REPORT
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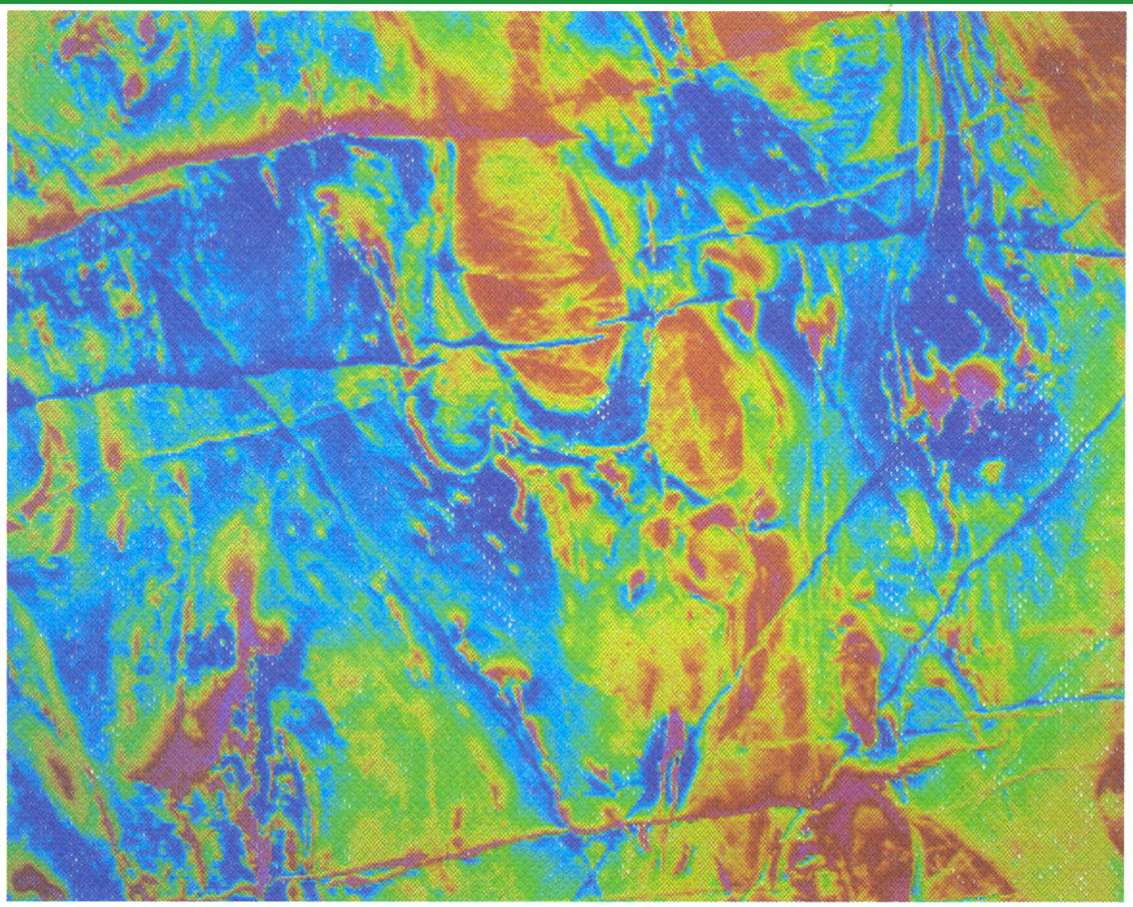
GEOLOGY OF THE GREENSTONE TERRANES IN THE KURNALPI–EDJUDINA REGION SOUTHEASTERN YILGARN CRATON

by C. P. SWAGER



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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Cover photograph:

Aeromagnetic image (processed total magnetic intensity) of the area approximately covering the Kurnalpi 1:250 000 map sheet. The two prominent east-northeast-trending, positively magnetized, Proterozoic mafic dykes close to the southern and northern boundaries are the Celebration and Ballona Dykes respectively. The image is published with the permission of World Geoscience Corporation Limited, from whom the digital data may be purchased.

Contents

Plate

Figures

Tables

Geology of the greenstone terranes in the Kurnalpi–Edjudina region, southeastern Yilgarn Craton

by

C. P. Swager

Abstract

Regional geological mapping has outlined several greenstone terranes to the east of the earlier proposed Barlee and Kalgoorlie Terranes in the Eastern Goldfields Province. Each terrane is bounded by regional faults and is characterized by one or more greenstone associations: 1. tholeiitic basalt plus komatiite, with isolated, contemporaneous felsic volcanic centres and extensive later felsic volcaniclastic piles; 2. a similar association, with banded iron-formation; 3. bimodal tholeiitic basalt–rhyolite/dacite; and 4. basalt/andesite/dacite calc-alkaline volcanic complexes. The greenstone terranes are locally overlain by isolated syntectonic basins which contain a fifth association, polymictic conglomerate, and possibly a sixth, turbiditic greywacke and BIF.

The westernmost terrane — the Gindalbie Terrane — contains three associations stacked across early low-angle faults. This terrane separates the Kalgoorlie Terrane from the Jubilee, Kurnalpi, and Mulgabbie Terranes which represent extensional basins with tholeiite–komatiite–felsic volcanic rocks. The Edjudina Terrane contains a series of calc-alkaline volcanic complexes with metasedimentary rock–BIF capping. The Pinjin Terrane may represent an uplifted portion of the Edjudina Terrane, or a separate BIF–tholeiite–komatiite association. The Linden Terrane, with substantial komatiite and tholeiite, represents another major extensional basin.

SHRIMP dates of felsic volcanic rocks from nearly all terranes indicate they have a similar age range, with early felsic volcanism as old as 2708 ± 4 Ma and the youngest rocks dated at 2673 ± 7 Ma.

The deformation history of the greenstones is characterized by an alternation of extension and compression episodes, including the greenstone basin-forming extension followed by thrusting. Subsequent regional extension of the stacked supracrustal sequence was followed by regional east–west shortening. High-grade gneiss domes may have developed just before or after this regional shortening.

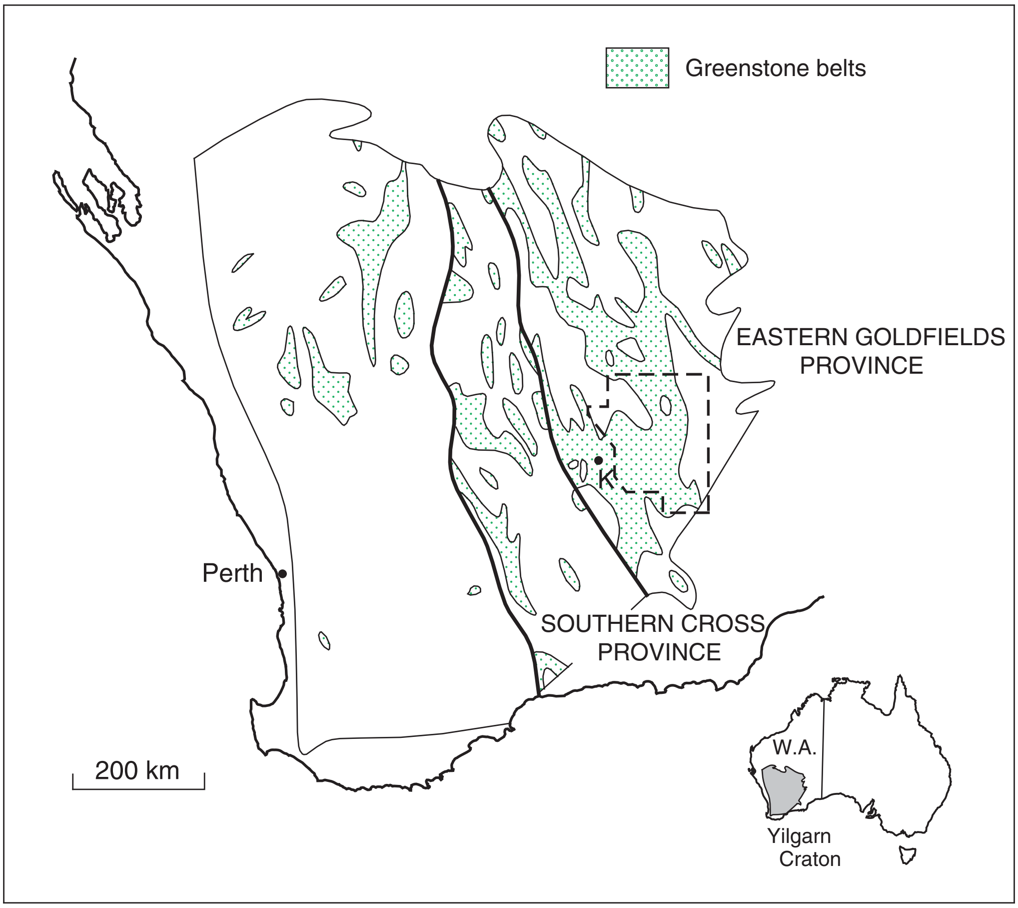
The terranes developed most probably as adjacent, contemporaneous, ensialic basins with possibly different rates of extension. Regional shortening suggests horizontal far-field stresses implying interaction of crustal plates, but much of the magmatic history, including komatiite volcanism and the two-stage model of granitoid generation, require mantle processes.

KEYWORDS: Yilgarn Craton, Eastern Goldfields Province, Late Archaean terranes, greenstones, granitoids, regional deformation

Introduction

The Kalgoorlie greenstone terrane within the Eastern Goldfields Province (Fig. 1) was defined as a distinct tectonostratigraphic, fault-bounded entity, primarily based on the recognition of a remarkably consistent c. 2.7 Ga volcano-sedimentary stratigraphy, characterized by a regional komatiite marker unit (Swager and Griffin, 1990a; Swager et al., 1990). The subdivision of the Kalgoorlie Terrane into domains is shown on Figure 2. To the west of the Kalgoorlie Terrane lies the Barlee Terrane which includes a considerably older greenstone sequence with sporadically preserved basal quartzite and prominent banded iron-formation (Wyche, 1993). To the east of the Kalgoorlie Terrane, recent mapping by the Geological Survey of Western Australia (GSWA) has delineated a number of terranes — from west to east: Gindalbie, Jubilee, Kurnalpi, Mulgabbie, Edjudina, Pinjin, and Linden (Fig. 3) — which contain more varied and more laterally discontinuous structural–stratigraphic sequences. Previous authors have recognized contrasts between these ‘eastern’ terranes and the Kalgoorlie Terrane, with interpretations ranging from shallow versus deep basins or rifts (Williams, 1974; Groves and Batt, 1984) and back-arc versus volcanic-arc settings (Barley et al., 1989; Witt, 1994b).

