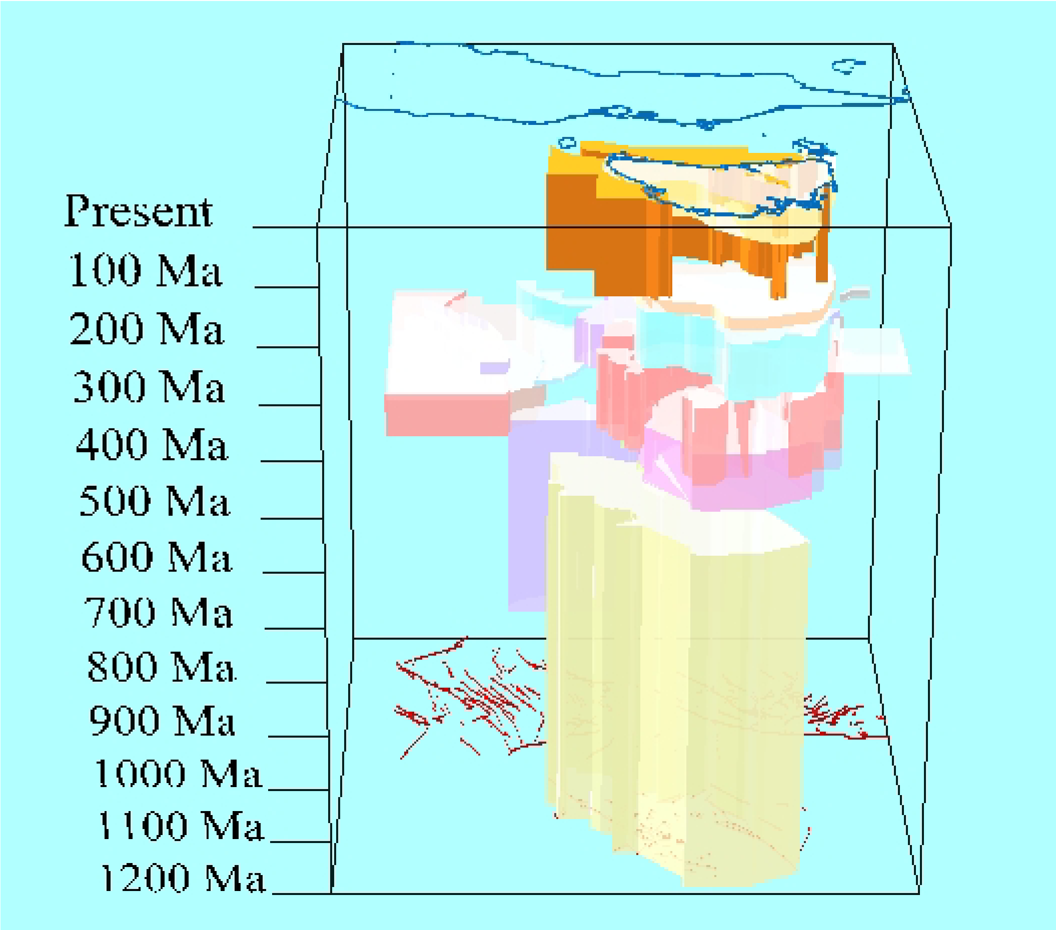

Figure 7 3D extrusion of temporal data: an example of Tasmanian provinces (courtesy of S. Stanley, Geoscience Australia)

Stratigraphic Information Database

A Stratigraphic Information Database was created for the eastern Yilgarn using Microsoft Access; an example of a Unit record is shown in Figure 8. Descriptions of named and unnamed rock units were obtained from literature such as mining company records or reports, research articles, map sheet explanatory notes, monographs and excursion guide notes. Where explanatory notes were not produced in conjunction with a map it was difficult to give a definition.

Information recorded includes:

- the unit's lithological name, if given;
- stratigraphic index number;
- library reference number as given on the Stratigraphic Names Query web page http://www.ga.gov.au/oracle/stratnames.html;
- mine site name (where possible);
- thickness;
- age;
- how the age was acquired;
- relationship with surrounding rock, eg. unconformity, fault, intrusion;
- description of the unit found in the legend of the map, and/or lithological description found in the literature. The description includes rock type, dominant mineral, any inclusions, any alterations, felsic or mafic, intrusive or extrusive;
- overlying and underlying formation/unit/ member;
- the 1:100 000 map name on which the unit is found; and
- whether the unit is cut by an intrusion, fault, dyke or sill.

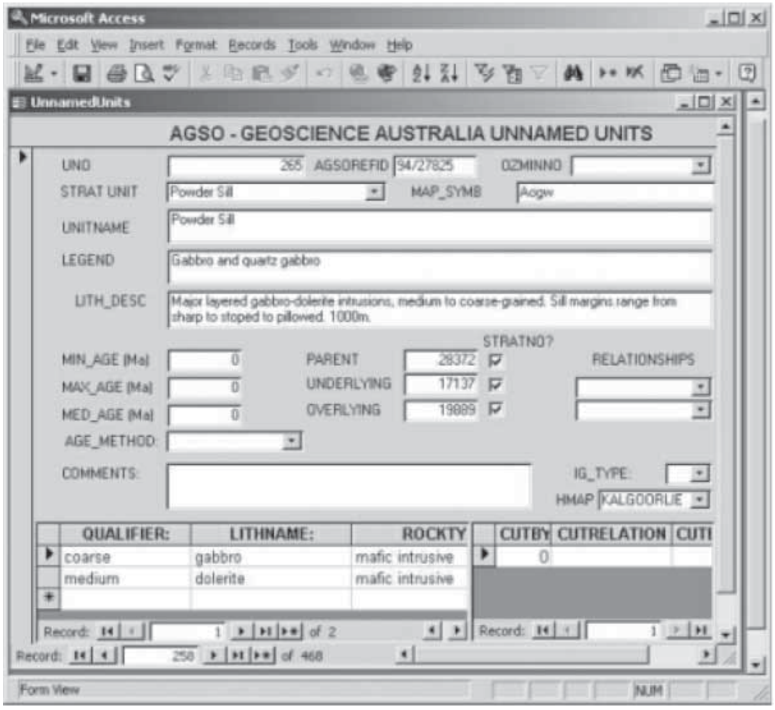

Figure 8 Example of a Unit Record of the Unnamed Units file in Microsoft Access

Once all the information for units in the eastern Yilgarn was obtained, unit information relevant to the Leonora-Laverton transect area was extracted and written in Visual Basic. It was then imported into VRML and linked to the transect area 3D model. Using Visual Basic, stratigraphic units were grouped according to mine location or by grid reference.

The end result is that stratigraphic unit information is easily obtainable by the viewer as pop-up windows on the transect area 3D model. Pop-up windows are geographically placed according to mine site, or grid reference. Stratigraphic information of an area viewed in pop up windows will provide a visual understanding of the order of stratigraphy from youngest to oldest units in different areas on the map. The stratigraphy of an area can be compared to the stratigraphy of another area, offering a better understanding of the geological history of the region. The information can be beneficial in the understanding of the eastern Yilgarn stratigraphy from the point of view of space and time.

The following section summarises the stratigraphic information for domains (see Cassidy et al., this volume) across the Leonora-Laverton transect area. Major faults and shear zones allow division of some domains into sub-domains.

West Agnew-Mt Clifford sub-domain

- The West Agnew-Mt Clifford sub-domain is located on the Wildara and Wilbah 1:100 000 map sheets.
- The Agnew gold camp (Emu-Redeemer-Cox-Crusader deposits) and Lawlers gold deposits are located within this domain.
- The succession in the Agnew gold camp comprises basal metamorphosed basalt, gabbro, dolerite and ultramafic flows of the informally named Lawlers greenstone formation. Conglomerate, arenaceous metasediment and greywacke of the Scotty Creek formation (now part of the Jones Creek Conglomerate) unconformably overlie and/or fault bound these basal units.
- The informally named Peperill Hill gneiss unit in the domain has a SHRIMP U-Pb zircon age of 2678 ± 7 Ma (Black et al., 2002).

The sequence at Agnew gold camp (Fig. 9) is:

Scotty Creek Fm
- -Unnamed sandstone
- -Unnamed ultramafic conglomerate

Lawlers Greenstone
- -Unnamed ultramafic conglomerate
- -Unnamed ultramafic flow
- -Unnamed felsic volcanic rocks
- -Unnamed ultramafic conglomerate
- -Unnamed ultramafic flow

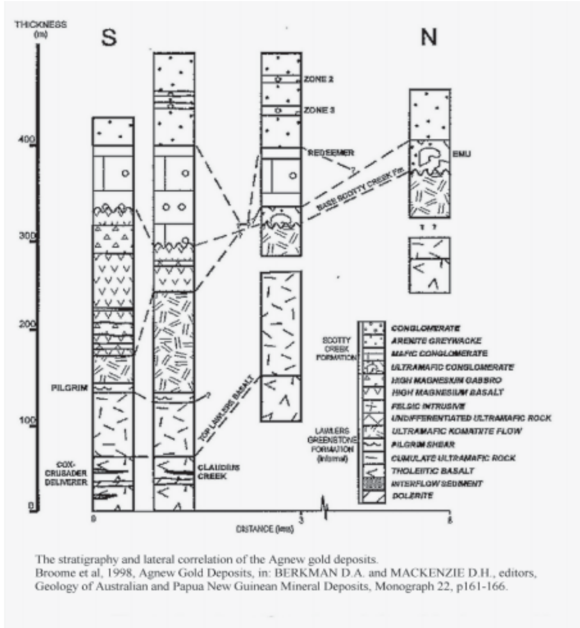

Figure 9 Lateral correlation of stratigraphy of gold deposits in the Agnew gold camp (from Broome et al, 1998)

East Agnew-Mt Clifford sub-domain

- The East Agnew-Mt Clifford sub-domain is located on the Leonora, Melita, Ballard 1:100 000 map sheets and the eastern part of the Wildara and Wilbah 1:100 000 map sheets.
- Gold deposits situated within this domain that are recorded in the stratigraphic units database, include Tarmoola, Tower Hill, Sons of Gwalia, and Harbour Lights (Fig. 10).
- The general succession of rock units within the domain includes granitoids of tonalitic, monzogranite or granodiorite to leucogranitic composition. The informally named Union Jack granite and Table Well granite have SHRIMP U-Pb zircon ages of ca. 2665 Ma (Cassidy et al., this volume). The informally named Auckland granite has an age of 2669 ± 7 Ma (Black et al., 2002).
- Banded gneiss within the domain have SHRIMP U-Pb zircon ages of between ca. 2650 and 2805 Ma (Black et al., 2002; Cassidy et al., this volume).
- The informally named Trump tonalite has a SHRIMP U-Pb zircon age of 2760 ± 10 Ma (Black et al., 2002).
- The greenstone units include mafic and ultramafic volcanic rocks, ultramafic to mafic schist, and sedimentary rocks.

Tarmoola Mine
Proterozoic dyke
ultramafics
basalt
basalt

Tower Hill Mine
schist
mafic schist
ultramafic unit
mafic schist
ultramafic schist
granitoid

Harbour Lights Mine
dolerite
sheared porphyry
porphyry
carbonate schist
ankerite schist
ankerite schist
tholeiitic basalt
carbonate schist
Gwalia slate
granitoid

Sons of Gwalia Mine
Clover Downs beds
Mt Leonora chert
East Leonora basalts
Gwalia slate
West Leonora basalts
Quartz dolerites
Gold Block Ultramafics
Tower Hill granite
Mine schist
Unnamed basalt

Figure 10 Schematic stratigraphic relationships in the East Agnew-Mt Clifford sub-domain

West Malcolm sub-domain

- The West Malcolm sub-domain lies on the Leonora, Melita and Yerilla 1:100 000 map sheets.
- Rock types within this domain include felsic volcanic rocks, tholeiitic basalt, dolerite and gabbro, and include the sequence at the Teutonic Bore VHMS base-metal deposit. Rhyolite and volcaniclastic rocks have SHRIMP U-Pb zircon ages of ca. 2692-2680 Ma (Nelson, 1997; Brown et al., 2001).
- The Niagara Layered Complex comprises gabbronorite, dolerite and anorthositic gabbro.
- The informally named Kent granite has a SHRIMP U-Pb zircon age of 2686 ± 7 Ma (Black et al., 2002).
- The Mulliberry granitoid complex comprises biotite monzogranite and granodiorite, interleaved with thin slices of greenstone.

The sequence at the Teutonic Bore deposit is:

dolerite
tholeiitic basalt
tholeiitic basalt
sulfide
chert and sedimentary rocks
tholeiitic basalt
felsic volcanic rocks

East Malcolm sub-domain

- The East Malcolm sub-domain lies on the Yerilla, Minerie and eastern-most part of the Leonora and Melita 1:100 000 map sheets.
- Rock types within this sub-domain as recorded in the stratigraphic units database include the stratigraphic sequence found at the Tassie Well deposit. This sequence comprises rhyolitic and rhyodacitic volcanic rocks, felsic tuffs, chemical sedimentary rocks and mafic volcanic basalt.
- The McAuliffe Well syenite has a SHRIMP U-Pb zircon age of 2651 ± 5 Ma (Nelson, 1997).

The Tassie Well deposit has the following sequence:

mafic volcanic rocks
felsic volcanogenic sequence made up of schistose rocks
volcanic fragmental rocks
volcanic fragmental rocks
chemical sedimentary rocks (and chert within a felsic tuff sequence)
rhyodacitic volcanic rocks with a felsic tuff sequence
rhyolitic volcanic rocks

North Murrin sub-domain

- The North Murrin sub-domain lies within the Weebo, Minerie and Nambi 1:100 000 map sheets.
- The Mertondale gold deposit is situated within this domain, and has the following stratigraphic sequence from oldest to youngest: felsic volcanic rocks; metabasalt; mixed mafic package made up of interlayered basalt, dolerite and carbonaceous sedimentary rocks; porphyry; Proterozoic dyke.
- The informally named Kilkenny gabbro is a layered tholeiitic gabbro sill.
- The Welcome Well Complex comprises andesitic lavas, agglomerate overlain by black shale/ sediment horizon, volcaniclastic breccia, feldspathic sandstone.

The sequence at the Mertondale deposit is:

Proterozoic dyke
porphyry

mixed mafic package made up of interlayered basalt
dolerite
carbonaceous sedimentary rocks
metabasalt
felsic volcanic rocks

The sequence of the Welcome Well Complex (Fig. 11) is:
feldspathic sandstone
volcaniclastic breccia
black shale horizon
agglomerate
andesitic lavas

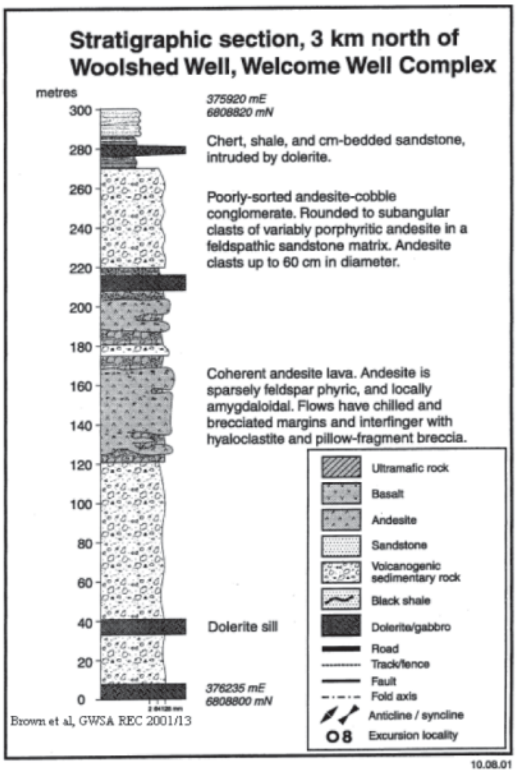

Figure 11 Welcome Well section (from Brown et al., 2001)

South Murrin sub-domain

- The South Murrin sub-domain lies within the Yerilla, Lake Carey and Laverton 1:100 000 map sheets.
- Rock units recorded in the stratigraphic units database include felsic volcanic rocks and the Bulla Rocks Monzogranite.

North Laverton sub-domain

- The North Laverton sub-domain lies predominantly within the Mt Varden and Laverton 1:100 000 map sheets.
- Deposits located within this sub-domain that are recorded in the stratigraphic units database include the Mt Windarra Ni (Fig. 12) and Lancefield Au (Fig. 13) deposits.

The sequence at the Mt Windarra deposit (Fig. 12) is:
unnamed basalt
Windarra ultramafic sequence
Inter BIF
Corridor ultramafic
Windarra BIF

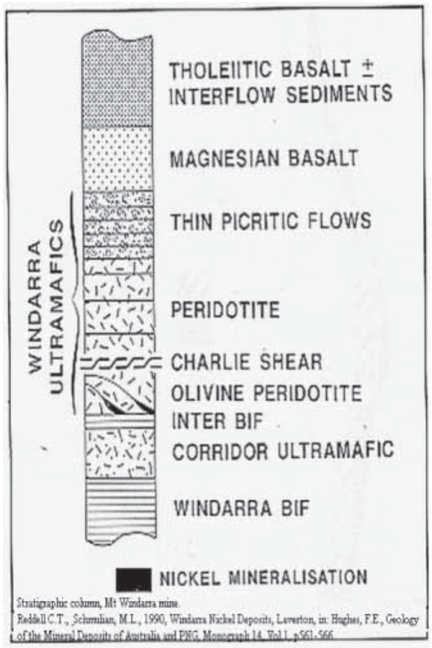

Figure 12 Mt Windara (from Reddell & Schmulian, 1990)

The sequence at the Lancefield deposit (Fig. 13) is:

Proterozoic dyke
hangingwall conglomerate sequence
hangingwall basalt
M1 sedimentary rocks (#179)
G10 dolerite (#178)
W10 sedimentary rocks
upper footwall basalt
W6 sedimentary rocks
lower footwall basalt
ultramafic volcanic rocks

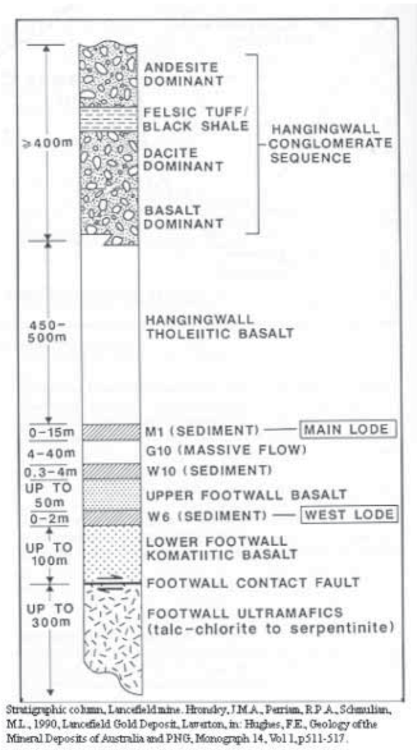

Figure 13 Lancefield (from Hronsky et al., 1990)

South Laverton sub-domain

- The South Laverton sub-domain is situated on the Lake Carey, Laverton and Mt Celia 1:100 000 map sheets.
- The stratigraphic sequence at the Sunrise Dam deposit includes interbedded sedimentary, volcaniclastic and volcanic rocks, coarse ash tuff, sandstone, banded iron-formation in the upper part of the sequence, mafic intrusive rocks, and porphyries.

- The stratigraphic sequence at the Granny Smith deposit includes conglomerate, felsic volcanic rocks, epiclastic sedimentary rocks, banded iron-formation, tholeiitic mafic and ultramafic volcanic rocks and the intrusive Granny Smith Granodiorite, which has a SHRIMP U-Pb age of 2665 ± 4 Ma (Hill et al., 1992).

Merolia Domain

- The Merolia Domain is situated on the Burtville, Mt Varden and McMillan 1:100 000 map sheets.
- The rock units recorded in the stratigraphic units database include the informally named Durang granodiorite with a SHRIMP age of 2672 ± 2 Ma, and the informally named Murphy granite with an age of ca. 2670 Ma (Black et al., 2002).

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Application of potential field data to constrain three-dimensional geological modelling in the Leonora-Laverton transect area

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Introduction

With more than 80 percent of the Yilgarn Craton covered by younger Cainozoic material (Chan et al., 1992), structural information obtained from surface mapping often provides an incomplete picture of geology at depth. Whilst initial geology-based interpretations do provide an insight into the area's structural architecture, the results may be ambiguous due to minimal outcrop and, therefore, limited structural measurements. The inherent non-uniqueness of solutions derived from potential field modeling often results in uncertainty about the validity of such models, similarly, providing a dubious solution when used in isolation. The integration of the surface mapping with two-dimensional gravity modelling, however, substantially increases both the accuracy and confidence of the structural interpretation by reducing the number of possible solutions to the problem.

Data and methodology

Geological setting

The geology of the Leonora-Laverton transect area consists predominantly of gneiss and granitoids, and to a lesser extent, supracrustal mafic/ultramafic volcanic rocks (Whitaker et al., this volume). A number of sedimentary and felsic volcano-sedimentary units are also present. The metamorphic grade of the region varies from greenschist to low amphibolite (Binns et al., 1976).

Five regional deformation events have been identified over the Leonora-Laverton region (Stewart, 2001). The initial, broadly north-south regional extension (D_{E1}), preceded a shortening event (D_1), which produced tight folding. Subsequent extension and ESE-WNW contraction episodes (D_{E2} and D_2 respectively), resulted in the formation of regional antiforms. A later regional ESE-WNW strike-slip faulting (D_3) led to minor changes in the regional east-west stress regime created through D_2 (Blewett et al., this volume).

Gravity and petrophysical data Sets

In general, the observed gravity field within a region tends to be unresponsive to minor variations in the shape of anomalous sources, particularly for bodies at depth (Telford et al., 1990). Two-dimensional modelling of the gravity field over the Leonora-Laverton transects was employed, therefore, to resolve gross geological features including the orientation of granite/greenstone contacts and depth of the greenstone sequence.

Commencing from an arbitrary northing of 6740000mN and spaced 20 km apart, nine east-west sections were selected for modelling in the Leonora-Laverton transect area. The Bouguer gravity data used for the modelling of these sections was extracted from a 600 m by 600 m grid generated from Geoscience Australia's gravity database (Fig. 1). This regional gravity dataset has an average station spacing between 2 and 4 km, and a probable Bouguer error of 0.22 mms^{-2} (Fugro Ground Geophysics, 2001).

Limited petrophysical data from the Leonora-Laverton transect area was available during the course of this study. Consequently, the modelling relied heavily on density measurements derived from similar lithological units in the Kalgoorlie-Kambalda region (Fig. 2; House, 1996; Bell et al, 2000).

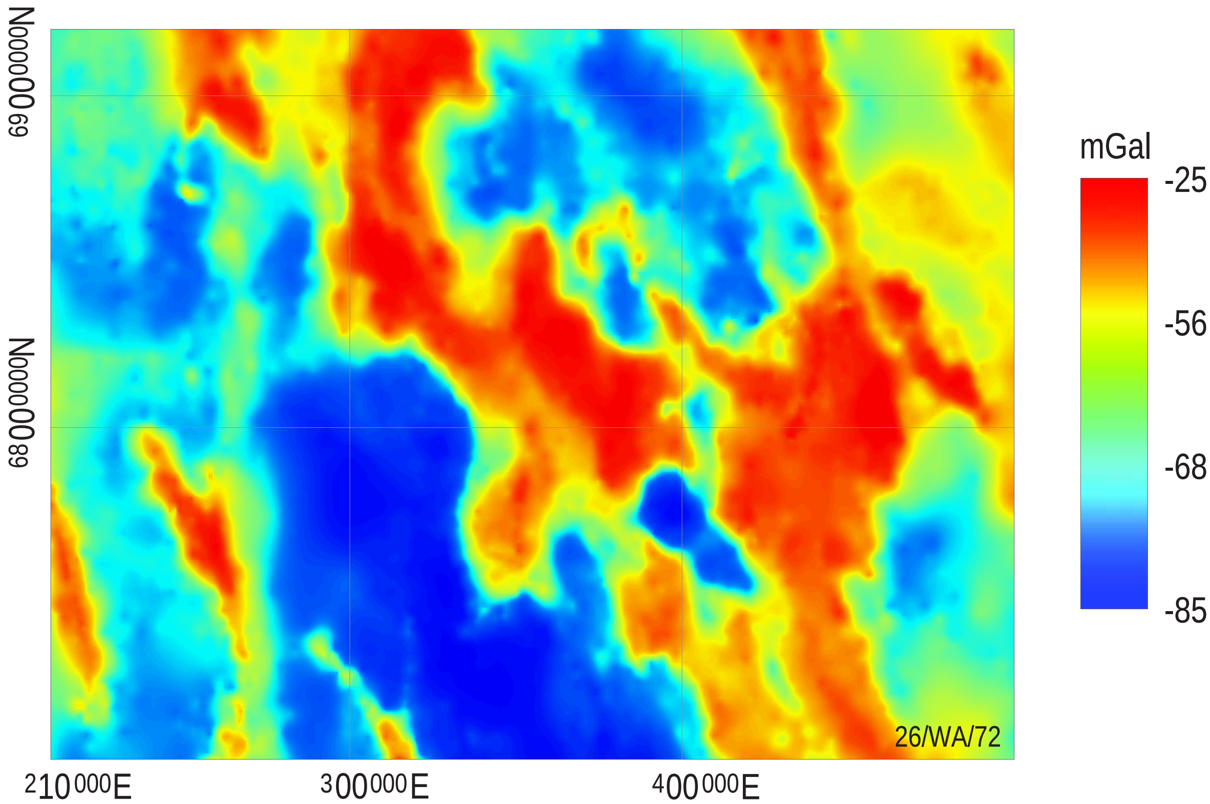

Figure 1 Histogram-equalised pseudocolour image of the Bouguer gravity over the Laverton-Leonora transect area

Figure 2 Bedrock density values used in gravity models for the Laverton-Leonora transect area

Lithology	Density (g/cm^3)
Granitoid/Gneiss	2.65
Sedimentary Rock	2.70
Felsic Volcanic Rock	2.74
Mafic/Ultramafic Rock	2.90
Background	2.71

26/WA/73

Modelling methodology and parameters

The initial geological interpretation of each section, described in detail by Blewett et al. (this volume), is under-pinned by a geological framework derived from 1:250 000 and 1:500 000 solid geology images (Liu et al., 2000; Blewett, 2001; Whitaker, 2001; Whitaker & Blewett, 2002). Structural measurements from outcrop mapping combined with various potential field images were used to determine dip direction of a number of lithological units and large-scale structures.

To refine the geological interpretation, two-dimensional gravity modelling was performed for each transect with the aim of replicating the observed gravity field. The fixed parameters were the position and density of lithological units at the surface, leaving the orientation of the units at depth and the vertical extent of the individual bodies as variables. After scanning each geological cross-section, they were imported into a modelling software package, ModelVision Pro (version 4.0), as spatially registered bitmaps. The boundary of each lithological unit was then digitised with each discrete polygon allocated an appropriate density according to Figure 2. No regional gravity field was removed from the data (cf Smyth & Barrett, 1994); rather the model endeavours to account for both long and short wavelengths gravity responses.

To identify changes in the gravity data, which may indicate the location of lithological or structural boundaries, a horizontal gradient filter (cf Blackey & Simpson, 1986; Grauch & Cordell, 1987; Archibald et al., 1999) was applied to six levels of upward continued bouguer gravity (500, 1000, 2000, 4000, 8000 and 12000 metres). Upward continuation attempts to reproduce the gravity response over an area as if it were recorded at a higher altitude. For example, a 500 m upward continued grid attempts to replicate the measured gravity anomaly as if it were recorded at 500 m above the ground. Since the magnitude of an observed anomaly caused by a body decreases proportionally as a function of depth (or vertical distance: Sharma, 1986), upward continuation effectively smooths the higher-frequency gravity anomaly (shallow sources) relative to lower-frequency anomaly (deeper sources). Consequently, increasing the level of upward continuation (height above the ground) essentially increases the depth of imaging but anomalies due to smaller bodies are lost.

Horizontal gradient filters calculate the rate of change of the measured gravity field (Δg) in the horizontal plane (Parasnis, 1997). This is highest at the inflexion point of a gravity anomaly, which corresponds with the edge of the causative body.Although the horizontal gradient function produces derivatives in two directions, x (east-west or Δg_x) and y (north-south or Δg_y), the total horizontal derivative, $(\Delta g_x{}^2 / \Delta g_y{}^2)^{1/2}$, only represents the magnitude of the anomaly. As a result, the amplitude of the horizontal gradient is primarily a product of density contrast; the larger the difference, the stronger the gradient.

Combining the processes of computing a horizontal gradient (which determines the position of geological boundaries) for a number of upward continuation gravity grids (providing a series of depth slices of the earth), geology can be mapped in three-dimensions.

Discussion

Results of two-dimensional gravity modelling

Within the study area, it is difficult to delineate between granitoid and gneissic units due to their small density constrast. Furthermore, as an interpreted gneissic crust underlies the majority of the granitic bodies, gravity modelling cannot resolve the depth extent of granitoids over the region. Similarly, the gradients of the Mount George and Kilkenny shear zones and the Celia Fault below the greenstone package are indistinguishable by gravity modelling due to the apparent homogeneity of the mid- and lower-crust.

Using root mean square (RMS) calculations to assess quantitatively the closeness of the model to the observed gravity response, two-dimensional potential field modelling of the Leonora-Laverton sections revealed:

- The thickness of the greenstone sequence east of the Celia Fault is reasonably constant at around 6 km;
- The depth extent of the greenstone package west of the Kilkenny shear zone appears to thicken from 3 km around the Niagara and Kookynie mines in the south to about 8 km near Teutonic Bore in the north;
- The greenstones are thinnest within the southern Murrin domain (see Cassidy et al., this volume) with a thickness of 2 to 3 km;
- The contact between the Raeside Batholith and the greenstone package dips approximately 40º to the east (Fig. 3);
- The Celia Fault has an easterly dip of around 35º in the southern area of the Leonora-Laverton transect area (Fig. 4);
- The bodies of granite within the Murrin domain (e.g., Bulla Rocks Monzogranite) appear to be steep-sided; and
- A number of small, discrete granitoids within the Malcolm and Murrin domains (cf Blewett et al, this volume) are underlain by greenstones (Fig. 5).

Figure 3 Computed root mean square (RMS) for various dip orientations within the greenstone sequence of the Mount George Shear. RMS measures the difference between the calculated and observed gravity values; the lower the value, the smaller the difference between the two curves

Dip of Fault (degrees to the East)	Root Mean Square (RMS) error
25	Not recorded
30	5.355
35	3.157
40	1.966
45	2.296
50	3.282
55	4.286

26/WA/77

Dip of Fault (degrees to the East)	Root Mean Square (RMS) error
25	7.285
30	3.447
35	2.015
40	3.921
45	6.032

26/WA/76

Figure 4 Computed root mean square (RMS) for various dip orientations within the greenstone sequence of the Celia Fault

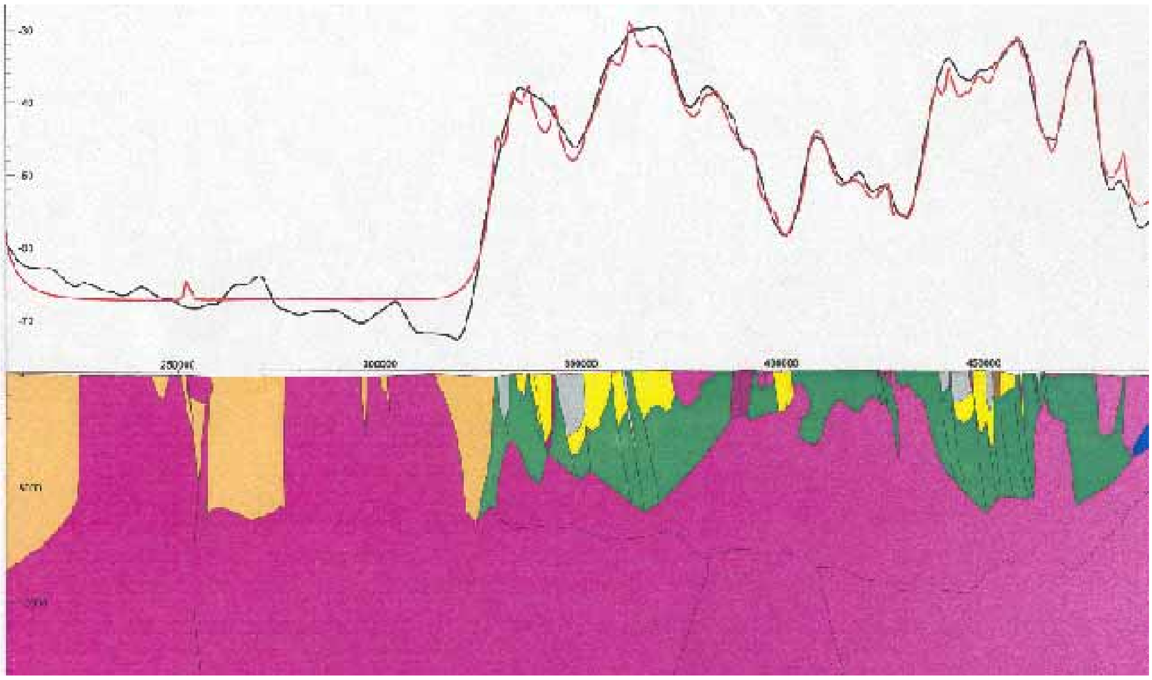

Figure 5 A representative modelled profile of a Laverton-Leonora section (682000 mN). Observed Bouguer gravity field in black and calculate response from model in red. Y-axis is mGals and ranges from –70 to –30. X-axis is eastings, commencing at 210000 mE and extending to 500000 mE. Cross-section depth extents to 10 kilometres. Pink polygons = granitoids; Grey = sedimentary; Yellow = felsic volcanics; Green = mafic; Purple = ultramafic

Results from horizontal gravity gradient images

Although a comprehensive analysis of the horizontal gradient data is yet to be completed for the Leonora-Laverton transect area, initial interpretation suggests that:

- The inferred granitoid/greenstone and gneiss/greenstone boundaries are located by this method (Fig. 6);
- Mafic units (or a lithology of similar density), which mark the boundary between the northern part of the Agnew-Mt Clifford and Murrin domains (Blewett et al, this volume) extend beneath the granitoid's margin. This is suggested by the series of horizontal gradient points occurring above the interpreted granite and sub-parallel to a granite/greenstone boundary;
- A major structure occurs along the eastern boundary of the Pig Well graben, dissecting the greenstone sequence.