These explanatory notes describe the eastern greenstone terranes (localities are shown on Figure 4); compare them with the Kalgoorlie and Barlee Terranes;



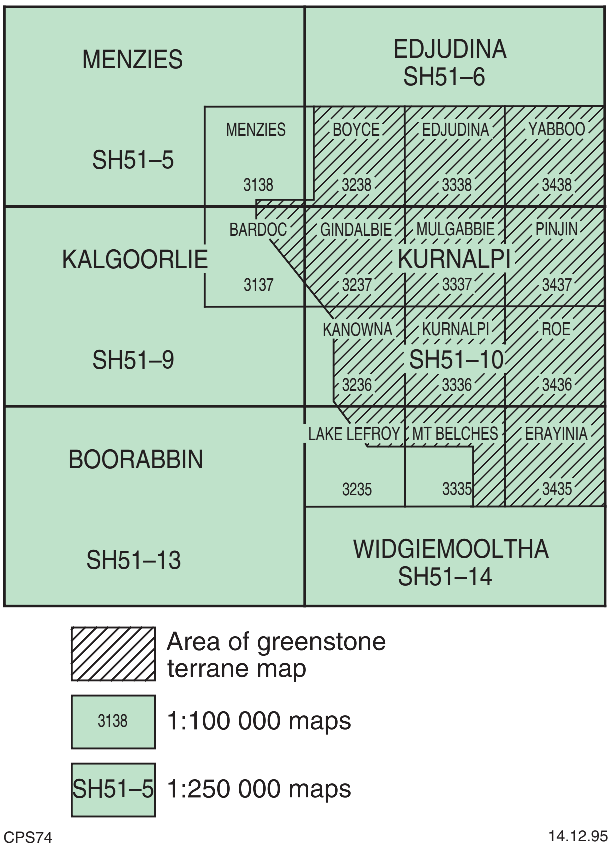


Figure 1A. **Granite–greenstone terrain of the Yilgarn Craton, showing distribution of Archaean greenstone belts. Outline highlights the area of the accompanying geological map of the greenstone terranes in the Kurnalpi–Edjudina region. K = Kalgoorlie**

Figure 1B. **Index map showing the geological sheets (shaded) used for the compilation of the terrane map. Both 1:250 000 and 1:100 000 sheets are shown**

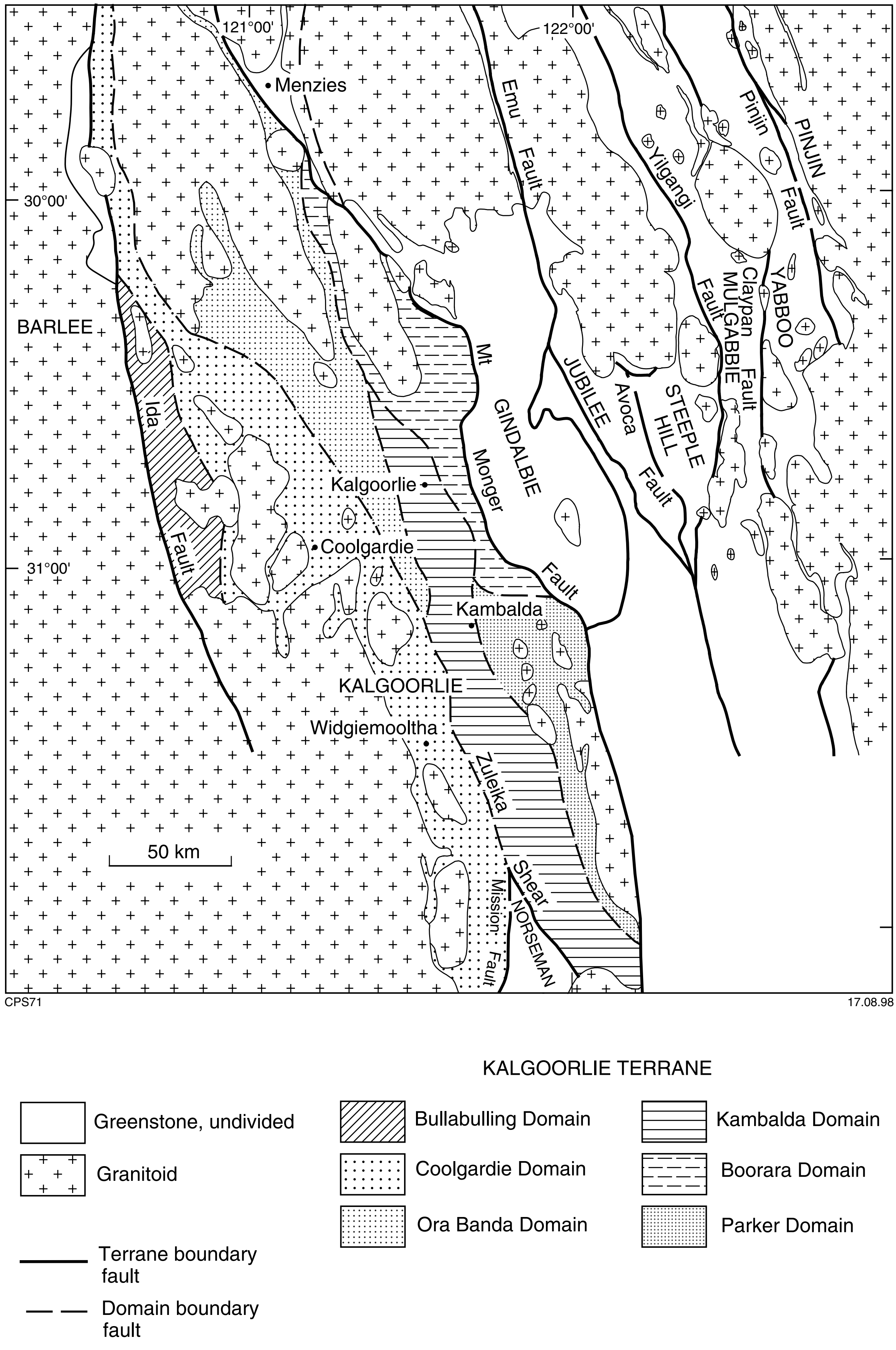


Figure 2. Greenstone terranes, with terrane boundary faults, in the southeastern Yilgarn Craton. Subdivision of the Kalgoorlie Terrane into domains is shown

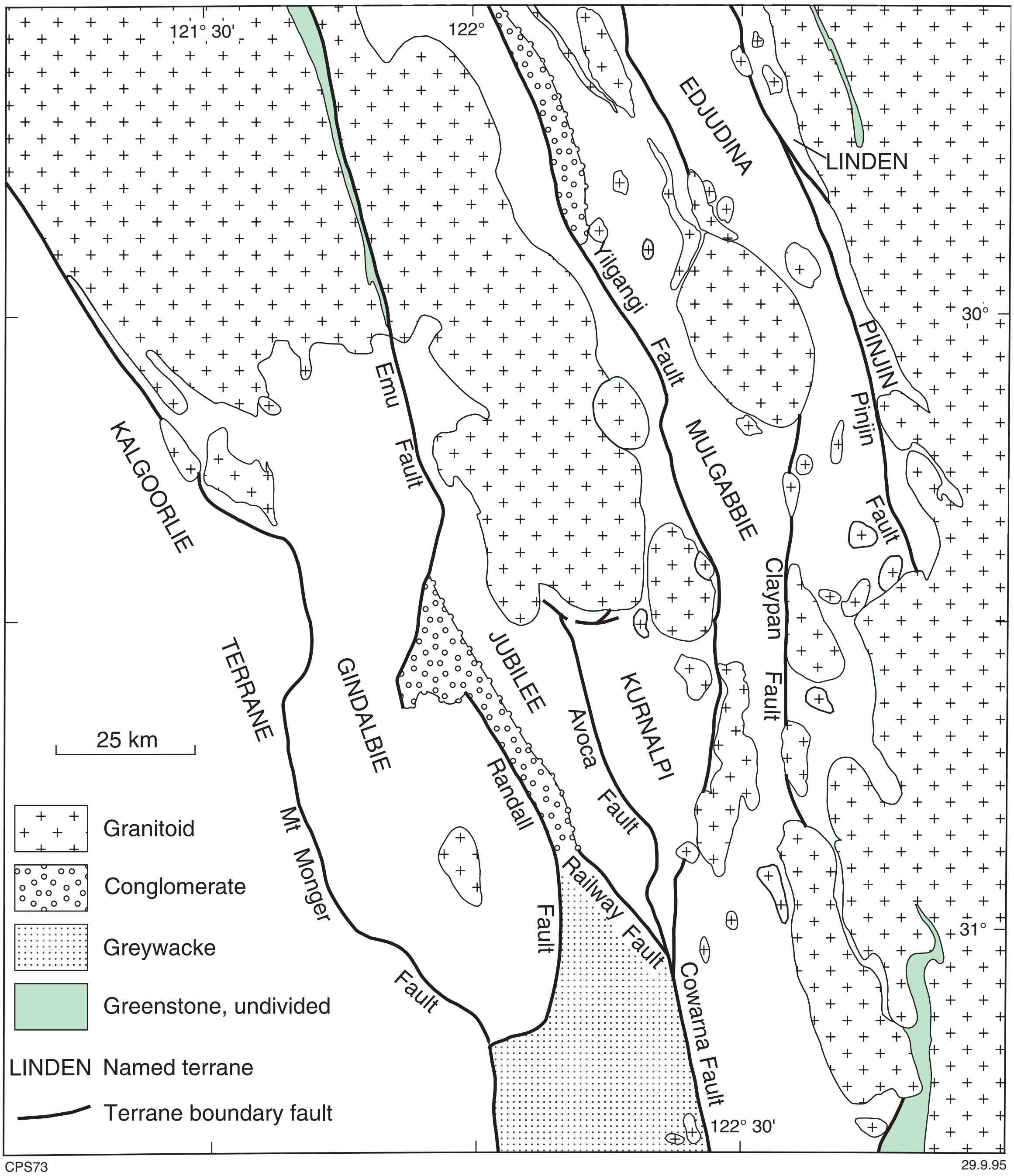


Figure 3. Greenstone terranes, and their boundary faults, in the Kurnalpi–Edjudina region. Conglomerate and greywacke occupy elongate basins overlying, or adjacent to, boundary faults

and discuss their development based on regional geological mapping and on geochronological studies (Nelson, 1995, in prep.). The 1:100 000 geological sheets — the foundation of this regional compilation — are KANOWNA; GINDALBIE; LAKE LEFROY; MULGABBIE; ROE; KURNALPI; PINJIN; EDJUDINA; and YABBOO* (Ahmat, 1995a; Ahmat, 1995b; Griffin and Hickman, 1988a; Morris, 1994; Smithies, 1994; Swager, 1993a, 1994a; Swager, 1994b; Swager and Rattenbury, 1994; Swager, 1994c, 1995). Data from three 1:250 000 geological sheets — KURNALPI (Swager, in prep.), WIDGIEMOOLTHA (Griffin and Hickman, 1988b) and EDJUDINA (Williams et al., 1976) — have also been used in the compilation. The terrane nomenclature used here replaces the more locally based domain terminology presented in the explanatory notes to the 1:100 000 sheets. Descriptions of rock types and local geology are also available in those explanatory notes. Detailed studies on most aspects of greenstones in the terranes are, however, few and far between, primarily because of the absence, or as yet undisclosed presence, of any substantial gold or base-metal mineralization.

* Capitalized names refer to standard map sheets.