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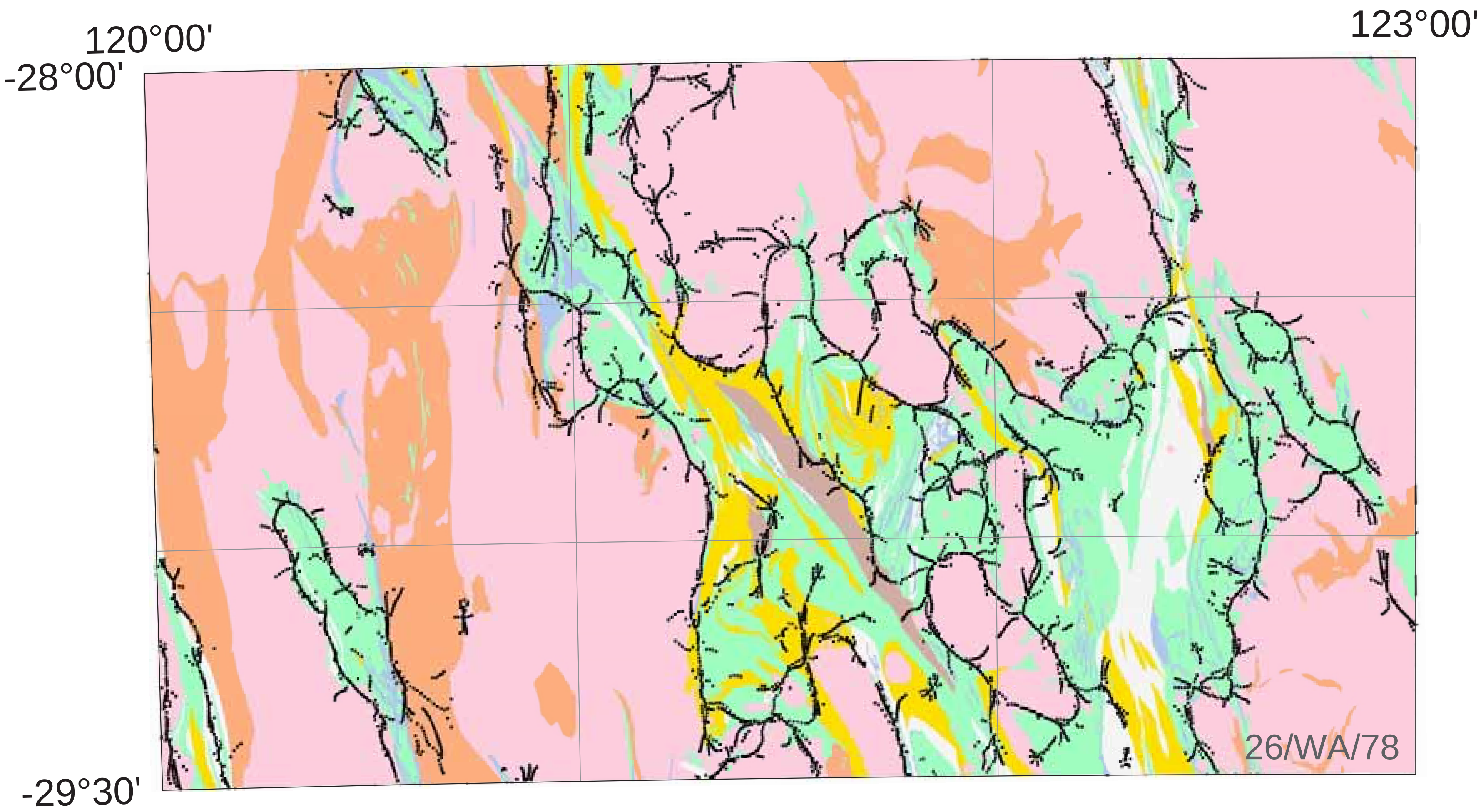

Figure 6 Horizontal gradient image of 2000 m upward continued Bouguer gravity data (black lines) over the Leonora-Laverton transect area solid geology. Only points where the horizontal gradient amplitude is greater then the calculated mean are shown

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Three dimensional (3D) model of the Leonora-Laverton transect area: implications for Eastern Goldfields tectonics and mineralisation

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Introduction

Three dimensional (3D) models are critical in understanding the structural architecture of a region. They help constrain a region's tectonics, and are critical for predicting fluid flow in an orogenic mineral system such as gold. Like planning, the process of model building is arguably more valuable to the participants than the outcome (the model). The actual process of integrating and building a regional 3D model thoroughly pushes a geologist's understanding and dogmas. Many geological concepts are repeatedly tested and require constant justification. Building a model in a team is by far the best way to advance the geological understanding of a group, and provides an opportunity for various specialists and generalists to integrate their knowledge in solving a common problem.

The Eastern Goldfields Province has a number of regional 3D models. The Australian Geodynamics CRC (AGCRC) published a model for twelve 1:100 000 geological sheets from Norseman to Menzies (Australian Geodynamics CRC, 1997). Goleby et al. (in press) developed a 3D model around the Kalgoorlie area. This later model built on the AGCRC model and incorporated a number of new seismic lines acquired in 1999. There is, therefore, a relatively good understanding of the third dimension in the southern part of the Eastern Goldfields.

This paper describes a new 3D model down to 15 km depth for the Leonora-Laverton transect area in the central Eastern Goldfields Province of the Yilgarn Craton. The model incorporates a transect of geology from eighteen 1:100 000 sheet areas, and is located north and northeast of the previously published models. The new model area is bounded between 28ºS and 29.5ºS and 120ºE and 123ºE, and includes the important mining centres, such as Agnew-Lawlers, Leonora, Laverton, Wallaby, and Sunrise (Fig. 1).

This paper documents the methodology and processes of how the new Leonora-Laverton model was built. We discuss the rationalisation of flat versus steep structures, strike-slip versus thrust faulting, alternative geometries for some areas within the model, likely tests of the alternatives, characterisation of the structural domains, and descriptions of geometry of the bounding structures. We also discuss the implications for Eastern Goldfields tectonics, contrast the southern area models, and consider implications for development of gold and nickel mineral systems.

Building the 3D model using the FIRSTO work flow process

Building the 3D model was an iterative process that involved the integration of 1:100 000 scale outcrop and solid geology and point observations, images of aeromagnetic data, gravity data (horizontal gradient anomalies, grids and stations), combined magnetic/gravity images, existing cross sections, seismic reflection data (line 01AGSNY1), and models and seismic reflection data along strike to the south. The model was built using the FIRSTO (K. Hill, written communication, 2001) work flow process developed for interpreting seismic data. The process provides rigour to interpretations, especially when diverse datasets are being integrated. The acronym stands for F-facts, I-interpretation/integration, R-regional, S-style, T-test, and O-open mind. Knowledge of the regional context (Regional) and structural style (Style) are important inputs in the interpretation process of the fundamental facts (Fig. 2).

F-facts

With increasing degrees of abstraction, successive levels of interpretation tend to lose sight of basic facts. We recognise that any geological map is an interpretation, however the geological layer can be taken as a fact for a number of reasons. Firstly, the model is designed to reflect the gross architecture at an order of magnitude scale smaller than the geological facts. Secondly, the detailed geology was much simplified in order to model, so any errors in interpretation were smoothed out in the simplification process.

The gravity and magnetic data were taken as facts. The magnetic data used were high-quality 200 m and 400 m flight line-spaced data that were gridded into various image presentations. The station spacing of the gravity data ranged from 1 km to 11 km (mainly <3 km for greenstone areas), so the accuracy of boundaries identified from gradients was assessed separately.

The seismic reflection line 01AGSNY1 transects the eastern half of the model area (Fig. 1), and provides an additional set of facts that can not be obtained from the potential field data. This seismic line also imaged structures located to the east of those observed in seismic lines to the south around Kalgoorlie, so provided new insights not obtainable from any other method. The processed data became available towards the end of the model building process, and helped provide additional constraints (such as dip of major structures) not available by the other datasets.

Regional

The Regional phase of the FIRSTO process considers the broader geological context of the model area, so the interpretation is not made in isolation. The knowledge of previous models and their underlying datasets from the Kalgoorlie region influenced the early interpretations and cross sections in terms of listric structures. The interpretation of domain boundaries was based on an assessment of which structures were province-wide. For example the Kilkenny lineament extends for several hundred kilometres north and south of the model area, has associated gravity and magnetic anomalies, and is clearly a major structure. A regional stratigraphic marker is the thick komatiite flows (Rattenbury, 1993). Regionally, these are dated at ca. 2705 Ma (Nelson, 1997).

Style

Look through any basic structural geology text book and it is apparent that there are numerous variations of deformation style. Dahlstrom (1969) noted that despite this variety that there was only a few styles or ‘families’ of deformation developed for any given package of rocks. This was considered to be due to the particular thermo-mechanical properties of the rock package, and the state of stress acting on them at that time. The implication of this observation is that for ambiguous areas it is better to maintain the style of deformation through the model, rather than radically alter it.

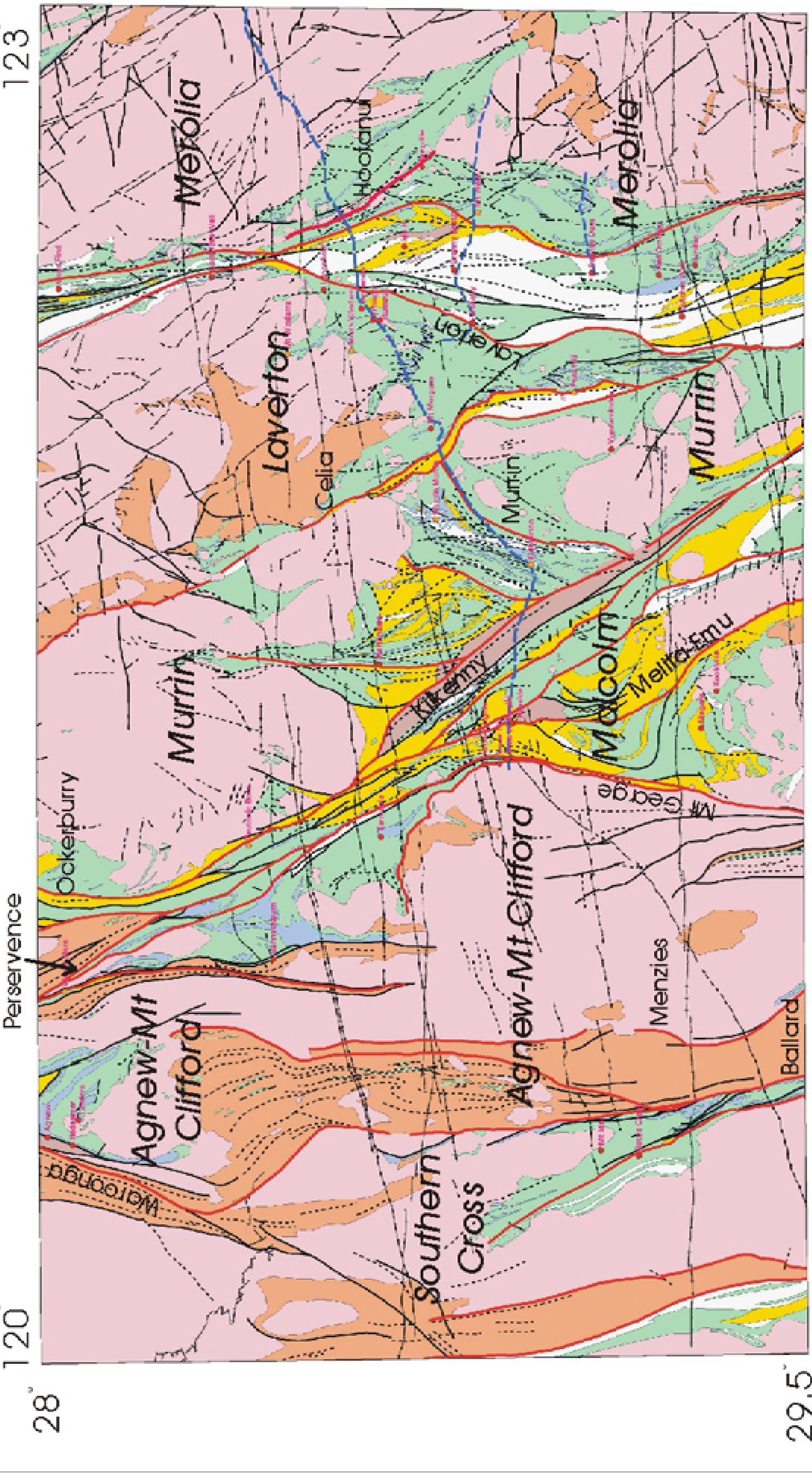

Figure 1 Solid geology map of Leonora-Laverton transect area with domains and their bounding structures

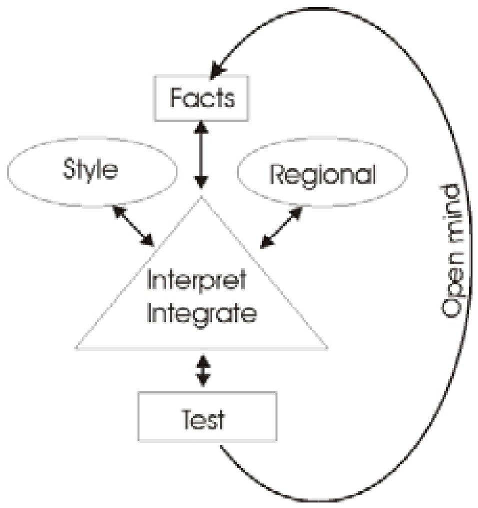

Figure 2 A schematic representation of the FIRSTO workflow process

An example of how this common style works can be seen in comparing the cross sections with the map patterns themselves. The style of the cross sections is similar to the actual map patterns, both contain phacoids of rock packages separated by sinusoidal faults or shear zones at all scales.

I-interpret/integrate

The interpretation-integration process uses a set of facts in the context of the regional picture and considers the likely style of deformation for the area. The interpretation process began with the construction of a base geological layer.

The underlying data for the base geological layer were a set of 1:100 000 scale solid geology maps that was derived from the interpretation of the gravity and magnetic data, various combinations of both, and integrated with the 1:100 000 scale geology (fact) maps (Groenewald, this volume). These solid geology maps were simplified and combined into a 1:250 000 scale solid geology map of the entire model area (Whitaker & Blewett, 2002), which provided the framework or base layer from which the model was built. This simplified map portrayed basic rock types such as granite, gneiss, ultramafic rock, mafic greenstone (basalt, gabbro and dolerite), felsic greenstone, sedimentary rocks, and conglomerate or ‘late’ basins (Fig. 1). These seven ‘units’ were chosen as they were the easiest to manage in terms of their geometry in 3D, and to potential field model to constrain the depths of the units (see Bell, this volume). The actual process of building the model meant that the base map was critically reviewed in 3D and found wanting in some areas. Changes were made back to the base solid geology map. This iteration reflects the ‘test’ phase of the FIRSTO process.

The third dimension of the model was obtained from drawing a series of E-W serial cross sections every 20 km for the model area. This process began before the seismic data were available for interpretation. The surface intercepts were obtained accurately from the GIS and the dips of boundaries and structures estimated from structural readings on the geology maps, the horizontal gradient anomalies, and/or the gravity/magnetic anomaly patterns. Based on previous modelling (Drummond et al., 1997; Goleby et al., 2000, in press) and the seismic knowledge around the Kalgoorlie area (Swager et al., 1997), the greenstones depths were taken to be about 7 km. The ‘style’ of the sections assumed a similar geometry to that from the Kalgoorlie area. For example the early sections were drawn with ~7 km greenstone depths and the fault dips were shallowed out into a ‘detachment’ at this depth at the base of the greenstone (Fig. 3). Some modification was made to the greenstone depth based on gradient changes in the gravity images.

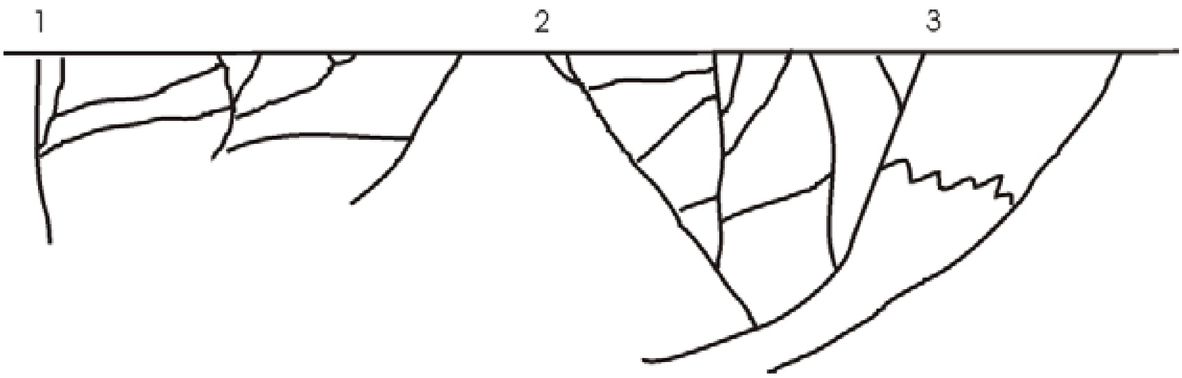

Figure 3 Example of the first iteration of the cross sections. Note the generally steep dips, and relatively deep greenstone (~7 km). 1 - George shear zone, 2 - Kilkenny shear zone, 3 - Murrin fault

These early serial sections were subsequently modelled to constrain the depths and attitude of structures and boundaries (see Bell, this volume). The sections were adjusted significantly following the potential field modelling. The team of geologists consistently overestimated the thickness of greenstone, and consistently overestimated the dips (too steep). The result was a new set of sections (Fig. 4) that were captured in gOcad® and a skeleton model was constructed.

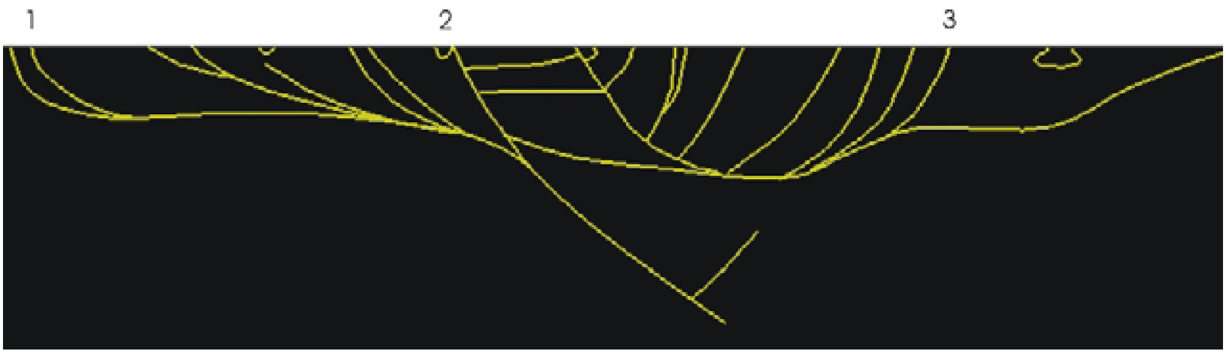

Figure 4 Example of the second iteration of the cross sections (same area as Fig. 3). Note the generally steep dips, and shallowing of the greenstone. 1 - Mt George shear zone, 2 - Kilkenny shear zone, 3 - Murrin fault

Test

One of the problems of the potential field data was the difficulty in constraining the geometry of structures below the base of the greenstones, or in the granite-gneiss-dominated areas. This is because of the lack of rock property contrasts in these areas. The seismic data are very good at imaging low-angle to moderately dipping structures. Most of us were surprised by the very shallow nature of the major bounding structures, and the enormous amount of 'structure' in the granite-gneiss domains.

The seismic reflection data provided an independent test of the 3D model, and in many cases the post-potential field modelled sections stood up to interpretations of the seismic data. The main area of difference in the serial cross sections was in the attitude of the structures.

A new set of serial sections was drawn to account for the more shallow dips, most flattening out to the east (Fig. 5). The process focussed on the area where the seismic line crossed, or was close to, the serial section lines. As the seismic line trends northeast, it crossed three of the serial section lines. New sections were drawn in parts and then extrapolated northwards and southwards to adjacent sections. The gravity data were reviewed in light of changing the dips on the bounding structures (and consequently their contained rock volumes) as this inevitably shifted mass eastwards.

The major bounding structures are modelled as surfaces. These surfaces were created from interpolation between the cross sectional lines. The geometry and style of the surface was maintained by sliding a template northwards and southwards to successive cross sections. Attempting to pick the ‘major structure’ in successive lines was a test in itself. The earliest sections were not consistent and parallel faults were sometimes chosen as the main bounding structure.

Each successive section in itself becomes a test of the adjacent section. This is particularly true where the geology is elongate and linear as the same surface is represented on all ten sections. New information is commonly available along strike, so the earlier sections may need to be revisited. The rigour of drawing serial sections tested assumptions about what structure was important, suggesting that this approach challenges the rigour of simply drawing a single section across a map in terms of representing the third dimension.

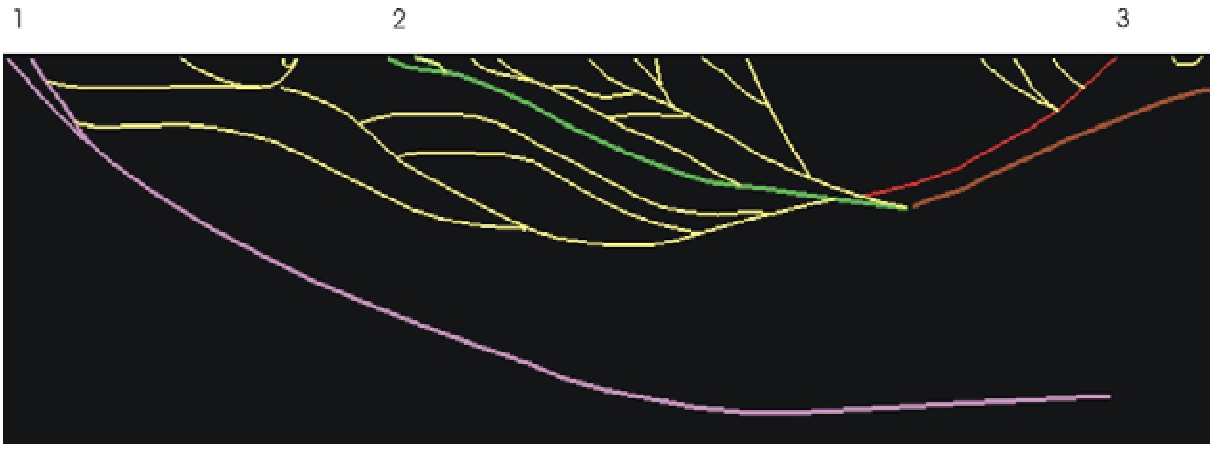

Figure 5 Example of the final iteration of the cross sections (same area as Figs. 3, 4), following input of seismic reflection geometry. Note the shallow dips, and relatively shallow greenstone. 1 - Mt George shear zone, 2 - Kilkenny shear zone, 3 - Murrin fault

Open Mind

Geology is not an exact science, and an open mind is needed so that other hypotheses may be considered. We have developed a simple model of the 3D structure of the Leonora-Laverton region that broadly satisfies the geology, potential field, and seismic data layers. What we do not have is a single deep drill hole to either prove or disprove our model.

We recognise that there are other ways to interpret all these datasets, and therefore many possible alternative models. It is scientifically healthy to consider multiple working hypotheses, but unfortunately constructing complete multiple models would be a very time consuming and expensive exercise.

Data standards

Geoscience Australia has been at the forefront in promoting national standards for digital data. There is no national standard for representing 3D geological models. One area particularly lacking is the confidence level of features in the model, and their lineage (what they were derived from). This is an area that must be developed and agreed upon if more models are to be built and, more importantly, merged together.

Features of the 3D model

The following is a list of the features of the 3D architecture of the Leonora-Laverton transect area:

- domains defined on the basis of surface geology and structure coincide with differences in the reflectivity of the seismic data;
- gravity modelling show that the crust below the greenstones is essentially felsic, and may be equivalent to the gneiss-migmatite dominated domains (external granites);
- greenstones are mostly shallow (<6 km), some areas are <1 km thick above gneiss/granite substrate;
- the greenstone to underlying granite/gneiss interface is modelled as a low-angle surface that dips gently to the east, a feature confirmed by the seismic reflection data;
- the seismic data image a number of low-angle shears (LASH), with several within the felsic crust below the greenstone base[1];
- the LASH's have 'topography' and it is difficult to determine if these are openly folded or part of a mega S-C geometry,
- exposed 'internal' granites are modelled as windows through the greenstone base, and they show that the greenstone base is partly intrusive;
- however, the seismic data show that some parts of the greenstone base is likely to be sheared by LASH's;
- forward modelling of the gravity data show that some of the 'internal' granites are thin sheets in 3D;
- major domain-bounding shear zones dip to the east at <45° and flatten out at depth;
- the timing between the major domain-bounding shear zones and the LASH's at depth is variable,
- there are few west-dipping structures, in the model area;
- the dip of penetrative fabrics generally is mostly steep at the surface;
- the main superimposed fabric or regional strike across the model is north-northwest;
- major domain-bounding shear zones in the east of the model have late extension (transtension) following earlier west-directed thrusting (transpression);
- major extension post-dates earlier compression of the Pig Well succession;
- out of plane movement (strike-slip deformation) is not easily resolved with the compression-extension geometry.

The 3D geometry of domain-bounding shear zones

Below the base of greenstone, or in granite-gneiss domains, it is difficult to establish the geometry of the major structures. The eastern half of the model has the benefit of the seismic reflection data to provide additional control, and it images many of the major domain-bounding shear zones as deep-penetrating structures. In the west of the model, some of the major domain-bounding shear zones (e.g., Ballard-Ida Fault) are imaged along strike to the south (in seismic data reported by Swager et al., 1997), also as deep structures.

The major faults and shear zones divide the model area into a series of domains (Fig. 1) that

[1] The term low-angle shear zone is preferred to that of detachment, because of the genetic connotations of the latter.

largely correspond to the tectonostratigraphic domains outlined by Cassidy et al. (this volume). Most of these structures are high-strain zones that trend north-northwest. Some may separate different lithostratigraphic packages and may have been initiated as basin-bounding faults with a prolonged kinematic history (Hallberg, 1985).

Waroonga-Ballard shear zones

At the western side of the model area, the Waroonga-Ballard shear zones strike mostly north-south and separate rocks from the Southern Cross Province to the west from Eastern Goldfields Province rocks to the east. The Waroonga-Ballard shear zones form the boundary between the Southern Cross Province domain and the Agnew-Mt Clifford domain (Fig. 1).

The Waroonga shear zone dips steeply to the west, flattening out at about 10 km depth into a listric geometry. It appears to transect the Ballard shear zone which is a steeply east-dipping structure to the bottom of the model at 15 km. The Waroonga shear zone and related faults record sinistral shear (Liu et al., 2002) along the northern arm, and dextral shear on the southern arm (Platt et al., 1978).

A blastomylonitic fabric in gneissic granite along the Ballard shear zone dips steeply to the east, hosts a gentle (<20°) south-plunging lineation, and records a dextral sense of shear on S-C planes. On the regional scale, the geometry of the Ballard shear zone is normal in the model, consistent with its along strike trace (the Ida Fault) to the west of Kalgoorlie (Swager et al., 1997). Slivers of amphibolite along the shear zone on the Wilbah 1:100 000 sheet area, record an additional steeper lineation and an earlier fabric. However, the steep lineation may be an intersection lineation between the two fabrics.

The Menzies shear zone

The Menzies shear zone is a wide zone of deformation with a prolonged movement history. Swager (1994) suggests that it may separate different tectonostratigraphic terranes. On the basis of alignment of aeromagnetic features, the Menzies shear zone trends northwest from Menzies and forms the north-trending eastern margin of the gneiss belt on the Wilbah 1:100 000 sheet area. Swager (1994) describes sinistral west-block down movement on the Menzies shear zone to the south.

The 3D model considers the base of the Wilbah gneiss to be dipping to the west, and deeper levels of gneiss to be preserved in the east. The Menzies shear zone is overprinted by undated granite plutons. At a depth of about 20 km under the town of Leonora (6.5 secs two-way travel time), are a set of strong reflectors that dip 20° to the east. These reflectors project to the surface at the Menzies shear zone some 60 km further west, and may represent the deep expression of this shear system.

The Moriaty-Mt George-Perseverance shear zones

The Mt George shear zone is the eastern splay of the Moriarty shear zone (Witt, 1994), and they separate the Agnew-Mt Clifford and Malcolm domains (Fig. 1). Witt (1994) described dextral shear on the Moriarty shear zone, and on the northeastern trace of the Mt George shear zone. Williams et al. (1989) described sinistral shear on the Mt George shear zone along the northwest trending segment to the north of Leonora.

The Mt George shear zone is interpreted as a listric structure, dipping moderately to gently to the east. The shear zone flattens out at about 17 km depth, below the base of the greenstones, and extends eastwards under the Malcolm and Murrin domains (Fig. 1) as a flat surface.

The Perseverance shear zone is the name given to the northwest-trending segment of the Mt George shear zone to the north of Mt Clifford. Intensely foliated and lineated granitic and greenstone rocks up to 1 km comprise the shear zone. Movement indicators are sinistral on steeply dipping mylonitic foliations (Liu et al., 2002). Eisenlohr (1992) described a steep south-southeast, and a gentle north-plunging lineation. The merging of relating faults into the Perseverance shear zone, and the asymmetry of folds, suggest that a component of west-directed thrusting across this structure (Liu et al., 2002).

The Melita-Emu shear zone

The Melita-Emu shear zone (Fig. 1), and is a splay of, or is transected by, the Kilkenny shear zone. Based on the coincidence of the gravity inflection and the shear zone across a granite-greenstone boundary, we suggest that the Melita-Emu shear zone dips to the east, and not west. The Emu Fault in the Kalgoorlie model area is interpreted to dip to the west (see Goleby et al., 1993; Swager et al., 1997). Chen et al. (2001) recorded sinistral shear as well as a component of dip-slip movement on the Melita-Emu shear zone.

The Kilkenny and Ockerburry shear zones

The Ockerburry shear zone is interpreted as the northern trace of the Kilkenny shear zone (Fig. 1). Both sinistral and dextral movement senses have been observed along the Ockerburry shear zone (Vearncombe, 1998; Chen et al., 2001). However, the overall architecture of the fault zone shows a Z-sigmoidal pattern, consistent with sinistral shearing (Chen et al., 2001). Lineations are mostly shallow plunging, indicative of strike-slip movements. An alternative model is to link the Ockerburry shear zone with the Mt George shear zone, thereby transecting the Kilkenny shear zone (see Whitaker et al., this volume).