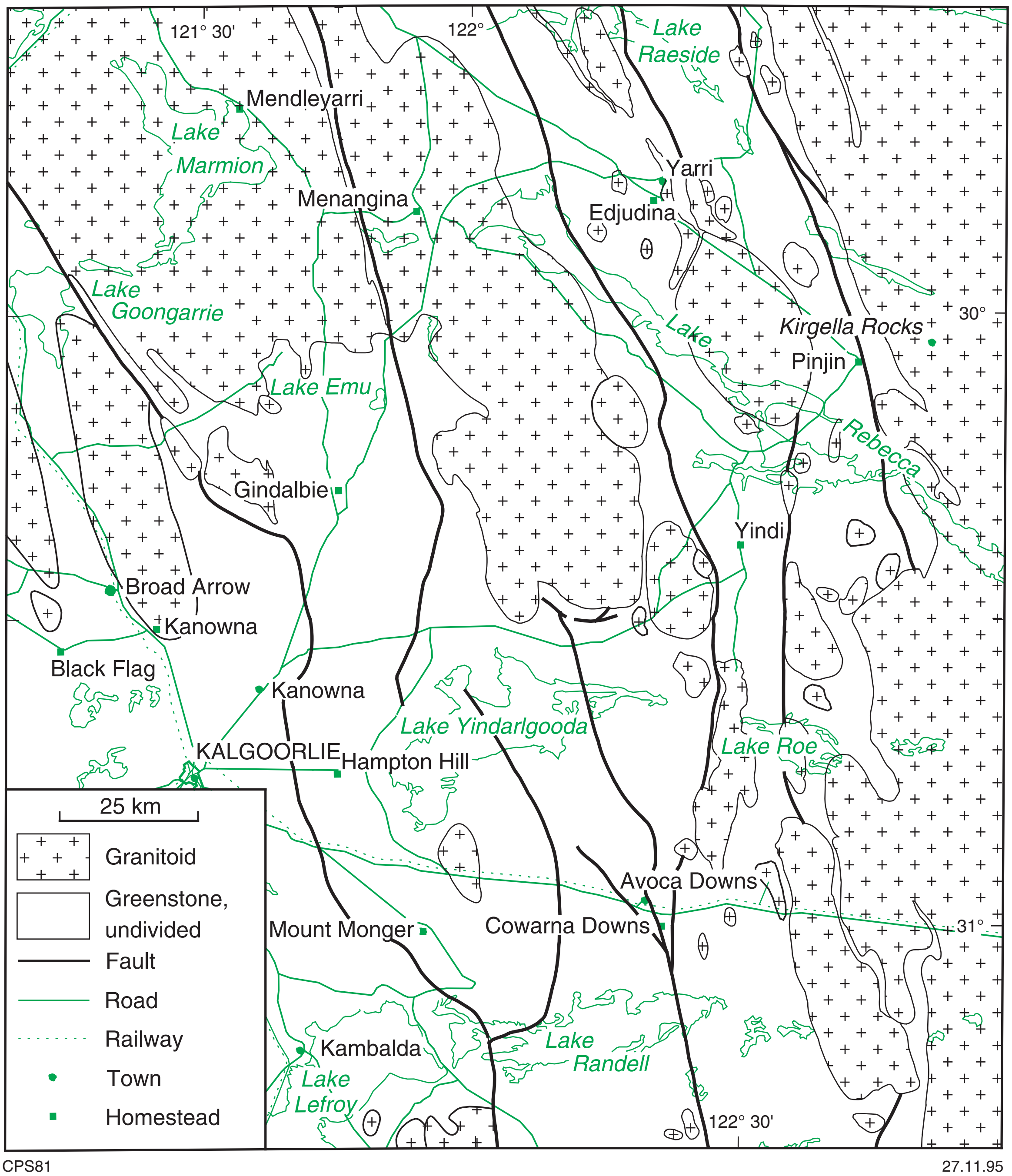


Figure 4. Locality map of the area of the Kurnalpi–Edjudina Terranes

Greenstone terranes

Greenstone terranes in the southeastern Yilgarn Craton (Figs 2–3) are structural–stratigraphic or structural–lithological units bounded by regional faults or shear zones and characterized by some distinguishing feature(s) — lithologic, stratigraphic, geochemical, tectonic and/or geochronologic — that sets them apart from adjacent terranes. This use of the term *terrane* does not imply that the terranes are necessarily allochthonous with respect to each other or were displaced over hundreds of kilometres, such as proposed for the exotic accreted terranes in the North American Cordilleran orogenic belt (Howell, 1989). It merely implies that there are enough contrasts or differences between the terranes to warrant suspicions about their original relationships. Wherever detailed stratigraphic–lithologic correlations can be reasonably proposed for adjacent fault-bounded units, the term *domain* is used for individual units, and *terrane* for a group of domains with the same stratigraphy and geological history. The status of a domain or terrane may change as a result of new data — including detailed geophysical data and geochronology — becoming available. In the North American Cordillera, the birthplace of the terrane concept, recent studies have shown that genetic relationships connect tectonostratigraphic terranes earlier regarded as entirely separate (Hacker et al., 1993).

In the recent terrane-type analysis of the Superior Province presented by the Ontario Geological Survey, use of the term *terrane* was avoided, with the acknowledgment that terrane may be equivalent to sub-province but that some sub-provinces may constitute aggregates of terranes (Williams et al., 1992, p. 1261; Jackson et al., 1994).

Terranes in the Eastern Goldfields Province have the later stages of tectonism and granitoid intrusion in common, with the main differences lying in the setting, the development and timing of the supracrustal sequences, and the very early stages of deformation. The subdivision of the terranes in this contribution to a large extent reflects the 'splitting stage' in the unravelling of greenstone belt development. At this stage differences tend to be emphasized. With increasing data and knowledge, it is quite likely that several terranes will be combined into better defined tectonic units.

Terrane analysis of Archaean cratons such as the Superior Province in Canada started many years ago (see review in Williams et al., 1992). In Western Australia the Yilgarn Craton was divided into granite–greenstone and granitoid gneiss provinces by Williams (1974, 1976) and Gee et al. (1981). This was followed by subdivision of the largest granite–greenstone province, the Eastern Goldfields Province, into several belts with different tectonic histories, including an interpreted deeper rift, the so-called Norseman–Wiluna belt. Recent regional mapping has led to the recognition of several terranes (Swager et al., 1992; this contribution). Myers (1992, 1993) and Myers and Swager (in press) applied the concept to the entire Yilgarn Craton, and regarded the Eastern Goldfields Province as a superterrane.

The terrane boundaries in the Eastern Goldfields Province are north-northwest-striking regional faults variously expressed by low-angle truncations of stratigraphy, locally associated with en echelon folds; contrasts or breaks in lithologic–stratigraphic features; partly exposed shear zones; and, in one example, metamorphic contrast. Boundary faults may be covered by coarse clastic sequences in elongate basins (see below), or intruded by post-regional folding granitoid. Domain boundary faults show similar features, including narrow zones of highly disrupted stratigraphy. Regional upright-fold traces (D_2) and early thrust geometries (D_1) cannot be traced across domain or terrane boundaries.

The greenstone sequences can be described in terms of lithostratigraphic associations, i.e. distinctive groups of rock types. The informal associations recognized here are similar to the *assemblages* defined by the Ontario Geological Survey in the southern Superior Province (Williams et al., 1992; Jackson et al., 1994), although assemblage appears to combine lithostratigraphic and structural criteria. A terrane may contain one or more associations.

Greenstone associations of the terranes in the Eastern Goldfields Province include:

1. Laterally extensive tholeiitic basalt plus komatiite, with either prominent and continuous (e.g. Kalgoorlie Terrane), or thin and discontinuous, komatiite. This association may contain isolated centres of felsic volcanic rocks, and is generally overlain by regionally extensive felsic volcanic–volcaniclastic piles. Substantial sequences of mafic–ultramafic volcanic rocks were deposited in relatively deep water, and developed in extensional settings, or rifts, with variations in relative amounts of rock types depending on various factors including thickness of existing crusts, relation to mantle plumes or mid-ocean ridges, and the presence of (fragments of) continental crust.

2. A similar association, with additional rock types that imply further constraints on the original volcano-sedimentary setting. The basalt–komatiite plus quartzite/quartz-pebble conglomerate plus BIF association characteristic of the Barlee Terrane may form in a more quiescent extensional environment overlying felsic crust.

3. Bimodal tholeiitic basalt–rhyolite/dacite (Gindalbie Terrane). This apparently unique association in the southern Goldfields suggests development of a rift basin in an ensialic setting.

4. Basalt–andesite–dacite or andesite–dacite–rhyolite association of general calc-alkaline affinity in distinct complexes and with broad lateral variations (Edjudina Terrane). This association is reminiscent of island-arc settings, but also contains regionally extensive BIF that suggest quiescent periods.

In addition to these volcano-sedimentary associations, there are two clastic associations:

5. Coarse clastic ?fluviatile sequences including polymictic conglomerate restricted to syntectonic basins.

6. Turbidite-facies metasedimentary rocks with local BIF. The 'Mount Belches greywacke' is the only example of this association. The greywacke occurs directly south along strike of the 'Penny Dam Conglomerate', possibly representing a deeper water facies (Dunbar and McCall, 1971).

The structural setting of four conglomerate plus sandstone associations (Kurrawang and Merougil in the Kalgoorlie Terrane; Penny Dam and Yilgangi in the Kurnalpi–Edjudina Terrane) indicates that they mostly developed adjacent to or over major faults. They can be considered as overlap sequences linking adjacent domains or terranes. They overlie and bury D_1 structures as well as low-angle stratigraphic truncations along the terrane boundary faults (see below). All occurrences contain a well-developed regional, upright foliation, and are metamorphosed and locally carbonated; some are also mineralized with gold. These basins developed after early thrusting (D_1) but well before regional shortening ceased, and may indicate a phase of regional extension rather than a strike-slip setting in a transpressional regime (Hallberg, 1986; Williams et al., in prep; Swager, 1993b). Figure 5 illustrates the structural setting of the Merougil

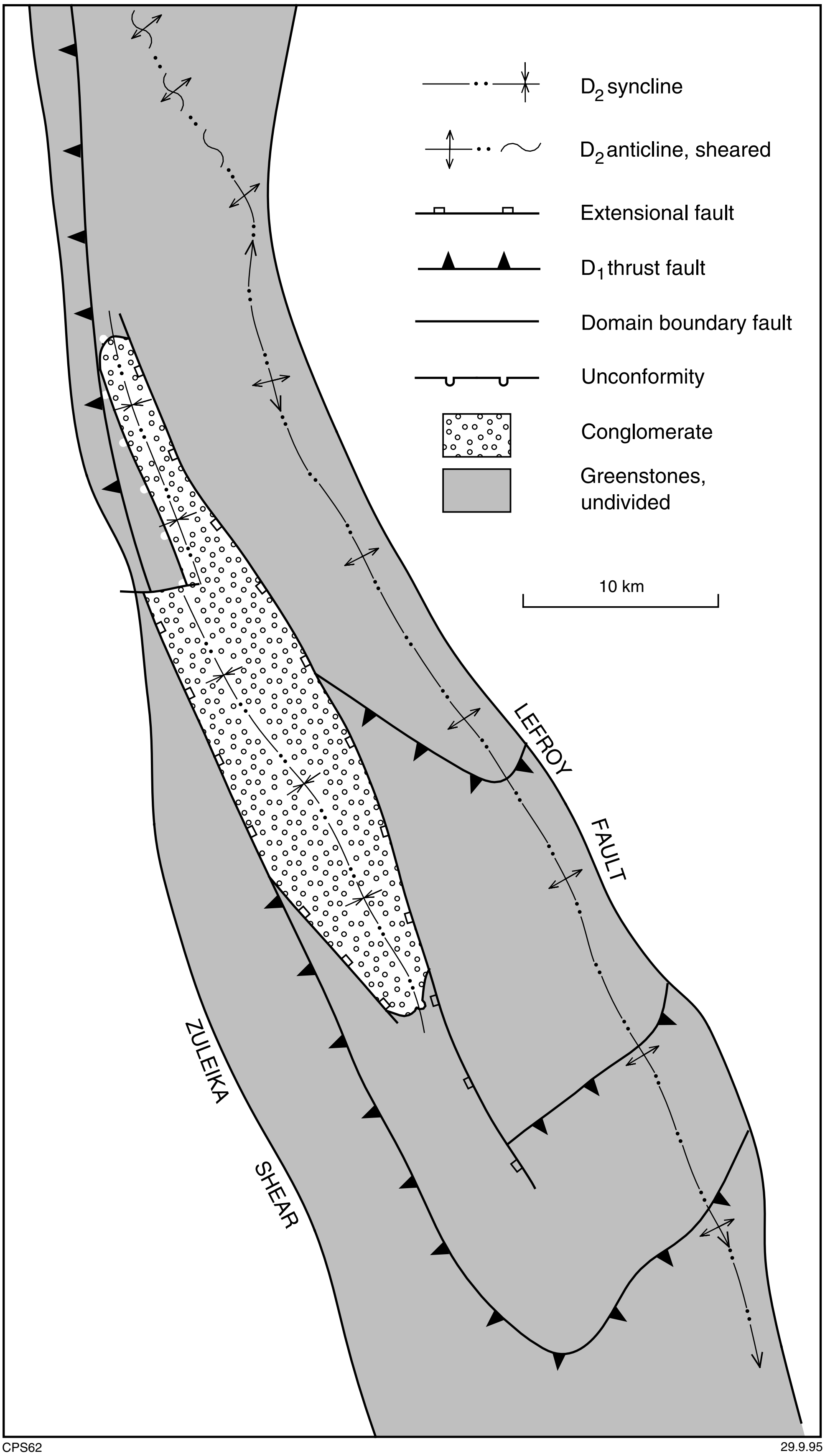


Figure 5. Structural setting of the Merougil Conglomerate — a syntectonic clastic basin in the Kambalda Domain of the Kalgoorlie Terrane. Note that the basin developed over a D_1 thrust duplex. After Swager and Griffin (1990b)