The Kilkenny shear zone is a prominent north-northwest linear zone of deformation that controls the present day topography. In the model area it contains and deforms the Pig Well sequence, which comprises canyon-fill conglomerate and coarse clastic metasedimentary rocks (Hallberg, 1985). Rocks considered equivalent to these have been dated elsewhere at <2665 Ma (Krapez et al., 2000). Early movements on the fault may have been important in controlling sedimentation of the Pig Well sequence, either as a extensional growth fault, or as a piggy back basin during foreland-directed thrusting.

The Kilkenny shear zone wraps around the western margin of the Mertondale Batholith, and merges with the Ockerburry shear zone. The Kilkenny shear zone separates the Malcolm and Murrin domains (Fig. 1). The Kilkenny shear zone marks a significant gravity low that is at a high angle to a gravity high located in the Welcome Well area to the east (North Murrin sub-domain). This gravity low along the Kilkenny is not simply due to thick accumulations of Pig Well metasedimentary rocks, because talc schists from the underlying basement are locally exposed. This suggests that significant older felsic greenstone (i.e., low-density rock) is incorporated into the Kilkenny shear zone at depth. Chen et al. (2001) described sinistral strike-slip movements that overprint an earlier phase of dip-slip movement. In the model, the Kilkenny shear zone dips 35-40° to the east, and is more planar than other major faults in 3D.

The Murrin Fault

The Murrin Fault divides the Murrin domains into north and south sub-domains (Fig. 1), and trends northeast between the younger Kilkenny and Celia shear zones. The seismic reflection line was acquired parallel to the Murrin Fault, however the fault is interpreted to dip northwestward and be truncated by structures parallel to the Kilkenny shear zone. The Murrin Fault is one of the few structures that dip with an apparent attitude to the west in the 3D model.

The Murrin Fault marks the southeastern extent of the geology ascribed to the Mt Kilkenny-Welcome Well area by Chen et al. (2001). To the southeast, in the South Murrin sub-domain, granites intrude the basalts.

The Celia shear zone

The Celia shear zone is another strike continuous north-northwest trending structure, with a pronounced aeromagnetic pattern reflecting a wide high-strain zone. The Celia shear zone dips moderately to gently to the east (30°), and cuts the Murrin Fault. Its last movements are interpreted as extensional as thick greenstone is preserved above the eastern footwall (Laverton domain), reflecting higher structural levels than the greenstone to the west (Murrin domain). Chen et al. (2001) described predominantly sinistral shear kinematics for some of the later movements. Swager (1995) inferred earlier thrusting and repetition of stratigraphy on the Celia shear zone, an interpretation supported by shallow-plunging folds and steeply-plunging lineations (Chen et al., 2001).

The Laverton shear zone

The Laverton shear zone is an east-dipping structure with an extensional (normal) geometry (on the base of the greenstones) and separates the Laverton domain into north and south sub-domains (Fig. 1). Imbrication of South Laverton sub-domain rocks during thrusting has been more than offset by a greater extensional reactivation (assuming the base of the greenstone is a reliable marker surface). In the 3D model, the Laverton shear zone is a splay of the Celia shear zone.

The Hootanui shear zone

The north-northwest trending Hootanui shear zone (Chen et al., 2001) dips gently to the east, and on the surface is marked by highly deformed (mylonitic) syenites that are dated at ca. 2664 Ma (Black et al., 2002). Kinematic indicators in the mylonites record early sinistral shear overprinted by a reworking of the fabric by dextral shearing. In both cases, lineations are gently dipping on moderately to steeply east-dipping mylonitic fabrics. Chen et al. (2001) also recorded earlier dip-slip movements. The Hootanui shear zone is a splay from a series of apparent west-directed thrusts deeper in the crust.

Geological curios, ambiguities, and new ideas

Most geologists who have traversed the Eastern Goldfields have noted the steep attitude of many of the planar structural elements at the surface (schistosity, cleavage, shear zones, bedding, etc). The seismic reflection technique is excellent at enhancing flat structures. This paradox between steep and flat structures can be explained in several ways (Fig. 6):

- all structures that are steep at the surface quickly flatten at depth;
- the low relief of the area has an aliasing effect on low-angle features;
- the low-angle features are the enveloping surfaces ‘containing’ packages of upright, steeply dipping structural elements, and/or;
- the geometry may be analogous to S-C fabrics at all scales (fractal), so that no matter where the crust is exposed the geometry will be constant.

The fundamental map view and cross sectional geometry is similar, i.e., the map view is an oblique section of the crust. However, the geometry of the cross sections, and of the seismic reflection data, is consistent with a strong component of thrusting and extensional deformation, roughly parallel to the section (east-west). The map patterns of much of the late structure is consistent with a large amount of strike-slip deformation (see discussion of domain boundaries above). This movement is out of the plane of the seismic data and the serial cross sections. A data dump from the OZROX database of all lineations in the model area show a spread of plunge from horizontal to vertical, with a slight predominance of lineations <50° (Fig. 7). However, the partitioning of strain between competent and incompetent rocks leads to orthogonal lineations under the same deformation regime (Goodwin & Tickoff, 2002).

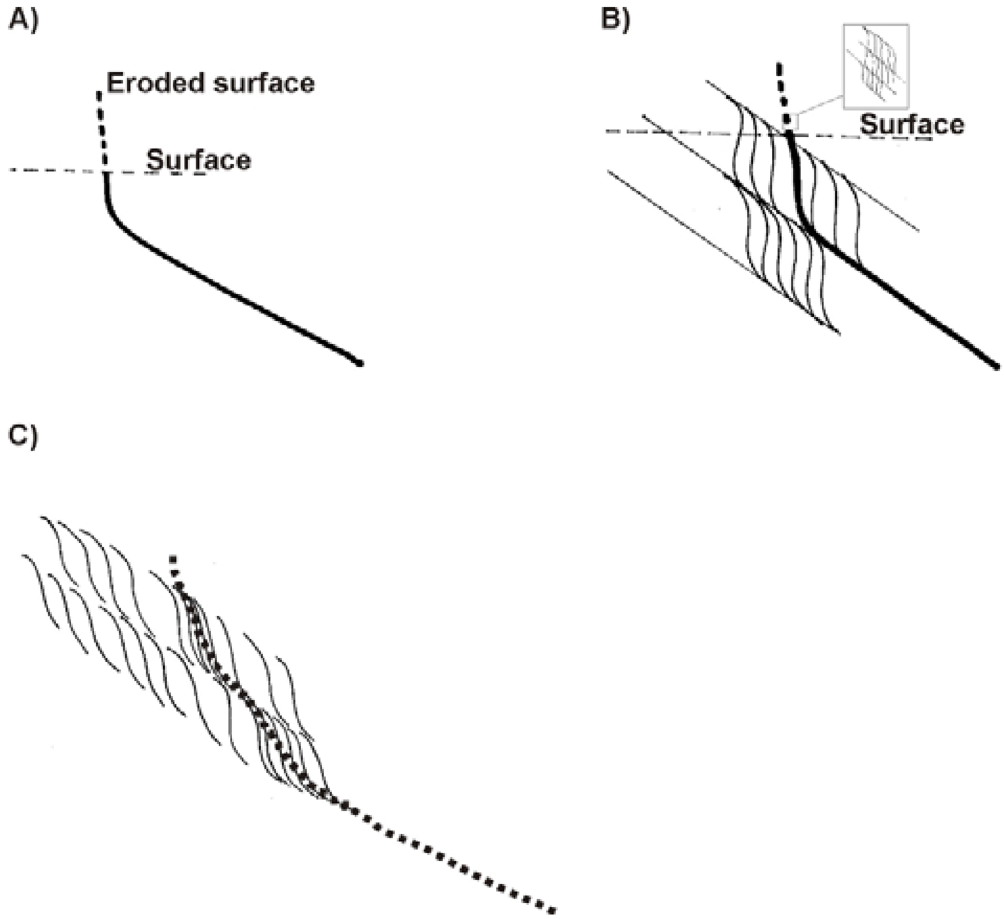

Figure 6 **Possible ways the steep structures at the surface can be reconciled by flat structures at depth: A) all structures that are steep at the surface quickly flatten at depth; B) the geometry may be analogous to S-C fabrics at all scales (fractal), so that no matter where the crust is exposed the geometry with be constant; C) C-planes are not developed as discrete fabric elements, rather the S-planes converge and strain is accommodated by ductile flow and attenuation of steep S-planes**

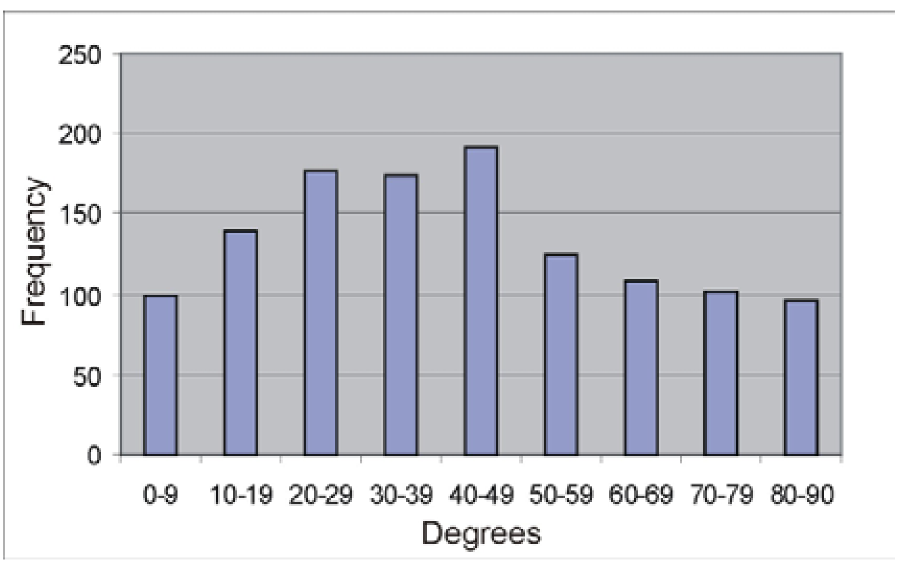

Figure 7 **Histogram of all lineation plunges in the model area from OZROX database (n = 1250). Note most lineations plunge <50°, but there are a significant number of steep (down-dip) lineations**

How are the orthogonal tectonics implied by the sectional views and the lateral tectonics to be reconciled? The Eastern Goldfields has had at least 5 km of erosion to the present level. It is possible that the classic strike-slip zones typified by flower structures in the highest structural levels, sole out depth into the geometries that are mapped here in the 3D model.

Poor outcrop and deep weathering/regolith is a feature of the Eastern Goldfields. This makes the development of solid geology maps difficult. Even with many drill holes, the inconsistency in the ways lithological data have been described, reduces their utility for interpretation. The potential field modelling requires input parameters such as density for gravity and magnetic susceptibility for magnetic modelling. These input parameters are estimated from the distribution and percentage of rocks at the surface and near surface, and are thus influenced by the reliability and accuracy of the solid geology maps. This obviously changes the depth estimates of the greenstones. Errors in these input parameters and on misidentified rocktypes can give large errors in the resulting models. Errors at the earliest stage in the process become carried through the entire model, and the model is only as good as the sum of its parts. For example, the basalts and the sediments are both difficult to separate on magnetic data. However, their densities are significantly different. An area of concealed greenstone can be interpreted as either thin basalt, or as thick sediment, and both interpretations honour the gravity and magnetic data.

Many of the major domain-bounding shear zones are close to the contacts with granite batholiths and plutons. In areas of poor outcrop, it is often difficult to determine in the aeromagnetic data if the shear zone is intruded by the granite (or late phases of it), or if the shear zone overprints the granite. These ambiguities have important implications for the timing of fault movements, and therefore the architecture of the area. The best approach to this problem is to work with multiple working hypotheses, rather than be wedded to a unique solution.

Time markers are a critical factor in any tectonic reconstruction. In this model, the 2705 Ma komatiites (Rattenbury, 1993), the 2640 Ma low-Ca granites, and the 2640 Ma (late) lode-Au event are considered time markers across the Eastern Yilgarn Craton. If these assumptions are valid, then the following inferences on the post-2705 Ma tectonic evolution can be made:

1. the stratigraphic section below the komatiites in the model area contains a significant section of older greenstone than that described in the Kalgoorlie Terrane;
2. there is not enough greenstone section available in the Kalgoorlie Terrane to accommodate the extent of this older Leonora-Laverton stratigraphy;
3. the Laverton stratigraphic section is below the komatiite marker, and yet this area is underlain by the some of the thickest greenstones in the model area;

   This can be explained in two ways:

   i. extensive thrust imbrication of the Laverton section accounts for the unusual thickness, and/or;

   ii. the stratigraphic section below Laverton is non-layer cake, thinning to the west and southwest, forming a Z-like ‘interwedging’ with the overlying Black Flag Group above the komatiite marker;
4. the Laverton shear zone records significant normal movement (collapse?) following earlier imbrication (point i above). This assumes stratigraphic continuity or an original continuous greenstone base;
5. syn-komatiite extension (2705 Ma) is required to explain the juxtaposition of high-grade gneiss and low-grade greenstone (i.e., core-complex extension of Williams & Whitaker, 1993);
6. the high-grade cores were not emergent as granite/gneiss detritus does not occur until after 2665 Ma (Krapez et al., 2000);

7. the early extension established the fundamental architecture of NNW-trending transfer structures by accommodating the N-S extension;
8. once established, these NNW-trending structures were repeatedly reactivated and inverted by later events (Table 1);
9. the orogen was tilted down to the SW as Black Flag equivalent rocks were stripped from the model area and the Late Basins were deposited directly onto pre-2705 Ma greenstone in the model area.

Significant tests of the veracity of these inferences would be provided by appropriate geochronology of 'Association 1' (Hallberg, 1985) showing a general progression to older greenstone sequences to the NW, and by improved knowledge of the structural history across and between domains.

In this model, the north-northwest-trending De transfer faults developed as domain boundaries, and they subsequently established the fundamental grain to the Norseman-Wiluna belt. This hypothesis implies that the transfer faults acted as lateral ramps during D1 thrusting to the north, and as frontal ramps during D2 thrusting from the east. Later D3 and younger strike-slip movements, and the possible late extensional event, reactivated these fundamental crustal weaknesses. If this model were correct, then the D1 form surfaces would be at a high angle (orthogonal) to the lateral ramps, and their intersection would plunge shallowly to the south. Most form surfaces are currently at a low angle to these fundamental structures. Transposition during D2 and D3 may account for this angular relationship.

Geological-tectonic implications of the 3D model

The 3D model provides a geometrical framework for the distribution of granites and greenstones, as well as the major domain-bounding shear zones for the Leonora-Laverton transect area. This framework when combined with structural, stratigraphic, geochemical, and isotopic (age) constraints provides a powerful starting point for the geological restoration of the area. However, most of the geometry and architecture of the model, and structures in the seismic reflection data, are recording the latest events.

Regional structural studies generally describe a De, D1, D2, D3 structural history for the Eastern Goldfields Province, and the Leonora-Laverton transect area (Archibald et al., 1978; Swager, 1989, 1997; Hammond & Nisbet, 1992; Williams & Whitaker, 1993; Chen et al., 2001) The successive phases of deformation are generally characterised by:

- De - low angle extension, top down to the southeast;
- D1 – top to the north thrusting;
- D2 – upright folding and thrusting due to east-north oriented compression;
- D3 and younger – a series of strike-slip faults and shearing.

The following discussion considers the 3D model in terms of this regional deformation framework (Table 1). The earliest geological events are recorded by the discovery of old (>2750 Ma) greenstone and granite/gneiss across a number of the domains mainly to the north of the Leonora-Laverton transect area at Wiluna, Dingo Range, and Duketon (Fletcher et al., 2001; Dunphy et al., in prep). The relationship between these old fragments, their deformation/metamorphic history, and the Kalgoorlie-based stratigraphy (and its deformation/metamorphic history), is unclear. The presence of ca. 2755 Ma Au mineralisation in the Leonora area (Witt, 2001) reflects deformation/metamorphism and fluid movement at least 50 m.y. before much of the Kalgoorlie stratigraphy was deposited.

A major komatiite event at ca. 2705 Ma (age from Nelson, 1997) reflects a major extensional event across the Eastern Goldfields Province. The komatiites were erupted with thick basalt flows, and intruded by gabbro and dolerite. Interflow sedimentary rocks include fine-grained clastics, epiclastics, and cherts, were also deposited. Evidence for an extensional event at this time occurred in the Laverton domain (see Williams & Whitaker, 1993), and at Lawlers in the Agnew-Mt Clifford domain (Hammond & Nisbet, 1992), and is best preserved along granite-greenstone contacts (lags). This event is variably defined as De, and involved top to the southeast movement. Variable extension resulted in the development of a series of basins, with movement accommodated by northwest-southeast transfer faults.