Table 1. SHRIMP geochronology of felsic-volcanic and volcaniclastic rocks in various terranes of the southern part of the Eastern Goldfields Province

Greenstone terrane/ domain	*Locality*	*Age (Ma)*	*Inheritance (Ma)*	
Norseman	Penneshaw Formation	2930 ± 4		
			2977 ± 9	xenocrysts
			3106 ± 13	xenocrysts
Kalgoorlie				
Boorara	Ballarat–Last Chance	2708 ± 7		
Parker	Nelsons Fleet	2681 ± 5		
Kambalda	Kapai Slate	2692 ± 4		
Ora Banda	Ghost Rocks	2691 ± 6		
Gindalbie	Perkolilli	2675 ± 3		
	Reidy Swamp	2682 ± 3		
	Maggies Dam	2681 ± 5		
	Wild Dog Dam	2708 ± 4		
			2737 ± 6	xenocrysts
			2761 ± 5	xenocrysts
	Bulong	2705 ± 4		
	Bulong Anticline	2672 ± 12		
Jubilee	Burton Tank	2706 ± 3		
Kurnalpi	Steeple Hill	2699 ± 4		
	Christmas Gift Dam	2711 ± 5		
	Jump Up Dam	2684 ± 3		
	Lake Rebecca North	2708 ± 7		
Mulgabbie	Yindi Woolshed	2673 ± 7		
Edjudina	East Liberty East	2708 ± 6		
Pinjin	Pinjin Homestead NE	2713 ± 4		

Note: All dates from Nelson (1995, in prep.), except for Kapai Slate (Claoué-Long et al., 1988)

Conglomerate in a small synclinal basin on a west-dipping limb of a regional anticline (Swager and Griffin, 1990b). The basin developed on top of a D_1 thrust duplex that was already tilted about a north-northwest axis (Fig. 5). The basin fill of conglomerate and sandstone buried part of the roof thrust and underlying fault-bounded blocks (or horses). During subsequent D_2 shortening the basin was closed into a discontinuous syncline (Fig. 5).

Detailed geochronology of the greenstone terranes is still scarce at this stage, although an initial program of single zircon U–Pb Sensitive High-Resolution Ion Microprobe (SHRIMP) dating has just been completed (Nelson, 1995, in prep.). Results obtained for felsic volcanic rocks are compiled in Table 1, and are discussed in more detail below. The only previously published date with detailed documentation (Claoué-Long et al., 1988) is the age of the Kapai Slate, a marker bed overlying komatiite in the Kambalda Domain of the Kalgoorlie Terrane. Other, conventional, U–Pb zircon dates were published by Pidgeon and Wilde (1990). In general, the greenstones were deposited around 2.7 Ga, with the exception of those in the Barlee Terrane which may be considerably older, at approximately 2.85–2.9 Ga (Nelson, in prep.). More SHRIMP data are available for granitoids than for volcanic sequences. Hill et al. (1989, 1992) have published some dates for post-regional folding plutons (c. 2665 Ma) in the terranes of the Kurnalpi–Edjudina region discussed here. Nelson (1995, in prep.) has published data for pre- and post-regional folding plutons.

Recent structural studies, including regional seismic profiling (Drummond and Goleby, 1993; Drummond et al., 1993; Goleby et al., 1993), and the application of new models have indicated a more complex deformation history than inferred from the mainly compressional features in the Kalgoorlie greenstones and elsewhere (Archibald et al., 1981; Swager and Griffin, 1990b). In particular, evidence for the occurrence of early and/or later phases of extension is presently being debated (Hammond and Nesbit, 1992; Williams and Currie, 1993; Williams and Whitaker, 1993; Williams et al., in prep.).

In this contribution, the original scheme of compressional deformation is retained: early (D_1) stacking of greenstones followed by a regional east-northeast to west-southwest shortening regime resulting in regional D_2 folds and reverse faults; followed by several stages (D_3–D_4) of strike, reverse and/or oblique faults, and continued foliation development. These D_3–D_4 structures, though

Table 2. Regional deformation history, including various proposed stages of extension inferred for different areas in the Eastern Goldfields

Extension	*Compression*	*Granitoid emplacement*
East–west extension: post-metamorphic, restricted to Ida Fault (Goleby et al., 1993)		Granitoid: late tectonic c. 2620 Ma
	Continued east–west shortening: strike- and reverse-slip faults (D_3–D_4)	
Granite–gneiss–migmatite complex (eastern margin of greenstones): final stage of uplift		Granitoid: post-regional folding c. 2660 Ma
	D_2 regional shortening: east–west upright foliation, ?inversion of extensional faults	
East–west regional extension: roll-over anticlines, and synclinal basins (Goleby et al., 1993; Williams, 1993) ?initial doming of gneiss complexes		?Granitoid: pre- to syn-regional folding
?Extensional shears in greenstones (Passchier, 1994)	D_1 thrusting: sequence repeats	
Extension D_e: low-angle shears along granite–greenstone margins (e.g. Hammond and Nisbet, 1992; Williams and Whitaker, 1993)		Granitoid: pre-regional folding c. 2719–2675 Ma

Notes: Key references for extensional deformation are shown in table; for additional references see text
Regional compressional deformation history after Archibald et al. (1981) and Swager et al. (1992)
SHRIMP U–Pb single zircon ages for granitoids from Campbell and Hill (1988), Hill et al. (1992) and Nelson (1995)

locally defining distinct events as in the Kalgoorlie mining district (Swager, 1989), developed during progressive east-northeast to west-southwest shortening, and on a regional scale are considered as late D_2. Regional extension (D_e) may have occurred (a) before D_1, possibly related to the later stages of basin formation; (b) between D_1 and D_2; and/or (c) at a late-tectonic/post-peak metamorphic stage (Table 2). Structures relating to extensional events are not pervasively developed in the greenstones. Rather, these events are traced through large-scale or crustal-scale structures, such as greenstone versus high-grade gneiss complexes and the development of syntectonic clastic basins. An added complexity is the inversion after extensional events erasing most of the smaller scale evidence.

Kalgoorlie, Barlee and Norseman Terranes

The Kalgoorlie Terrane (Swager and Griffin, 1990a; Swager et al., 1990; Swager et al., 1992) is characterized by a relatively simple stratigraphy dominated by a regionally persistent komatiite marker unit (Figs 6–8). This apparently simple, c. 2.71–2.68 Ga, greenstone sequence was stacked, folded and disrupted during the regional deformation, but can still be recognized in several domains (Figs 6A and B). No unequivocal basement has so far been found to this sequence. Recent seismic profiling and gravity data (Goleby et al., 1993) suggest that the Kalgoorlie greenstones are floored by a major, sub-horizontal detachment, and that they are partly underlain by a stacked sequence (?duplexes) of felsic rocks that are not exposed anywhere within the terrane (Fig. 7).

The complete stratigraphy of the Kalgoorlie Terrane (without the felsic rocks) is only preserved in two central domains (Ora Banda, Kambalda) with one or more units absent or discontinuous in marginal domains (Coolgardie, Boorara). Witt (1994a) has given a detailed account of the well-preserved and little-deformed regional stratigraphy in the Ora Banda area. Recent SHRIMP U–Pb zircon dating of felsic volcanic rock interlayered with komatiite in the Kanowna area of the Boorara Domain (2708 ± 7 Ma; Nelson, 1995; Table 1) indicate that early felsic volcanic centres are contemporaneous with the earliest komatiite eruptions (Fig. 8). Domain boundary faults are interpreted as long-lived structures probably with a precursor history as syn-volcanic growth faults.

Testing of this suspiciously simple structural–stratigraphic model by SHRIMP age dating is still

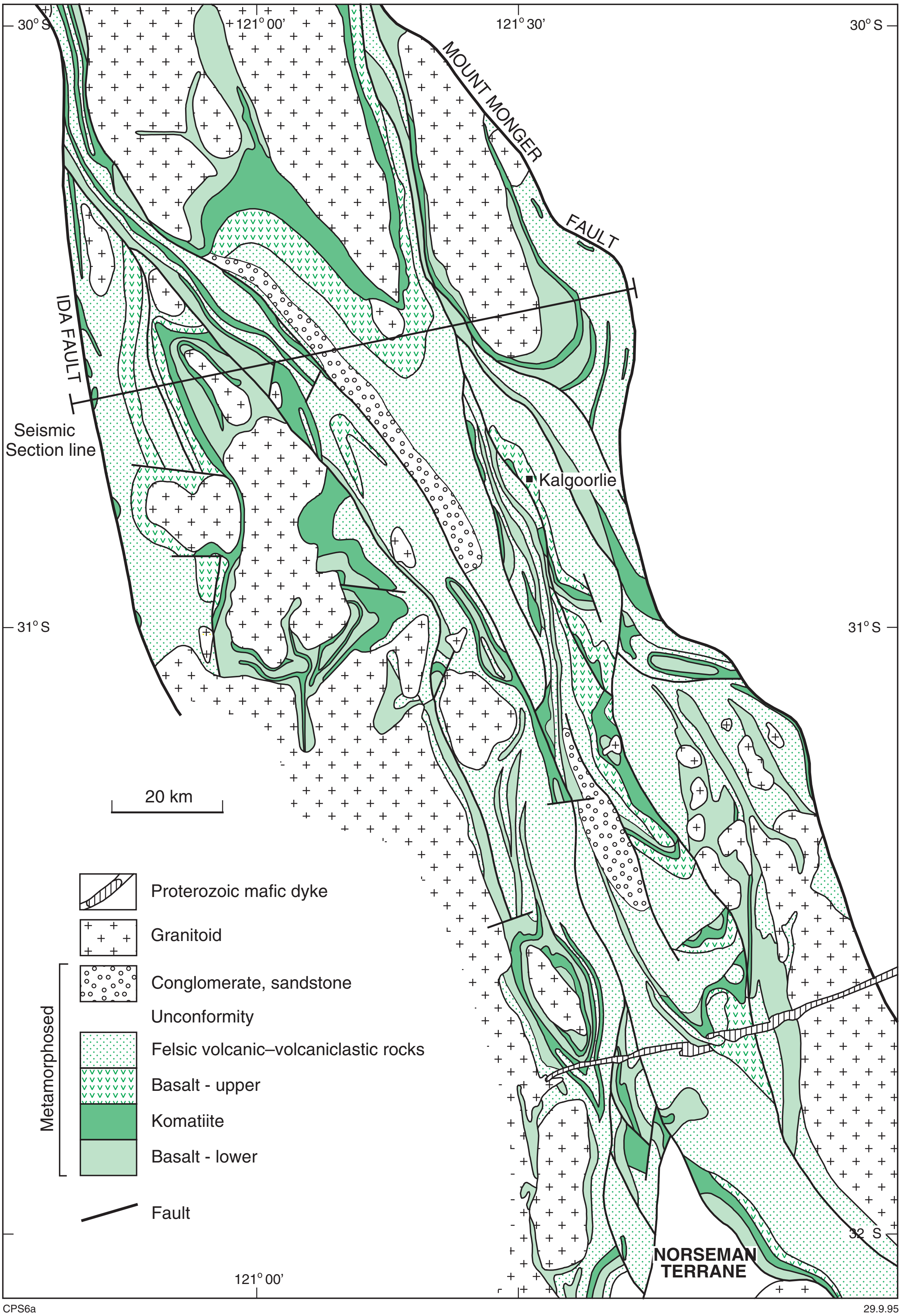


Figure 6A. Simplified geology of the Kalgoorlie Terrane (after Swager and Griffin, 1990a)

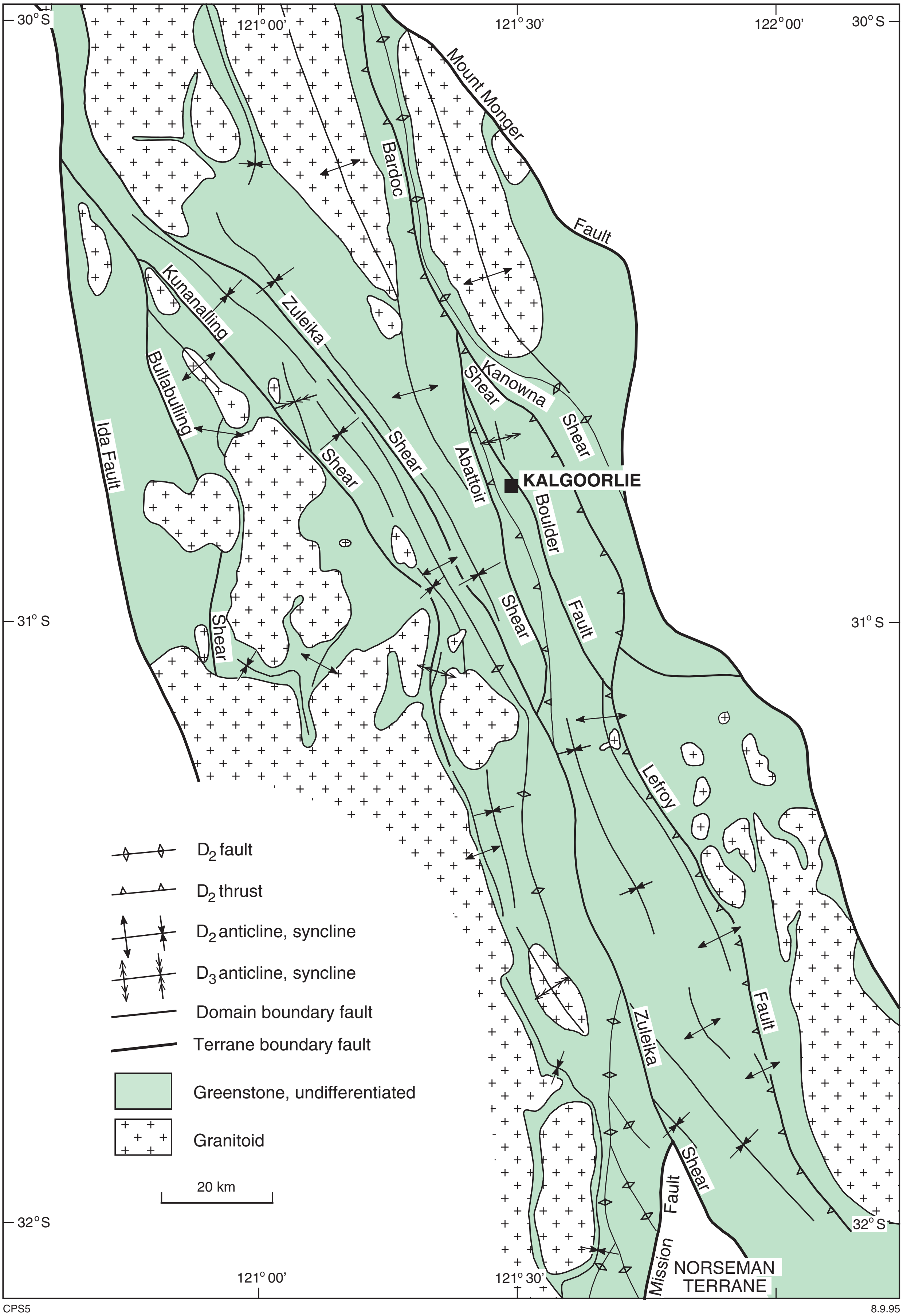


Figure 6B. Regional D_2 and D_3 structures in the Kalgoorlie Terrane (after Swager and Griffin, 1990a)

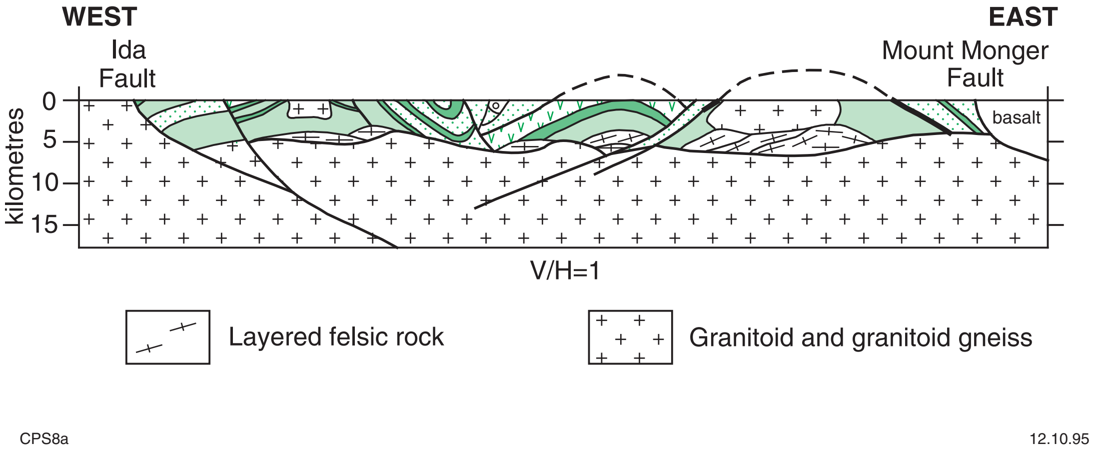


Figure 7. Natural-scale cross section, based on the 1991 AGSO seismic profile (Goleby et al., 1993), through the northern part of the Kalgoorlie Terrane. For the location of the seismic line and section see Figure 6A

incomplete. Figure 8 shows a composite stratigraphic section based on data from several domains and from seismic and gravity studies. Regional geochemical studies of (ultra-)mafic volcanic rocks (Morris, 1993) have shown compositional variations in stratigraphically equivalent basalt units in different domains, indicating that the domains may represent sub-basins rather than faulted portions of a single basin. Alternative explanations may include as yet unrecognized regional stacking. The upper felsic volcanic–volcaniclastic unit consists largely of subaqueously erupted dacite–rhyolite flows and associated pyroclastic and epiclastic rocks (Hallberg et al., 1993). Subaqueous to subaerial andesitic to dacitic lava flows and subvolcanic equivalents form more isolated volcanic centres at various levels within the unit (Morris, in prep.).

The presence of substantial layered or differentiated gabbro sills within the felsic unit indicates that mafic magmatism had not ceased entirely at that stage (Witt, 1995), although basalt is absent or rare higher up in the sequence.

The Barlee Terrane lies to the west of the Kalgoorlie Terrane (Fig. 2), separated from it by the Ida Fault. The two terranes are defined by differences in greenstone association and age (Wyche, 1993). They also appear to be exposed at different crustal levels.

The Barlee greenstones (>2.73 Ga, possibly 2.8–2.9 Ga) are considerably older than the Kalgoorlie sequence, and contain quartzite and/or quartz-pebble conglomerate at or near the base of the sequence; basalt with interleaved komatiite and regionally persistent banded iron-formation; and, towards the top, metasedimentary rocks and felsic volcanic complexes. In the Marda area these greenstones are unconformably overlain by a calc-alkaline volcanic complex with a conventional U–Pb zircon age of 2736 ± 10 Ma (Pidgeon and Wilde, 1990).

The supracrustal rocks are exposed in a series of elongate, narrow greenstone belts (Fig. 9) surrounded by granitoid and granitoid gneiss, and commonly are metamorphosed to relatively high grades (Ahmat, 1986), in contrast to the broad zones of low-grade greenstones in the Kalgoorlie Terrane (Binns et al., 1976). The outcrop patterns, the contrast in metamorphic grade, and the normal movement along the crustal-scale Ida Fault as revealed by seismic profiling (Goleby et al., 1993), suggest that the Barlee Terrane is exposed at generally lower crustal levels than the Kalgoorlie Terrane.

The Norseman Terrane is exposed in a small wedge to the south of the Kalgoorlie Terrane (Swager and Griffin, 1990a; Figs 2 and 6), and can be correlated with the Barlee Terrane on the basis of greenstone association (they are both BIF bearing). Nelson (1995) obtained an age of 2930 ± 4 Ma for rhyolite in the Penneshaw Formation of the Norseman Terrane (Table 1). This result confirms the ‘old’ age for the Penneshaw Formation reported earlier (Hill et al., 1989). The rhyolite also contains xenocryst populations of 2977 ± 9 Ma and 3106 ± 13 Ma.

Terranes in the Kurnalpi–Edjudina region

Gindalbie Terrane

The Gindalbie Terrane lies to the east of the Kalgoorlie Terrane, and is bounded by the Mount Monger Fault in the west, the Emu Fault and ‘Penny Dam Conglomerate’ in the east and the Randall Fault in the southeast (Fig. 3). The terrane contains three greenstone successions separated by regional low-angle faults (Figs 10 and 11). These early (D_1) faults are folded and offset by subsequent (D_2 and D_3) folds and faults.