D1 shortening from the north or south inverted the greenstone basins, with thrusting to the north on previous extensional shear zones, and macroscale folding about east-west axes. The De transfer faults were reactivated as lateral ramps.

D2 shortening from the east resulted in macroscale refolding of F1 folds in a number of areas, prior to the so-called late basins (e.g., Pig Well sequence). Associated with the east-west shortening was the reactivation of D1 lateral ramps into frontal ramps of major west-directed thrust faults, resulting in duplicated stratigraphy and the west-directed vergence.

The late-stage sedimentary rocks may have been deposited in intermontane basins during piggy-back thrusting, or in roll-over anticlines (Swager, 1997). Alternatively, extension occurred and these basins were developed on reactivated thrusts. Davis et al. (2001) describe a hiatus in east-west compression at Mulgarrie (to the south of the Leonora-Laverton transect area), perhaps reflecting this event. Compression continued/renewed and inverted and deformed the late-stage basins.

D3 strike-slip was mostly sinistral on the major domain-bounding faults, followed by dextral shearing (Swager, 1997; Chen et al., 2001). Hammond & Nisbet (1992) point out that many of the so-called D3 sinistral strike-slip faults are D2 tilted D1 thrusts, and that the apparent sinistral movement is consistent with earlier flat-lying south over north thrusting. This may be partly true, however, as sinistral shear zones cut ca. 2640 Ma Low-Ca granites in the 3D model area, indicating that at least some of these structures are late.

One of the main new findings of this study is the suggestion of significant late extension/ transtension, which resulted in the reactivation of a number of deep penetrating faults. This extension may reflect an orogenic (gravity?) collapse, and be associated with exhumation of the orogen. What influence this had on the fluid pathways of the orogenic gold system is unknown, but if true, adds a new dimension to our understanding of the mineral system.

The last event was a rotation of the entire area, manifest by the development of numerous small-offset (sinistral), east-west brittle faults (see Whitaker et al., this volume).

Mineralisation

The 3D model provides a number of new findings that impact on the mineral systems of the region.

- The world-class deposits of the Leonora-Laverton transect area are hosted near major **deep-penetrating** shear zones, e.g., the Laverton shear zone and the Mt George shear zone. However, other deep-penetrating structures (e.g., Celia shear zone) do not contain world-class deposits.
- The late extension, inferred from the geometry of the 3D model, may also have controlled fluid focussing during the late-stage orogenic gold event. Support for an extensional setting for orogenic gold occurs in major deposits in the South Laverton sub-domain, where low-angle late extension is associated with mineralisation (B. Davis, written communication, 2002).

Table 1 Event chronology in Leonora-Laverton transect area

Age Ma	Regional event	Event Characteristics	Gst	Grt	Au
		Basement developed and deformed (thrusted?)[1], only remnants preserved			
2760					Leonora[1]
		Extension? In an arc/backarc setting?? Welcome Well? and other sequences below regional komatiite marker eg Kurnalpi domain			
~2705	De	Mantle upwelling (plume); N-S extension (core-complex)[3]; develop N-S transfer structures; juxtaposition of external gneiss and greenstone; [2]komatiite, basalt, & high Mg basalt/komatiite			
	D1	N-S compression develop E-W folds, equivalent to N-directed thrusting[4]			
		Extension? regional tilt down to SW (preservation of BFG to Kalgoorlie Domain); erosion not too base of greenstone as few granite clasts in Late Basins			
>2665	D2	ENE compression, major folding, imbrication of structurally lower (older?) west over structurally higher (younger?) packages in east; develop main NNW fabric			[7]Jundee?
<2655[5]		Late Basins (Pig Well) in inter-montane or piggy back basins			
<2665	D3	Sinistral strike-slip (NNW) followed by dextral strike-slip; dextral strike-slip (N and NE); transpression[6]			
2640					Main Au
		Inferred extension (collapse?) down to east, inferred from base of greenstone offset and greenstone thickness changes			
~2400		E-W sinistral shearing rotated entire Goldfields ~15 anticlockwise; E-W dykes			

Sources: [1]Witt, 2001; [2]Nelson, 1997; [3]Williams & Whitaker, 1993; [4]Swager, 1997; [5]Krapez et al., 2000; [6]Chen et al., 2001; [7]Yeats et al., 2001. (Gst-greenstone; Grt-granite).

- Assuming that Witt (2001) is correct in identifying >2750 Ma gold mineralisation at Leonora, then the prospectivity of the old terranes is enhanced as they would have had the opportunity to be mineralised more than once.
- If the Kalgoorlie Terrane ultramafic volcanic rocks (ca. 2705 Ma) correlate with the top of “Association 2” in the transect area, then the Laverton komatiites of “Association 1” (i.e., at Windarra), are older. It, therefore, follows that there is more than one age for magmatic Cu-Ni-sulfide mineralisation in the eastern Yilgarn.

Conclusions

The 3D model provides a geometrical framework for the distribution of granites and greenstones, as well as the major domain-bounding shear zones for the Leonora-Laverton area. This framework when combined with structural, stratigraphic, geochemical, and isotopic (age) constraints provides a powerful starting point for understanding the tectonic evolution of the Eastern Yilgarn Craton. The 3D model highlights gaps in the geological understanding and identifies and focuses on the key issues that need to be further addressed in order to resolve the tectonic and metallogenic history of the region.

Acknowledgements

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Release of the GA-GSWA-*pmd**CRC seismic reflection data, 2001 Northern Yilgarn seismic survey

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In excess of 430 km of deep seismic reflection data were acquired along two seismic traverses in the northeastern portion of the Yilgarn Craton of Western Australia in 2001 (Fig. 1). These seismic data were acquired by Geoscience Australia and the Geological Survey of Western Australia in conjunction with the Predictive Mineral Discovery Cooperative Research Centre. This data set is now processed and ready for release. Acquisition and processing information is in Jones et al. (this volume).

Line 01AGS-NY1 was 384 km long. It commenced near the 'Sons of Gwalia' mine at Leonora, headed eastwards through the township of Laverton towards the Great Victoria Desert, and ended just to the east of Lake Yeo. Line 01AGS-NY3 was 52 km long, began at the eastern end of 01AGS-NY1, and headed northeast across the western margin of the Officer Basin. 01AGS-NY3 tied to the mineral exploration drill hole NJD1 that bottomed in sedimentary rocks of the Neoproterozoic Officer Basin underlying the Palaeozoic Gunbarrel Basin.

The seismic data released as part of this project include:

01AGS-NY1

Display Type	Record Length	Horizontal Scale	V/H @ 6 km/s
Stacked Section	4 sec	1:25,000	1
Stacked Section	18 sec	1:100,000	1
Migrated Section	4 sec	1:25,000	1
Migrated Section	18 sec	1:100,000	1

01AGS-NY3

Display Type	Record Length	Horizontal Scale	V/H @ 6 km/s
Stacked Section	4 sec	1:25,000	1
Stacked Section	16 sec	1:100,000	1
Migrated Section	4 sec	1:25,000	1
Migrated Section	16 sec	1:100,000	1

Paper copies of the seismic sections are available from Geoscience Australia on request. (Contact the Sales Centre via email: sales@ga.gov.au, tel: (02) 6249 9519, fax: (02) 6249 9982 or post: Geoscience Australia Sales Centre, GPO Box 378, Canberra, ACT, 2601, Australia). There will be a charge for production of these sections.

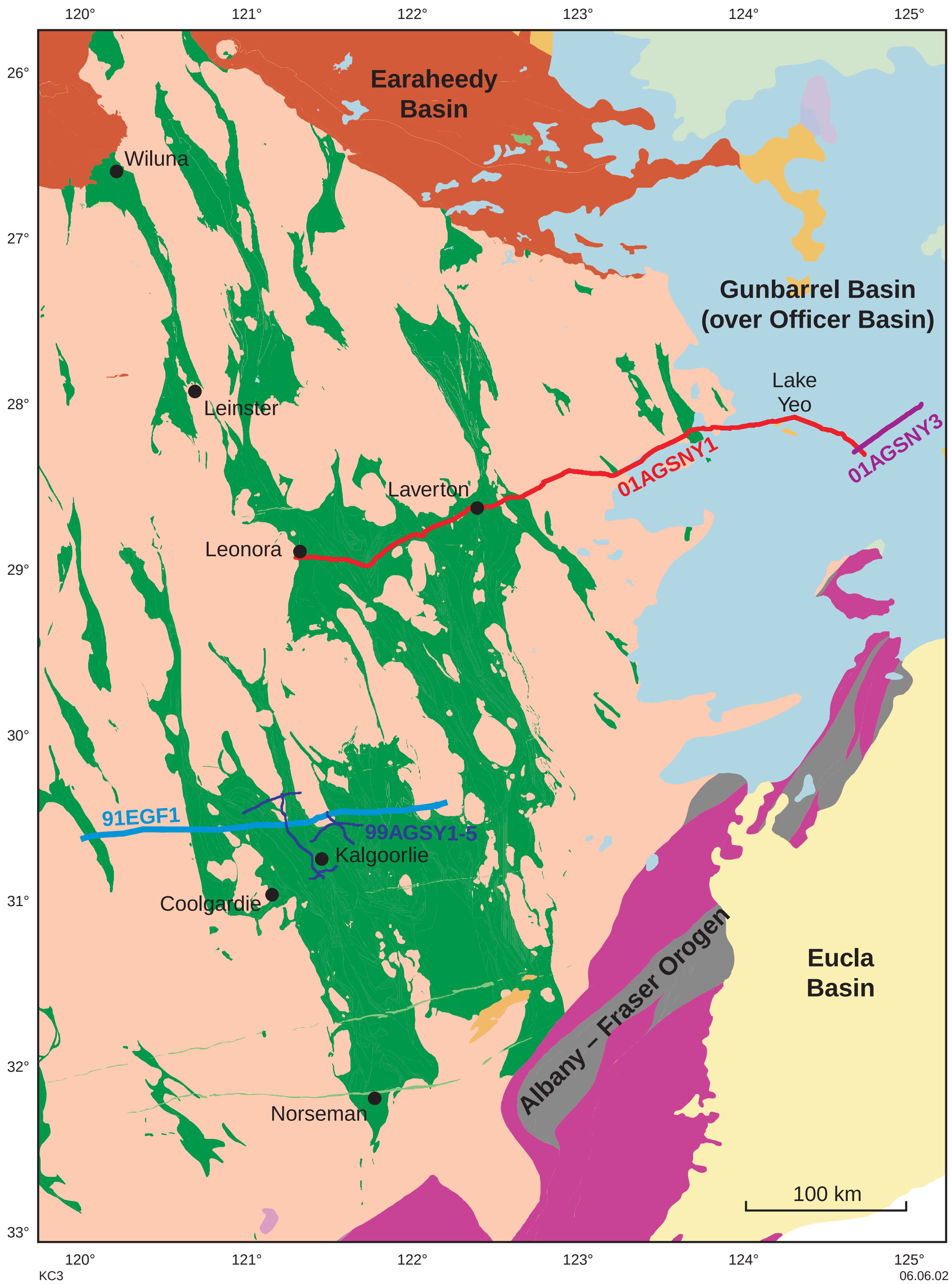

Figure 1 Location of the 2001 Northern Yilgarn seismic reflection survey, showing lines 01AGS-NY1 and 01AGS-NY3. The location of the 1991 and 1999 seismic reflection surveys are also shown

Digital copies of either the migrated or stacked data in SEG-Y format are available from Geoscience Australia on request. (Contact Mr David Johnstone via tel: (02) 6249 9449). There will be a charge for production of the tapes.

A graphic format version of these sections is available for download from either from Geoscience Australia or the Geological Survey of Western Australia web site.

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Tectonic setting of the 2001 "Northern Yilgarn" deep seismic reflection survey, eastern Yilgarn Craton and adjacent Officer and Gunbarrel Basins

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The 2001 "Northern Yilgarn" deep seismic reflection survey (Fig. 1) follows on from the successful 1991, 1997 and 1999 surveys in the Archaean Eastern Goldfields Granite-Greenstone Terrane of the Yilgarn Craton. The earlier surveys (Goleby et al., 1993, 2000; Swager et al. 1997) concentrated on the granite-greenstones around Kalgoorlie, which contain world class gold and nickel deposits. The new survey was intended to test the Kalgoorlie-based model in the Leonora-Laverton area, also within the Eastern Goldfields Granite-Greenstone Terrane. The opportunity was taken to extend the survey towards the buried eastern margin of the Yilgarn Craton, onto the Neoproterozoic Officer Basin and the Phanerozoic Gunbarrel Basin. The eastern end of the survey passes through a mineral exploration drillhole NJD1, which penetrated part of the Officer Basin succession.

The earlier surveys provided information that contributed to a 3-D model for the greenstones of the Kalgoorlie area. The data was used to determine the thickness and internal structure, the shape of certain granite intrusions, and the geometry of faults, and possible deformation surfaces and histories. One of the most important results was the recognition of a basal detachment surface below the greenstones (Swager et al., 1997). The 2001 survey will allow comparisons to be made between the Kalgoorlie and Leonora-Laverton areas of the Eastern Goldfields Granite-Greenstone Terrane. It will test the nature of boundaries and structural style within the area, including evidence for a basal detachment. This will provide constraints on the timing and relative importance of compressional, extensional, and strike-slip deformation.

The eastern margin of the Yilgarn Craton is unconformably overlain by Neoproterozoic rocks of the Officer Basin, and by Permian rocks of the Gunbarrel Basin. Previous interpretations of available geophysical data (Shaw et al., 1996) shows that the Yilgarn Craton extends to the east, beneath the younger basins, and is truncated by the Albany-Fraser Orogen to the southeast, and by the Capricorn Orogen to the northeast (Fig. 2).

Apak & Moors (2000, 2001) showed from shallow seismic and well data that the Officer Basin sedimentary sequence dips and increases in thickness to the northeast. They were unable to recognise the sub-divisions of the Officer Basin put forward by Iasky (1990). The deep seismic survey will test whether these sub-divisions, which were based on potential field data, represent Palaeoproterozoic and Mesoproterozoic sedimentary basins or igneous and metamorphic complexes buried beneath the Officer Basin. The survey will also provide data on the thickness of the crust at the margin of the craton, and the nature and extent of Proterozoic tectonic reworking.

Since the initial 1991 seismic survey, other geoscientific datasets for the Yilgarn Craton have expanded considerably. These include regional geophysical coverage, SHRIMP U-Pb zircon geochronology, whole-rock geochemistry and geological maps. 1:100 000-scale geological mapping of the Eastern Goldfields Granite-Greenstone Terrane is available as a series of GIS datasets (Groenewald et al., 2000, 2001; Painter et al., in press), and mapping at 1:100 000-scale extends into the adjacent Southern Cross Granite-Greenstone Terrane (Chen & Wyche, 2001). New geological mapping is also available along the northern margin of the craton where it is in contact with the Palaeoproterozoic rocks of the Capricorn Orogen (Occhipinti et al., 2001; Pirajno et al., 2002).

From the new data, the greenstones of the Eastern Goldfields Granite-Greenstone Terrane show a different geological history to the terranes to the west prior to c. 2660 Ma, and are predominantly younger, being deposited between c. 2720 and c. 2650 Ma (Nelson, 1997; Brown et al., 2001). The remnants of an older c. 2960 to c. 2930 Ma greenstone sequence is preserved in the south of the terrane, with evidence for >2750 Ma greenstones in the north (Kent & Hagemann, 1996). Xenocrystic zircons from a c. 2910 to c. 2730 Ma source occur within felsic volcanics, consistent with the presence of continental crust that may have been basement to the greenstones (Nelson, 1997; Brown et al., 2001). Widespread granite magmatism occurred in the Eastern Goldfields Granite-Greenstone Terrane, and across the craton as a whole, between c. 2750 and c. 2600 Ma (Nelson, 1997; Brown et al., 2001; Chen & Wyche, 2001; Occhipinti et al., 2001; Wilde, 2001), with the majority of gold mineralization regarded as occurring between c. 2640 and c. 2600 Ma (e.g., Kent et al., 1996).

Rocks forming the rest of the Archaean Yilgarn Craton range in age from c. 3730 Ma to c. 2600 Ma. The oldest rocks (c. 3730 to c. 3000 Ma) occur in the predominantly gneissic Narryer and South West Terranes along the western margin of the craton, where metamorphic grades are generally higher (Occhipinti et al., 2001; Wilde, 2001). In the Murchison and Southern Cross Granite-Greenstone Terranes the oldest rocks are c. 3000 Ma greenstones, with younger sequences of predominantly felsic volcanic rocks at c. 2750 to c. 2730 Ma (Pidgeon & Hallberg, 2000; Chen & Wyche, 2001). Very old detrital zircons (c. 4400 to c. 3100 Ma) are present in metasedimentary rocks from the Narryer Terrane, the South West Terrane and the central part of the craton (Occhipinti et al., 2001; Wilde, 2001; Riganti et al., 2002). These terranes may have been close to their present relative positions at c. 3000 Ma with a common source area of very ancient continental crust either nearby and subsequently removed, or still part of the craton but not exposed (Wyche et al., in prep.).

Each of the granite-greenstone terranes has a deformation history in which low-angle thrusting or extensional faulting or a combination of both is followed by upright folding and then by strike-slip faulting, the later stages of which are associated with mineralization. However, the timing of the events varies (e.g., Greenfield et al., 2001). The earliest deformation in the Southern Cross Granite-Greenstone Terrane took place between c. 3000 Ma and c. 2730 Ma, with the second deformation taking place at c. 2730 Ma, and the third by c. 2660 Ma. In contrast, in the Eastern Goldfields Granite-Greenstone Terrane the earliest two deformations took place after c. 2720 Ma but before c. 2660 Ma, with the third and fourth occurring between c. 2660 Ma and c. 2600 Ma.

Two main models have been suggested for the tectonic evolution of the Yilgarn Craton (see discussions in Witt et al., 1998; Groenewald et al., 2000). One envisages the greenstones as remnants of ensialic basins formed by the rifting of pre-existing continental crust, possibly driven by the effects of mantle plume activity. The other envisages the greenstones forming at an active continental margin as a series of arcs and back-arc basins or marginal basins, with the craton forming by (micro)plate collision and terrane accretion.

The expanding geophysical, geochronological, and geochemical datasets and the new 1:100 000-scale geological mapping will contribute to the development of a consistent geodynamic

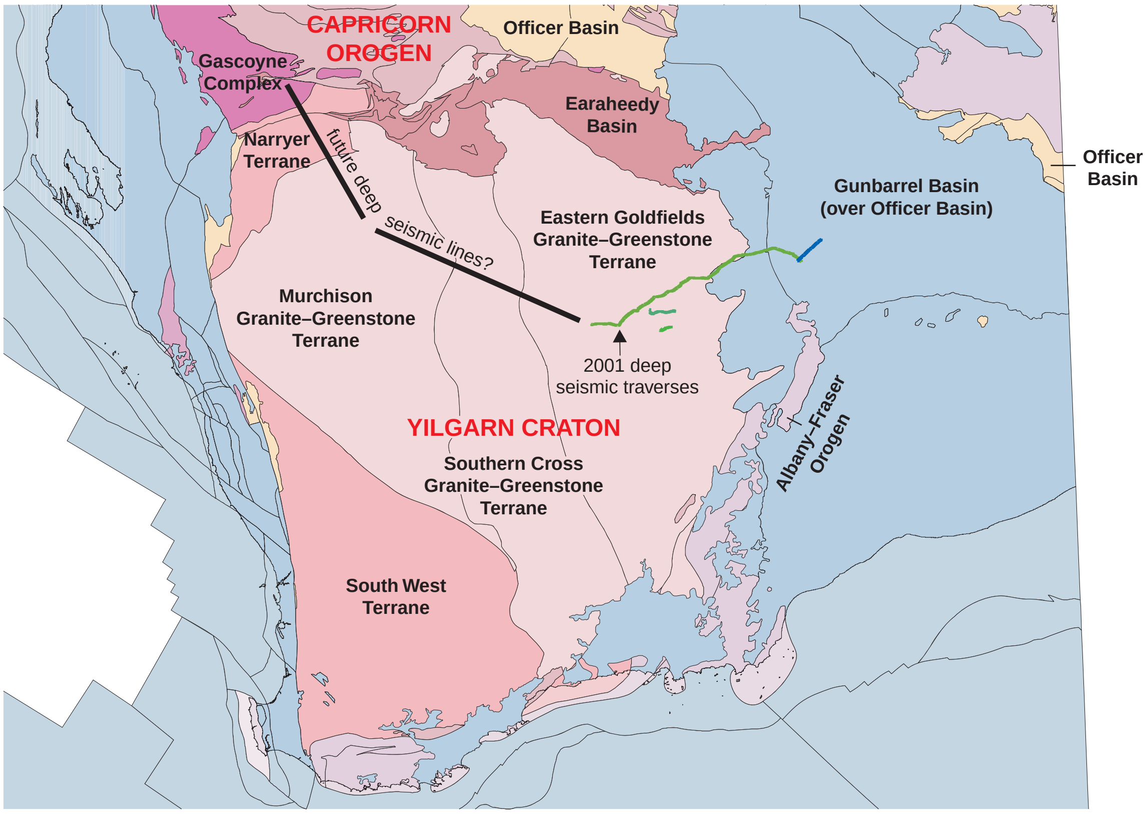

Figure 1 Tectonic setting of the 2001 seismic survey

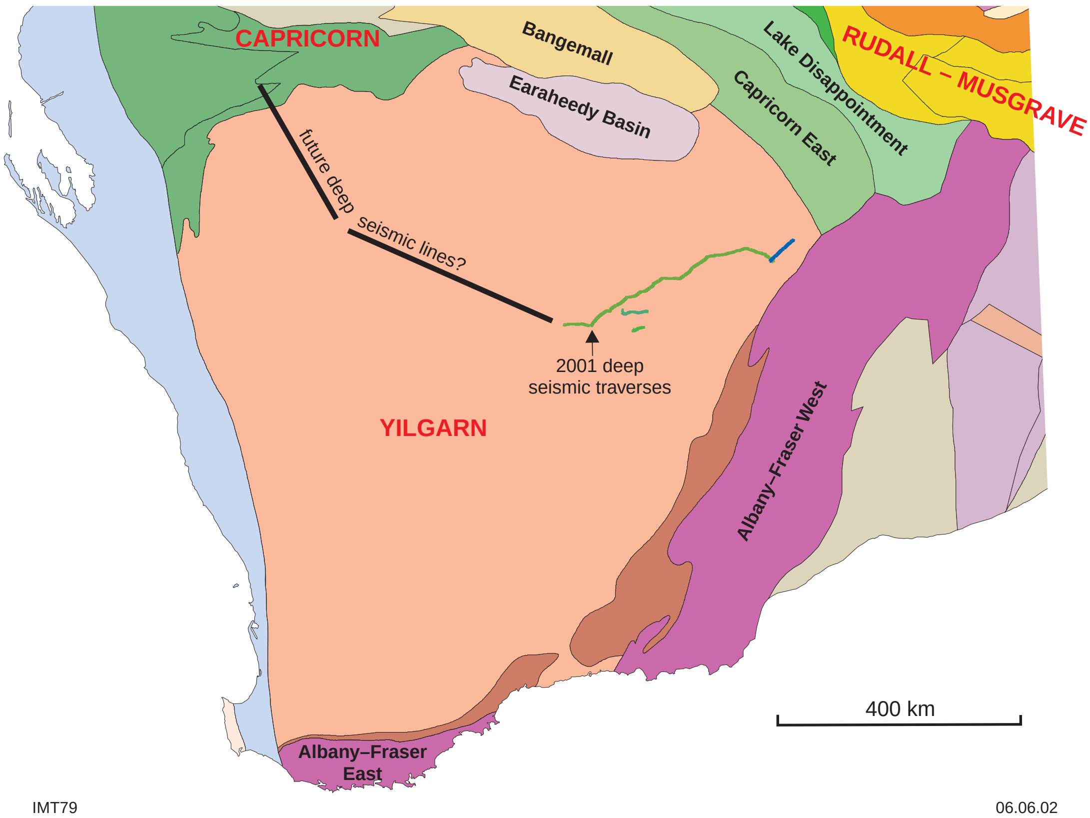

Figure 2 Crustal elements of southwestern Australia (after Shaw et al., 1996)

model for the Yilgarn Craton. An essential control on any such model will be an understanding of the crustal structure across the craton. The 2001 seismic survey provides the starting point for a deep seismic traverse across the entire northern Yilgarn Craton that could extend across the Southern Cross Granite-Greenstone Terrane, the Murchison Granite-Greenstone Terrane, and the Narryer Terrane into the Palaeoproterozoic Gascoyne Complex of the Capricorn Orogen (Fig. 1). Seismic imaging of the major faults and shear zones that mark the boundaries between terranes within the craton (Myers, 1997; Myers & Hocking, 1998; Witt et al., 1998; Tyler & Hocking, 2002), as well as those marking its northwestern margin (Occhipinti et al., 2001), would provide an insight into the nature, geometry and history of these structures. New SHRIMP data indicating that the western part of the craton was assembled prior to c. 3000 Ma is consistent with terrane boundaries representing relatively old sutures within the craton. It is likely that these old sutures have been reactivated during late compression and strike-slip deformation in response to westward thrusting of the Eastern Goldfields, and that these reactivated structures may have provided large-scale pathways for craton-wide mineralizing fluid systems.

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Seismic data acquisition and processing – 2001 Northern Yilgarn seismic reflection survey (L154)

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Introduction

The 2001 Northern Yilgarn seismic reflection survey (L154) was conducted in August/September 2001 and included the regional traverse consisting of lines 01AGS-NY1 and 01AGS-NY3, jointly sponsored by Geoscience Australia and the Geological Survey of Western Australia, in conjunction with the Predictive Mineral Discovery Cooperative Research Centre (*pmd**CRC). Two other lines, 01AGS-NY2 and 01AGS-NY4, were acquired in the Laverton Tectonic Zone under the auspices of Geoscience Australia and the Minerals and Energy Research Institute of Western Australia (MERIWA), involving Anglogold, Placer Dome and the University of Western Australia. The Australian National Seismic Imaging Resource (ANSIR) was responsible for seismic data acquisition (through its facilities manager Trace Energy Services), as well as for field QC and preliminary in-field processing.

The report is concerned only with lines 01AGS-NY1 and 01AGS-NY3. 01AGS-NY1 was a 384 km line, commencing in the vicinity of Leonora and extending to the east into the Officer Basin, whereas the much shorter 01AGS-NY3 lay entirely within the Officer Basin. The location of the lines is shown in Figure 1.

Acquisition

Most of the deep seismic reflection data was acquired along the edge of currently used and maintained shire roads or the Leonora-Laverton railway access road. The line was cleared for 01AGS-NY3. The station coordinates were surveyed using differential GPS by Dynamic Satellite Surveys (2001). A split-spread geometry was employed with the source nominally at the centre of the spread. The receiver groups were centred between the station pegs, while the source array was centred on the peg. Three IVI Hemi-60 (60,000 lb) vibrators were used in-line, using three varisweeps with moveup between sweeps.

A summary of acquisition parameters is given in Table 1. Further details are provided by Barbour (2001). The main differences between the long regional line (01AGS-NY1) and the Officer Basin line (01AGS-NY3) are the group interval, VP interval and source move-up, and the sweep frequency ranges, which were designed to give higher resolution in the Officer Basin sedimentary rocks.

Table 1 Summary of acquisition parameters for the regional lines in Survey L154

LINE	*01AGS-NY1*	*01AGS-NY3*
AREA	Leonora to Lake Yeo (WA)	East of Lake Yeo (WA)
DIRECTION	W to E	SW to NE
LENGTH	384 km	52.62 km
STATIONS	992 - 10592	1040 - 2794
CDP RANGE	1984 - 20862	2080 - 5509
GROUP INTERVAL	40 m	30 m
GROUP PATTERN	12 in-line @ 3.33 m	12 in-line @ 2.5 m
# VIBE POINTS	4780	1226
VP INTERVAL	80 m	30 m and 60 m
SOURCE TYPE	3 x IVI Hemi-60	3 x IVI Hemi-60
SWEEP TYPE	3 x 12 s: 7-56 Hz, 12-80 Hz, 8-72 Hz	3 x 8 s: 8-72 Hz, 12-100 Hz, 6-80 Hz
SOURCE PAD-PAD	15 m	15 m
SOURCE MOVE-UP	15 m	10 m
# CHANNELS	240	240
FOLD (NOMINAL)	60	120 and 60
RECORD LENGTH	16/18 s @ 2 ms	16 s @ 2 ms

Processing

The final processing flow, including migration, for 18 s of data is shown in Table 2 for line 01AGS-NY1. For adequate resolution, only 4 ms sampling is required. Essentially the same flow was used for 16 s of data for line 01AGS-NY3.

The processing flow was designed to be as simple as possible, with the aim of enhancing reflections and preserving amplitudes. Some key processing steps are discussed briefly, concentrating on those necessary for understanding the data prior to seismic interpretation, and those that resulted in the most improvement in data quality.

Table 2 Final processing flow for 01AGS-NY1

[1]	line geometry and crooked line definition (fixed CDP interval)
[2]	field segy to 'disco' data format; resample to 4 ms
[3]	quality control displays and trace edits
[4]	spectral equalization (with removable 1000 ms AGC)
[5]	common mid point sort (bin wide open)
[6]	gain recovery (spherical divergence option)
[7]	trace amplitude balance across user defined gates
[8]	surgical air wave mute
[9]	bulk shift +100 ms
[10]	application of refraction statics, datum 350 m (AHD)
[11]	application of automatic residual statics
[12]	bandpass filter
[13]	velocity analysis using velex, 1st pass after refraction statics, 2nd pass after automatic residual statics
[14]	normal moveout correction (15% stretch mute)
[15]	common mid-point stack (alpha trimmed mean)
[16]	trace amplitude balance
[17]	finite difference migration with dip corrected velocities
[18]	bandpass filter
[19]	signal enhancement (digistack 0.85)
[20]	linear gain and trace amplitude scaling

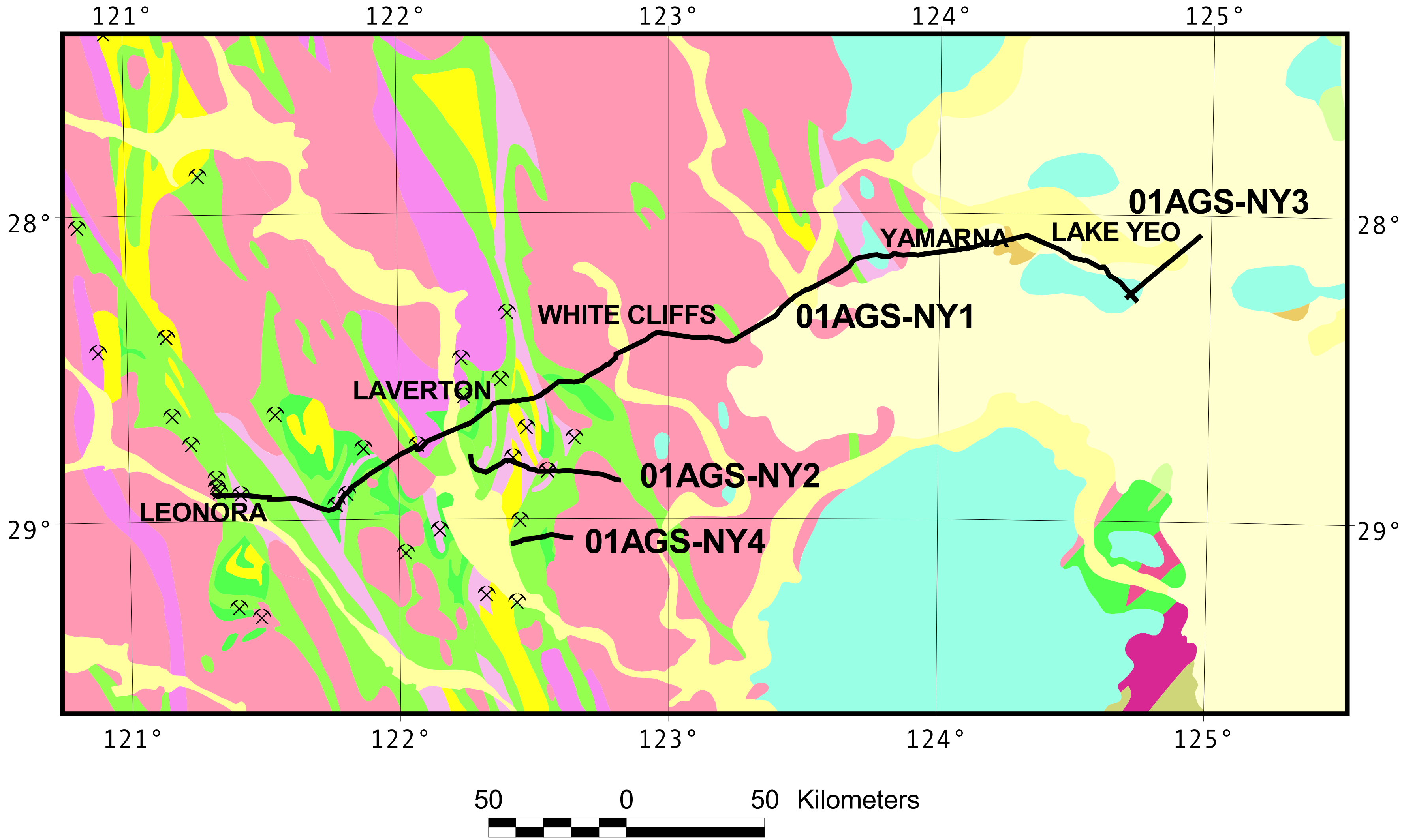

Figure 1 Location of the 2001 Northern Yilgarn seismic reflection survey, overlain on a simplified solid geology map. Archaean greenstone units are as follows: mafic and ultramafic rocks - green, felsic volcanic and sedimentary rocks - yellow, granitoids - pink, gneiss - purple; overlying Paleozoic units in cream and blue; Cainozoic unit in pale yellow

Crooked line definition and CMP/CDP sort

Ideally, for a horizontal reflector, the midpoint between a source and receiver pair lies vertically above the depth point (or reflecting point) for that pair, so that identifying seismic traces with a common midpoint (CMP) amounts to finding traces with a common-depth-point (CDP). For dipping reflectors, this correspondence no longer holds, but the CDP terminology is so entrenched in seismic processing that it is used in place of the more correct term "common midpoint". Note that midpoint spacing along a straight line is half the receiver group interval.