The two structurally lower successions are restricted to the southern part of the terrane (Fig. 10), and are exposed in the regional D_2 Bulong Anticline (Hickman, 1986; Griffin and Hickman, 1988a; Griffin, 1990; also

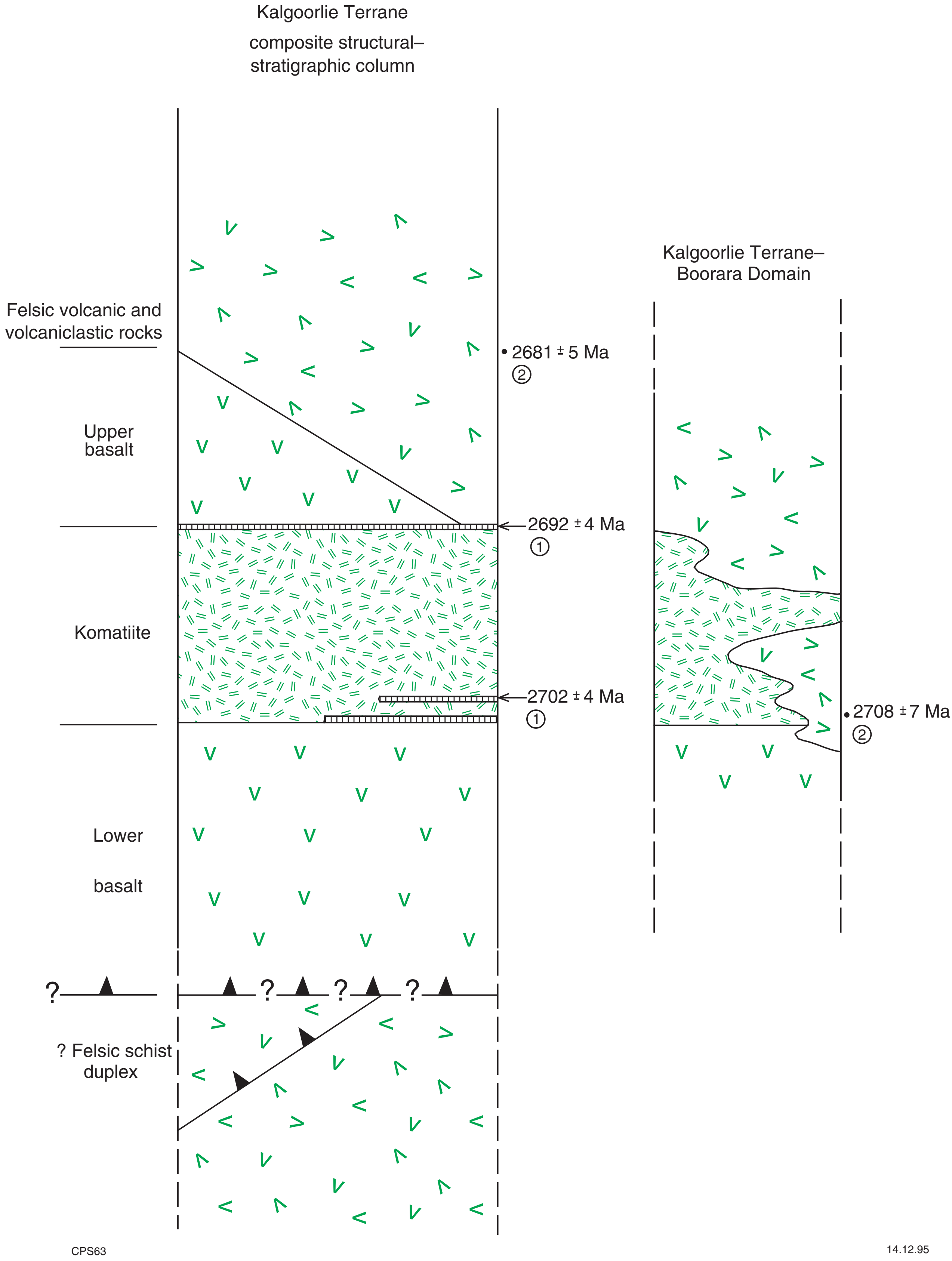


Figure 8. Composite structural–stratigraphic column for the Kalgoorlie Terrane. The Kalgoorlie stratigraphy is shown in faulted contact with underlying felsic schist duplexes interpreted from seismic reflection data (Goleby et al., 1993). Single zircon U–Pb ages from Claoué-Long et al. (1988) (1) and Nelson (1995) (2)

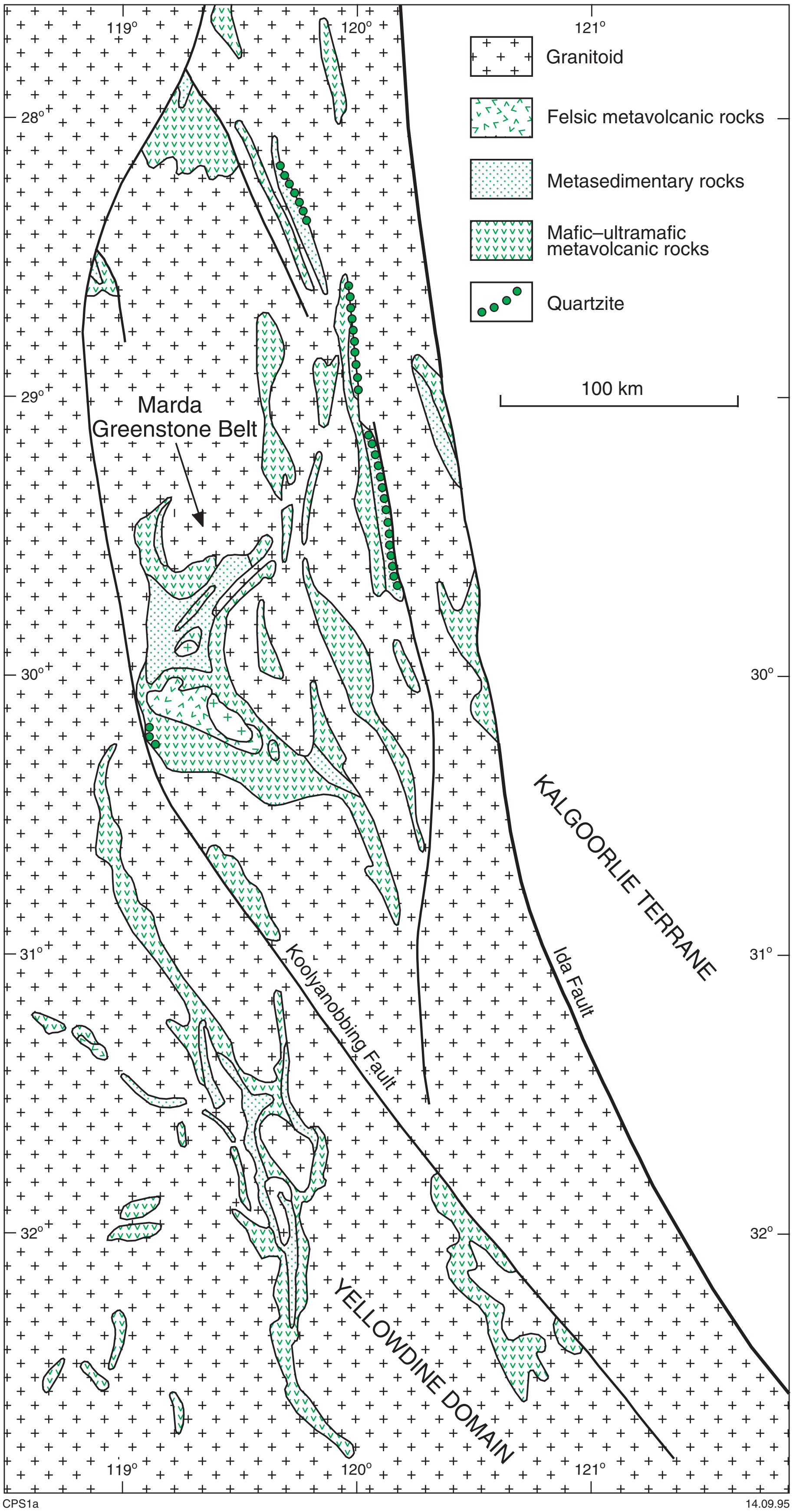


Figure 9. Simplified map of the Barlee Terrane including its southeastern Yellowdine Domain. Adapted from Ahmat (1986)

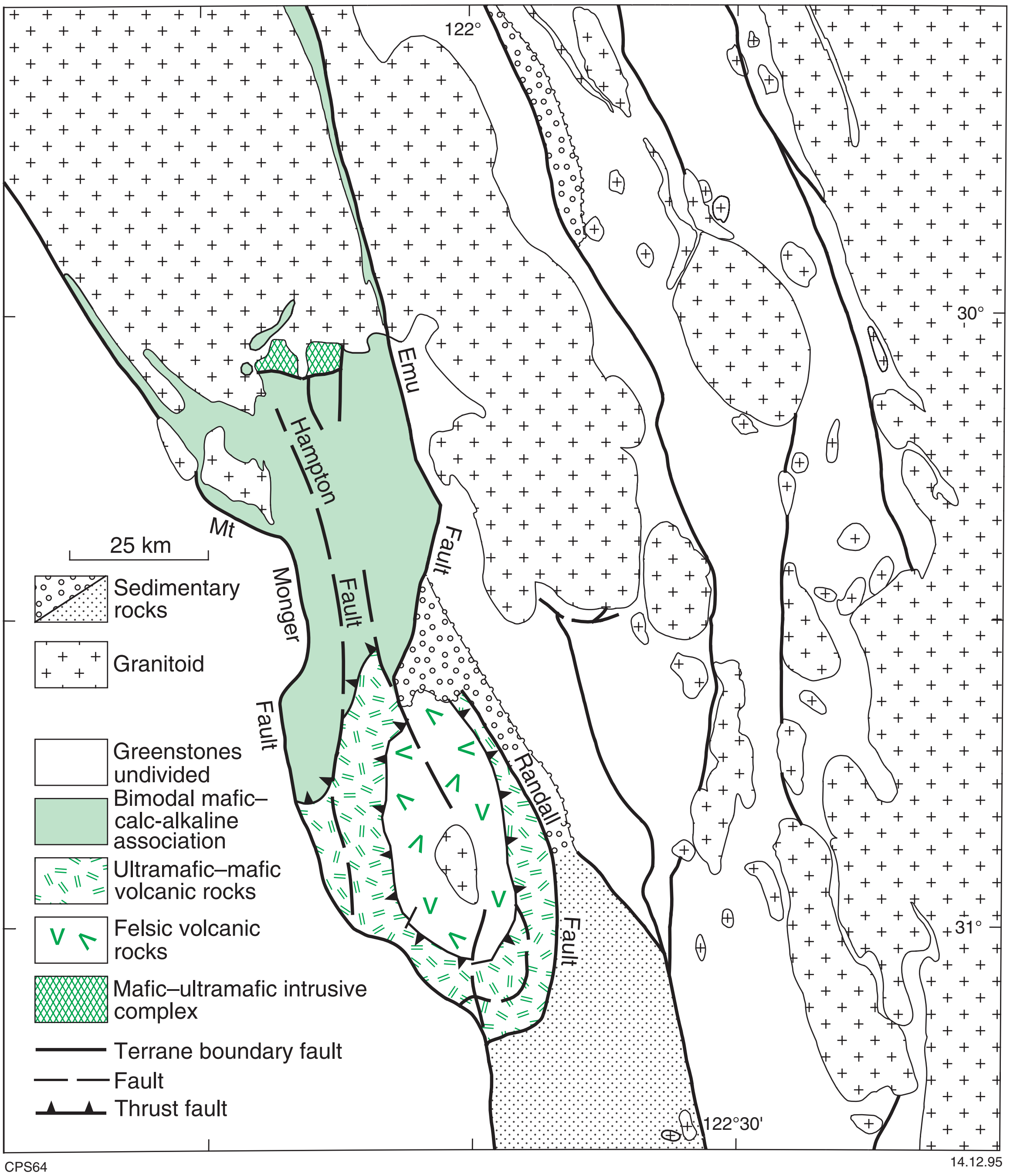


Figure 10. Structural–stratigraphic subdivision of the Gindalbie Terrane, showing three distinct greenstone successions separated by low-angle faults

known as the Yindarlgooda dome). The lowermost calc-alkaline succession contains a range of rocks from andesitic basalt to rhyolite, with predominant dacite and andesite. Lava flows may be present but are subordinate to pyroclastic rocks (Hickman, 1986). These volcanic rocks are overlain by finer grained sedimentary rocks particularly in the southern hinge and eastern limb of the Bulong Anticline. They include carbonaceous, locally pyritic, slate close to and along the interpreted fault contact with the overlying mafic–ultramafic association. Nelson (1995) obtained a 2672 ± 12 Ma age for a porphyritic metadacite in the volcanic sequence just below the metasedimentary rocks. A fault-bounded, isoclinally folded tholeiitic basalt–gabbro package restricted to the western limb of the anticline is regarded as a separate thrust slice with early recumbent folding.