Crooked line processing was necessary for 01AGS-NY1, due to bends in the existing roads. In the crooked line case, the midpoints do not always lie along the line defined by the surveyed stations. The CDP line is defined as a smoother representation that follows the highest density of midpoints, while keeping as close as possible to the original line (Fig. 2). A seismic trace is then assigned to a particular CDP on the basis of its midpoint location, that is, to the nearest CDP.

For both lines, the CDP line was defined with a constant CDP interval (20 m for 01AGS-NY1 and 15 m for 01AGS-NY3). Since the CDP line is shorter than the line of stations, the CDP number will be less than twice the station number. A common midpoint sort gathers the data into sets of traces with the same midpoint (or CDP); these traces will later be stacked (added together) after correction for travel time differences for different source-receiver offsets. The stacked seismic data is displayed as a section along the CDP line, the annotated stations being merely those closest to the CDP locations.

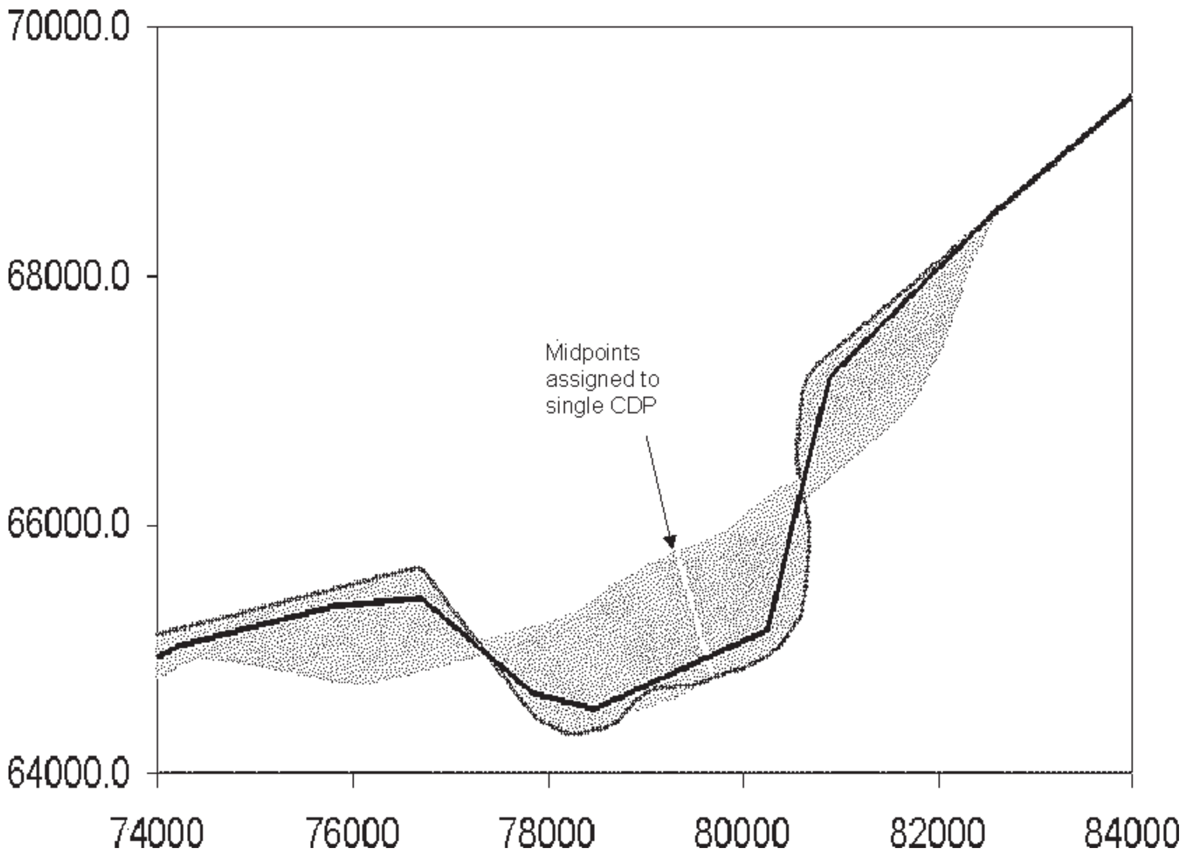

Figure 2 Illustration of crooked line geometry, with X and Y coordinates in metres. The grey line is the surveyed station line. The black line is the CDP line. Shaded area is the spread of midpoints. Unshaded strip perpendicular to the CDP line shows midpoints assigned to a single CDP

Refraction statics and datums

Statics corrections are applied to remove variability in seismic travel times due to surface topography, or variations in regolith thickness or velocity (or a combination of these). The travel times of refracted waves, recorded as the first arrivals in seismic reflection data, are analysed to obtain a model of the main refracting interface, that is, the regolith/bedrock boundary (Fig. 3). Refraction statics are calculated by (1) subtracting the vertical travel time calculated for the lower velocity regolith, and (2) adding the vertical travel time calculated from datum to bedrock at a higher replacement velocity.

For both lines 01AGS-NY1 and 01AGS-NY3, a datum of 350 m (AHD) was used in calculating statics. For 01AGS-NY3, a replacement velocity of 4000 m/s was used. Since 01AGS-NY1 crossed the boundary between Archaean craton (bedrock velocity ~6000 m/s) and Proterozoic/ Palaeozoic basins (bedrock velocity ~4500 m/s), a variable replacement velocity was required: 5500 m/s for stations 992 to 9500, 4500 m/s for stations 10200 to 10592, with linear interpolation in between.

It is important to note that prior to application of statics a bulk shift of +100 ms was applied. This was done to prevent shallow information being removed and to keep the processing approximately surface referenced (the average two-way static being of the order of 100 ms). Thus, the 100 ms line on the processed seismic data corresponds to the 350 m datum.

Spectral equalisation and filtering

A key processing step that reduces low frequency noise and enables reflections to be seen is spectral equalisation, or balancing in the frequency domain. This is particularly critical at shallow depths where the fold is lower and where source-generated noise interferes with reflections. The automatic gain control (AGC), used as part of the spectral balancing algorithm, was removed afterwards in order to preserve amplitudes for later processing steps, particularly migration.

Bandpass filters were also applied to suppress high and low frequency noise. Prior to final

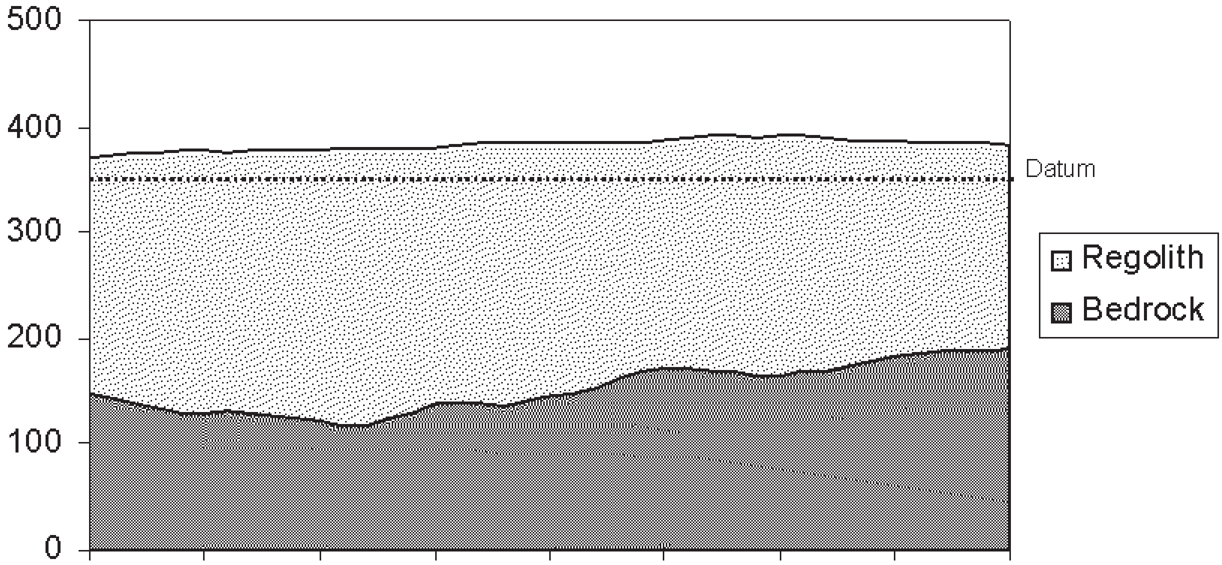

Figure 3 Refractor model near the eastern end of line 01AGS-NY1, showing lower velocity regolith overlying higher velocity bedrock. Elevations are metres above sea level and horizontal extent is 8 km

display, a bandpass filter with more limited range at large two-way travel time (TWT) was aimed at improving appearance of deeper reflections that would have lost any true high frequency due to attenuation in the earth.

Stacking velocity analysis and median stack

Another critical processing step is the correction of seismic data for the offset dependence of travel time, the normal moveout (NMO) correction, which depends (inversely) on seismic velocity and two-way travel time. With the appropriate choice of velocity for NMO correction, a refection event will add constructively when the traces of a common-midpoint gather are stacked. In the shallow section (less than 1 to 2 s TWT), the quality of the stack is quite sensitive to changes in the stacking velocity, but becomes progressively less so for the deeper data.

Stacking seismic traces improves the signal to noise ratio. An improved technique for suppressing large bursts of noise, such as vehicle noise, is a type of median stack. The alpha trimmed mean stack examines trace amplitudes at each sample time, and omits a designated percentage of the highest and lowest amplitudes from the stack, in this case 15 percent at each end.

Migration

On an unmigrated final stack section with V/H=1, no reflectors will be visible at angles greater than 45°. Migration is the process of moving the recorded reflections into their true spatial location. Thus, dipping reflectors will be steepened, shortened and moved up dip. Diffractions from discontinuities, such as reflector terminations at faults, are collapsed in the process. Stacking velocities corrected for dip were used as the migration velocities.

Coherency enhancement

A signal enhancement algorithm (digistack) was applied for final display only to the stacked and migrated data. Digistack enhances events that are coherent across several traces, thus making reflections stand out better against background noise.

Example of processed seismic data

A small window of migrated data within the Laverton Tectonic Zone illustrates the quality of acquisition and processing along line 01AGS-NY1 (Fig. 4). This is typical of the data, showing east-dipping reflectors that can be imaged almost to the surface. Data quality is good to excellent along most of the traverse, with obvious reflectors throughout the crust to the Moho.

Conclusions

The regional seismic reflection data have been processed to a high standard, facilitating interpretation of geological structure throughout the crust from the near surface. Detailed processing in selected areas to enhance particular features of interest may be of benefit at some future date.

Acknowledgements

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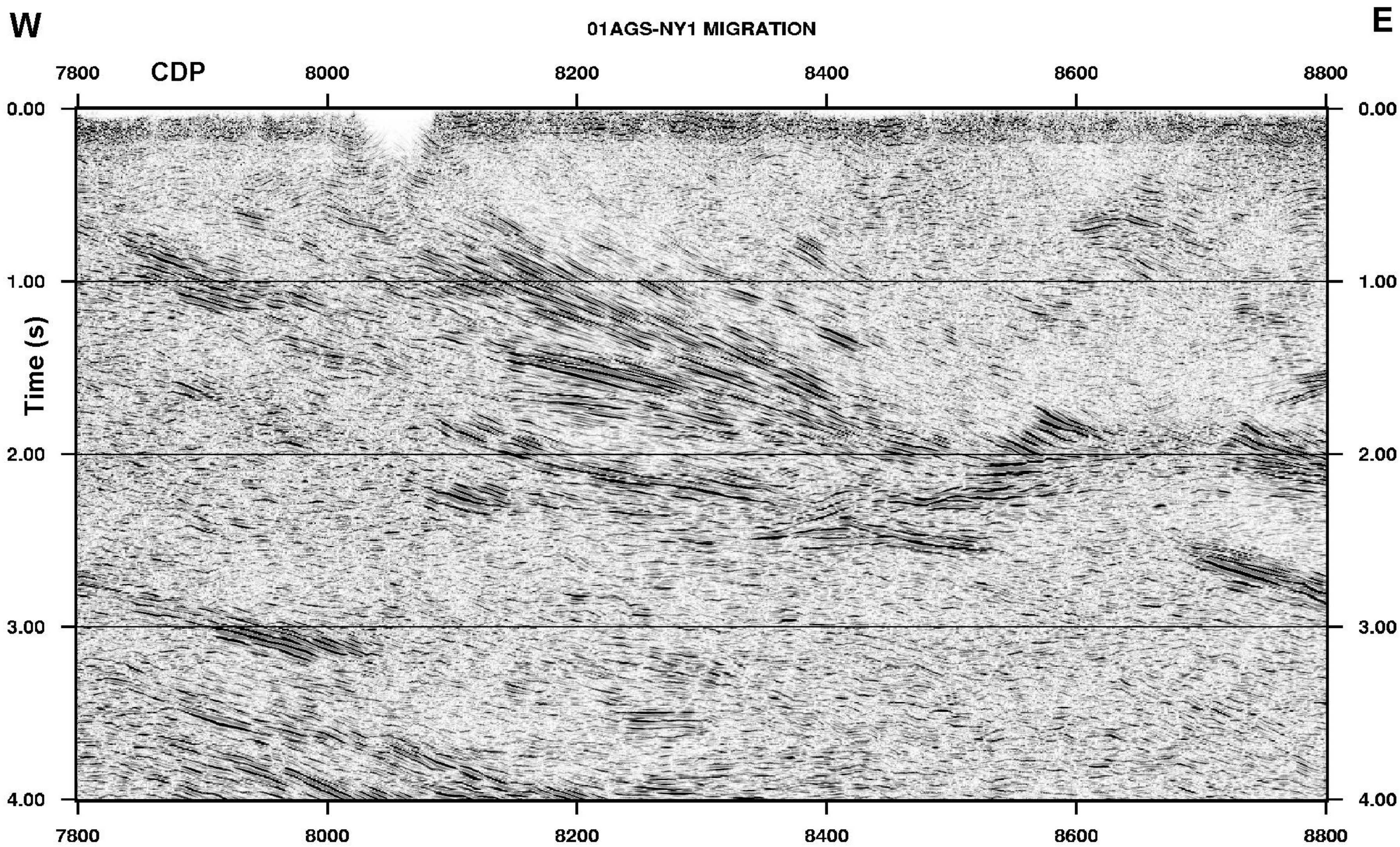

Figure 4 **Small part of migrated section for 01AGS-NY1. Horizontal axis is CDP and vertical axis is two-way travel time (s). V/H = 1, assuming an average crustal velocity of 6 km/s. Horizontal extent is 20 km and vertical extent is 12 km. Shallow section is missing through Laverton township where the IVI Hemi-60 vibrators could not be operated**

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