The lowermost succession is overlain by mafic–ultramafic rocks dominated, on the western limb of the Bulong Anticline, by komatiite that contains thin interlayered felsic tuff layers dated at 2705 ± 4 Ma (Nelson, 1995; Table 1). To the southeast and east, i.e. on the eastern limb of the Bulong Anticline, the komatiite

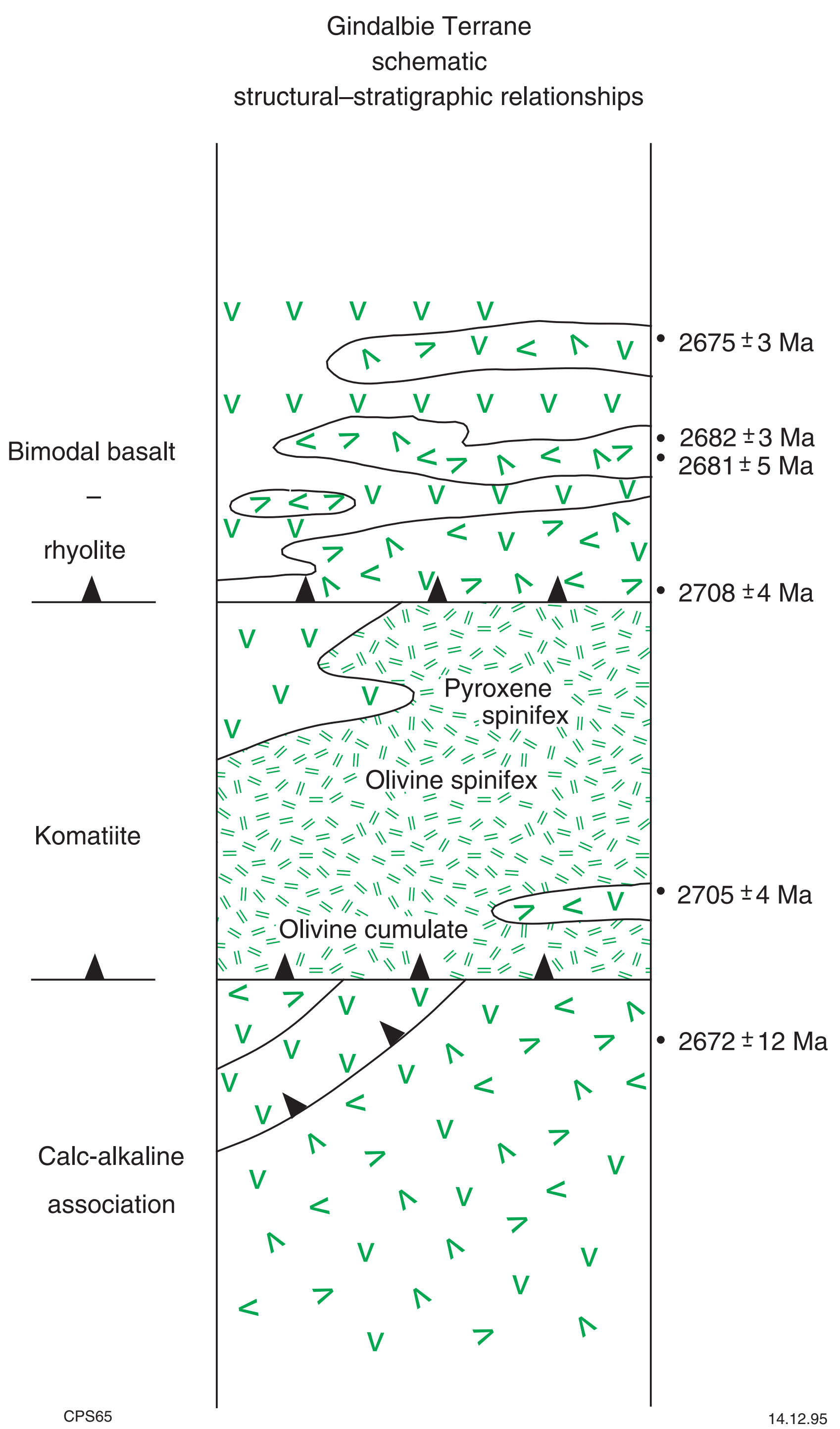


Figure 11. Schematic structural–statigraphic relationships of the Gindalbie Terrane. Single zircon U–Pb ages from Nelson (1995; in prep.)

is interleaved with increasing volumes of tholeiitic basalt. On this eastern limb the sequence becomes thinner to the north, and is absent in the northern hinge of the anticline. The komatiite–tholeiite association (2705 ± 4 Ma) is older than the felsic association (2672 ± 12 Ma) it overlies. This geochronology confirms the mapping interpretation that the komatiite–tholeiite association is thrust onto the younger felsic association.

Detailed mapping (Ahmat, 1995a) has shown that massive olivine cumulate in the west is transitional to and interleaved with olivine-spinifex and komatiitic basalt layers that generally increase in volume upwards in the sequence. The preferred interpretation here is that the massive olivine cumulate is volcanic in origin (Ahmat, 1993) rather than intrusive (Williams, 1970), and is an essential part of the komatiite sequence. Several major differentiated mafic–ultramafic bodies in the southern hinge of the Bulong Anticline are interpreted as subvolcanic sills (Williams, 1970; Hickman, 1986).

The komatiite lies in fault-bounded blocks in which isoclinal folds are locally defined by preserved hinges and/or opposite younging directions in differentiated gabbro (Ahmat, 1995a). These structures are interpreted as D_1 duplexes and recumbent folds developed during stacking of the sequence onto the underlying felsic association.

The uppermost association forms the northern part of the terrane (Fig. 10), and contains a bimodal basalt–felsic volcanic (dacite–rhyolite) sequence with ages of 2682 ± 3 Ma, and 2675 ± 3 Ma (Nelson, 1995). The bimodal sequence — possibly dominated by basalt — appears to be underlain by felsic volcanic rocks with only subordinate lenses of mafic to intermediate volcanic rocks. The lower felsic rocks have an age of 2708 ± 4 Ma, and contain well-preserved zircon xenocryst populations of 2737 ± 6 Ma and 2761 ± 5 Ma (Nelson, 1995; Table 1). This lower sequence correlates in age with, and may be the distant lateral equivalent of, the felsic volcanic lenses within the komatiite-dominated association. The ages of the upper felsic-volcanic rocks correspond with those for the felsic volcanic – volcaniclastic unit in the Kalgoorlie Terrane. The low-angle fault contact with the underlying komatiite association is displaced sinistrally along the D_3 Hampton Fault. The bimodal association, including local rhyolite-dominated volcanic centres (Hallberg, 1986; Hallberg et al., 1993; Morris, in prep.) can be traced to the north where similar rocks are exposed in the Kookynie–Melita area (Hallberg and Giles, 1986; Witt, 1994b).

Basalt, with lenses of sedimentary rock, dominates directly above the fault contact with the underlying komatiite, and is interleaved with felsic volcanic rocks on all scales. These felsic rocks become the dominant rock type further north. Hallberg et al. (1993) suggested that a line of geochemically distinct, rhyolite-dominated felsic centres can be traced from the Perkolilli area in the southern Gindalbie Terrane via Melita to Teutonic Bore, some 200 km along strike to the north. That the Kanowna felsic volcanic rocks are part of the belt, as suggested by these authors, appears doubtful on structural–stratigraphic and geochemical grounds. Unpublished geochemical data (Nelson, D. R., 1994, pers. comm.) suggest distinct REE patterns for all dated felsic volcanic rocks in the Gindalbie Terrane — similar to those reported by Hallberg et al. (1993). The Kanowna felsic volcanic sequence (of the Kalgoorlie Terrane) has different REE signatures.

The internal structure of the bimodal association is complicated by tight to very tight folding and numerous faults, including a major north-trending ?strike-slip fault, the Hampton Fault. At the northern contact with a major granitoid complex, the intrusive mafic–ultramafic Carr Boyd Complex, though itself folded (Ahmat, 1993; and 1994, pers. comm.) appears in faulted contact with the greenstones. Its geological setting is poorly understood, but it is different in character from the prominent layered sills further south in the Gindalbie and Kalgoorlie Terranes. The complex contains Ni–Cu deposits in breccia pipes emplaced late in the crystallization history. This mineralization style is unique in the Eastern Goldfields Province.

The Gindalbie Terrane thus contains three distinct greenstone successions bounded by early, low-angle faults. Structurally higher successions are older or show the same age range as the rocks they overlie (Fig. 11). Possible correlation with the Kalgoorlie Terrane greenstones can be based on the prominent komatiite which was deposited in the interval between about 2705 and 2692 Ma. In both the Kalgoorlie and Gindalbie Terranes the lower felsic and overlying ultramafic–mafic association are in faulted contact, but only in the latter is there evidence that the ultramafic–mafic association is allochthonous on top of a younger sequence. In the Gindalbie Terrane this association is itself stacked in numerous fault-bounded slices, with or without tight, recumbent folds, and, in contrast to the Kalgoorlie Terrane, displays a pronounced lateral change to a tholeiite-dominated sequence. The mafic–felsic bimodal association has no direct equivalent in the Kalgoorlie Terrane.

Jubilee Terrane

The Jubilee Terrane is bounded to the west by the Emu Fault, to the southwest by the ‘Penny Dam Conglomerate’, the ‘Mount Belches greywacke’, and the Railway Fault, and to the east by the Avoca Fault and post-folding granitoids (Fig. 3). The northern continuation is not clear, and the terrane may wedge out. To the south the Jubilee greenstones appear to wedge out between the Avoca Fault and the ‘Mount Belches greywacke’, though they may be buried below the latter over a large area.

The terrane contains a west-dipping, west-younging homoclinal sequence (Figs 12 and 13) of mainly basalt with several marker units of komatiite dominated by olivine cumulate with minor gabbro and local basaltic facies with pyroxene-spinifex textures. Regional lateral changes from basalt-dominated to felsic epiclastic-dominated packages are interpreted as original depositional features. Several duplex structures and possible repetition of komatiite layers suggest that early D_1 thrusting has resulted in at least local stacking of part of the greenstone sequence. The greenstone association would thus consist of mafic–ultramafic volcanics with local coeval felsic volcanic centres. Felsic volcanism may involve thin epiclastic deposits surrounding a thicker, central volcanic pile (Hallberg and Giles, 1986). Nelson (1995) dated a felsic volcanic unit between two komatiite layers at 2706 ± 3 Ma, i.e. directly comparable in age to similar associations in the Kalgoorlie (Boorara Domain) and Gindalbie Terranes. The contact with the overlying ‘Penny Dam Conglomerate’ locally appears to be an unconformity, but may also be faulted.

Kurnalpi Terrane

The Kurnalpi Terrane lies between the Avoca Fault, which is for a large part stoped out by granitoids, and the Yilgangi

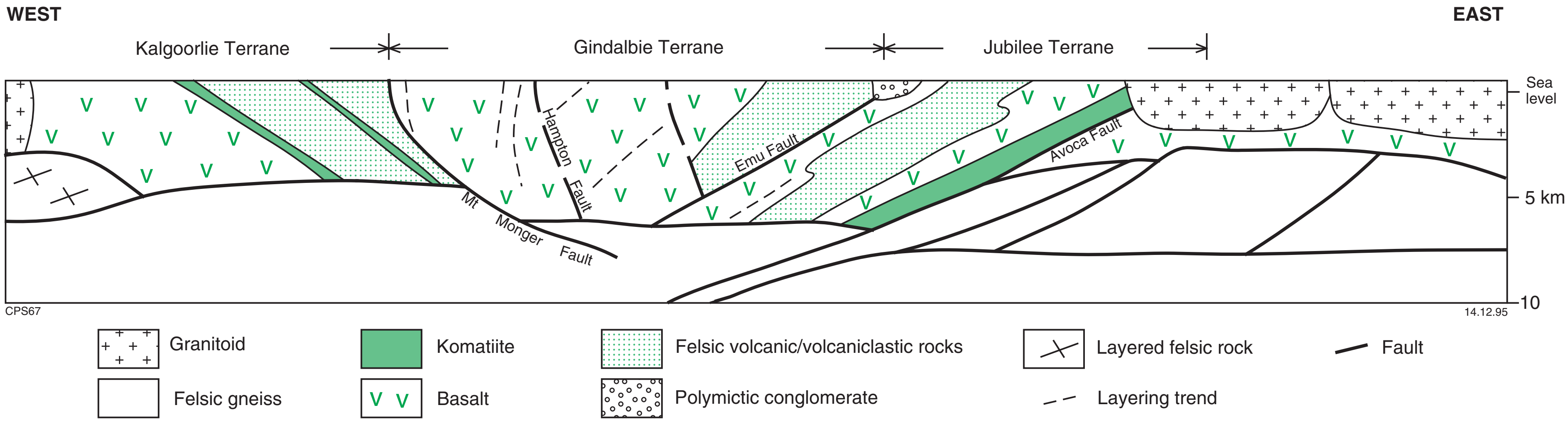


Figure 12. **Natural-scale cross section, based on the 1991 AGSO seismic profile (Goleby et al., 1993), across the Gindalbie and Jubilee Terranes, just at the northern end of the 'Penny Dam Conglomerate' (Fig. 10)**

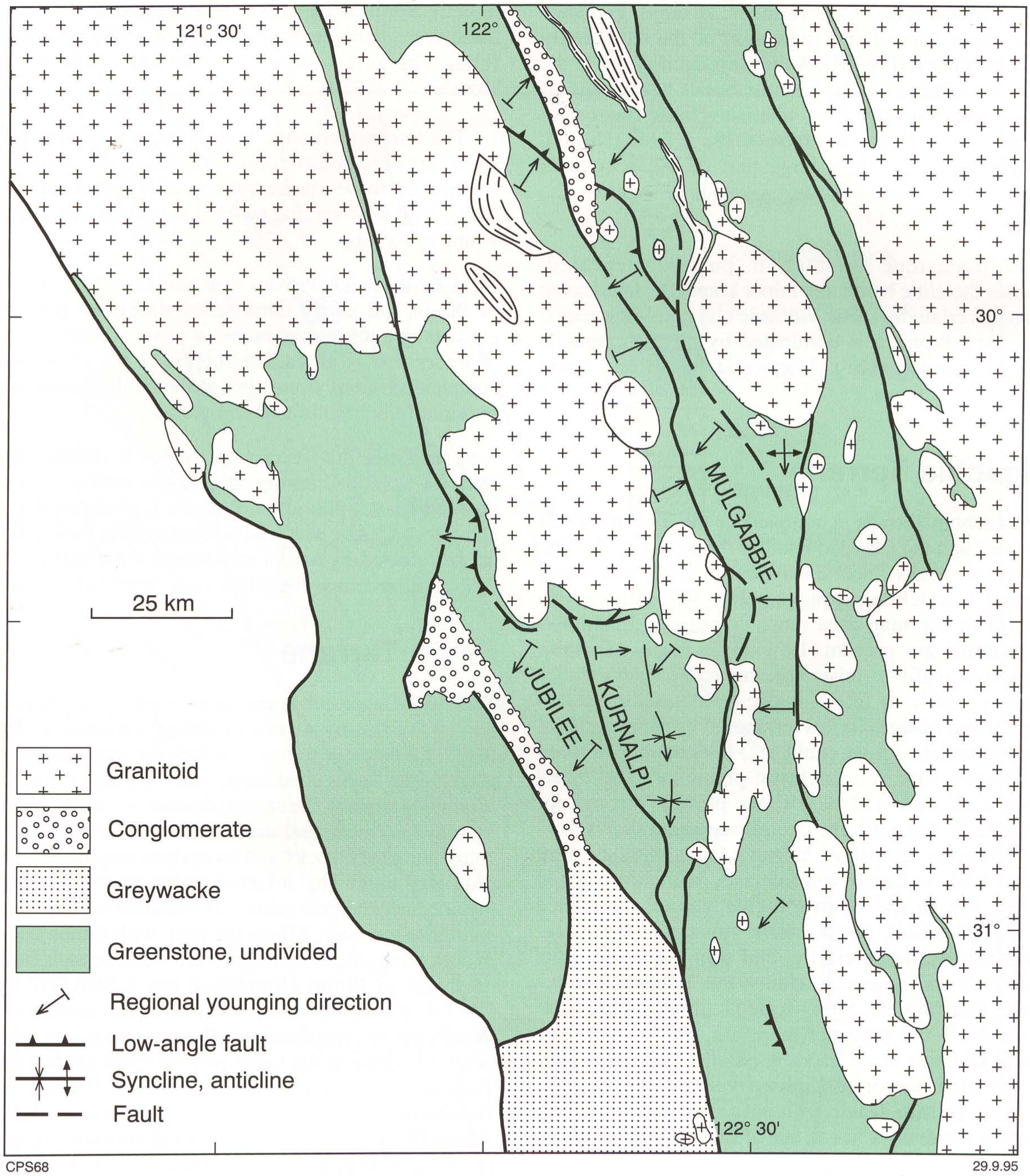


Figure 13. Major low-angle faults, folds and regional younging directions in the Jubilee, Kurnalpi and Mulgabbie Terranes

Fault to the east (Fig. 3). The main regional structures are the Steeple Hill syncline in the southern part and a complex east-dipping and east-younging sequence in the north.

The D_2 Steeple Hill syncline has folded a sequence of basalt–dolerite with thin and discontinuous komatiite towards the top, overlain by a felsic volcanic–volcaniclastic centre (dated at 2699 ± 4 Ma; Nelson, 1995), including some intermediate volcaniclastics followed by fine-grained metasedimentary rocks including grey slate and banded iron-formation. The lowermost felsic rocks have been dated at 2711 ± 5 Ma (Christmas Gift Dam; Nelson, 1995). The lowermost basalt is well-exposed around Kurnalpi townsite, where it appears largely fault-bounded. In the south, where the greenstones are wedged out between the Avoca and Yilgangi Faults, the sequence is refolded by D_3 en echelon folds.

Northwards, the sequence dips and youngs to the east; it contains several basalt – felsic volcanic and volcaniclastic packages; and shows sub-stantial lateral variation in mafic versus felsic rock volumes. A major bedding-parallel shear zone shows truncation of the structurally highest basalt unit (Fig. 14). A thin rhyodacite layer at the base of the structurally uppermost basalt has an age of 2684 ± 3 Ma (Nelson, 1995), whereas a felsic fragmental unit below the fault has an age of 2708 ± 7 Ma (Nelson, in prep.) In the north, a large part of the sequence, including early thrust faults, is truncated against the Yilgangi Fault (Fig. 14).

The greenstone association, possibly repeated, comprises tholeiitic basalt and minor komatiite, interleaved with and overlain by felsic volcanic and epiclastic rocks. Komatiitic volcanism is dominated by olivine-cumulate rock with minor gabbro, komatiitic basalt and some olivine-spinifex flows.

Mulgabbie Terrane

The Mulgabbie Terrane is bounded by the Yilgangi Fault to the west and the Claypan Fault to the east (Fig. 3). The supracrustal rocks occur in a west-dipping and west-younging homoclinal sequence (Fig. 13), although to the north of the map area more complicated fold and fault patterns are present. Low-angle faults, multiple sequences of mafic-to-felsic volcanic rocks, lateral facies variations (mafic to felsic, mafic to metasedimentary) are prominent features in this terrane. Substantial andesite and intermediate schist packages, presumably derived from intermediate volcaniclastic precursors and inter-layered with slate and basalt, are present throughout the terrane. In the north the overall sequence shows low-angle truncation against the Yilgangi Fault, with an entire mafic to felsic volcanic–volcaniclastic sequence wedged out (Fig. 14). In the south a highly variable sequence with several basalt, intermediate volcaniclastic, meta-sedimentary–felsic epiclastic, and thin komatiite units similarly shows truncation against the Yilgangi Fault – Cowarna Fault system. Small-scale D_1 thrust duplexes are inferred from the regional mapping, and suggest the presence of larger scale bedding-parallel faults that may have repeated and/or juxtaposed various supracrustal packages. A thin felsic volcanic unit between two substantial basalt units has an age of 2673 ± 7 Ma (Nelson, 1995).

Edjudina Terrane

The Edjudina Terrane — bounded by the Claypan Fault and the Pinjin Fault (Fig. 3) — is characterized by prominent banded iron-formation marker beds that are intruded in the north by extensive dolerite sills. However, volumetrically, the terrane is dominated by several basalt–andesite–dacite–rhyolite volcanic complexes and by laterally extensive belts of intermediate schist derived from predominantly andesitic precursors. Thin basalt with or without komatiite layers forms a narrow eastern belt. The overall relationship between these rock packages is not known. The regional BIFs can be traced for a long distance further north where they are replaced by less Fe-rich ferruginous chert (Williams et al., 1976). Hallberg (1985) distinguished several calc-alkaline volcanic complexes directly north along strike, and suggested that some of these were partly subaerial. Nelson (1995) has dated a felsic volcanic centre some 40 km south of Pinjin Homestead at 2708 ± 6 Ma.

The internal structure is little known: analogous with some exposed mesoscopic structures, the sequence is interpreted to be stacked across east-dipping D_2 thrust faults, with west-verging inclined to upright folds, and may young to the east.

A fault-bounded ovoid structure, centred 30 km south of Pinjin and partly outlined by disrupted BIF layers, consists of a substantial mafic-to-felsic volcanic complex. Whether this is an early structure is not clear, but the complex geometry occurs just to the north of a major post-regional-folding granitoid complex.

The Edjudina Terrane provides a contrast to the terranes described earlier. It contains minor volumes of tholeiitic basalt plus komatiite, and is dominated by calc-alkaline, andesitic volcanic complexes and their epiclastic debris, capped by and/or interleaved with BIF, chert and fine-grained metasedimentary rocks intruded by dolerite.

Pinjin Terrane

The Pinjin Terrane is bound to the west by the Pinjin Fault and to the east by a zone of strongly foliated granitoids (Fig. 3). The greenstones — which are metamorphosed at amphibolite-facies conditions, with the highest temperature assemblages along the eastern contact — consist of closely interlayered felsic and mafic schists, intermediate schist, some ultramafic rocks and an eastern amphibolitic basalt plus BIF unit. The inferred supracrustal associations include andesite-dominated calc-alkaline rocks to the west and tholeiites with BIF to the east, with minor komatiite in both zones. A felsic fragmental volcanic rock from just northeast of Pinjin Homestead has a SHRIMP age of 2713 ± 4 Ma (Nelson, 1995). Despite structural and metamorphic complications, these associations are quite similar to those in the lower metamorphic grade Edjudina Terrane. This prompts the suggestion that the Pinjin Terrane may represent an uplifted portion of the Edjudina Terrane (see below). However, an alternative explanation is that the Pinjin Terrane contains a BIF–tholeiite–komatiite association similar to that found in the Barlee Terrane.

Linden Terrane

The Linden Terrane forms a narrow belt east of the Edjudina and Pinjin Terranes, and is largely stoped out by the intrusive granitoid complex further east (Fig. 3). Only the southernmost part of the terrane is exposed in the area discussed in these notes. The greenstone association includes tholeiitic basalt, komatiite with substantial komatiitic basalt, and felsic volcaniclastic sequences, and appears to young to the west. The medium- to high-grade metamorphic zone in the greenstones adjacent to the foliated granitoids is only narrow, compared to the distribution of the medium- to high-grade greenstones in the Pinjin Terrane.

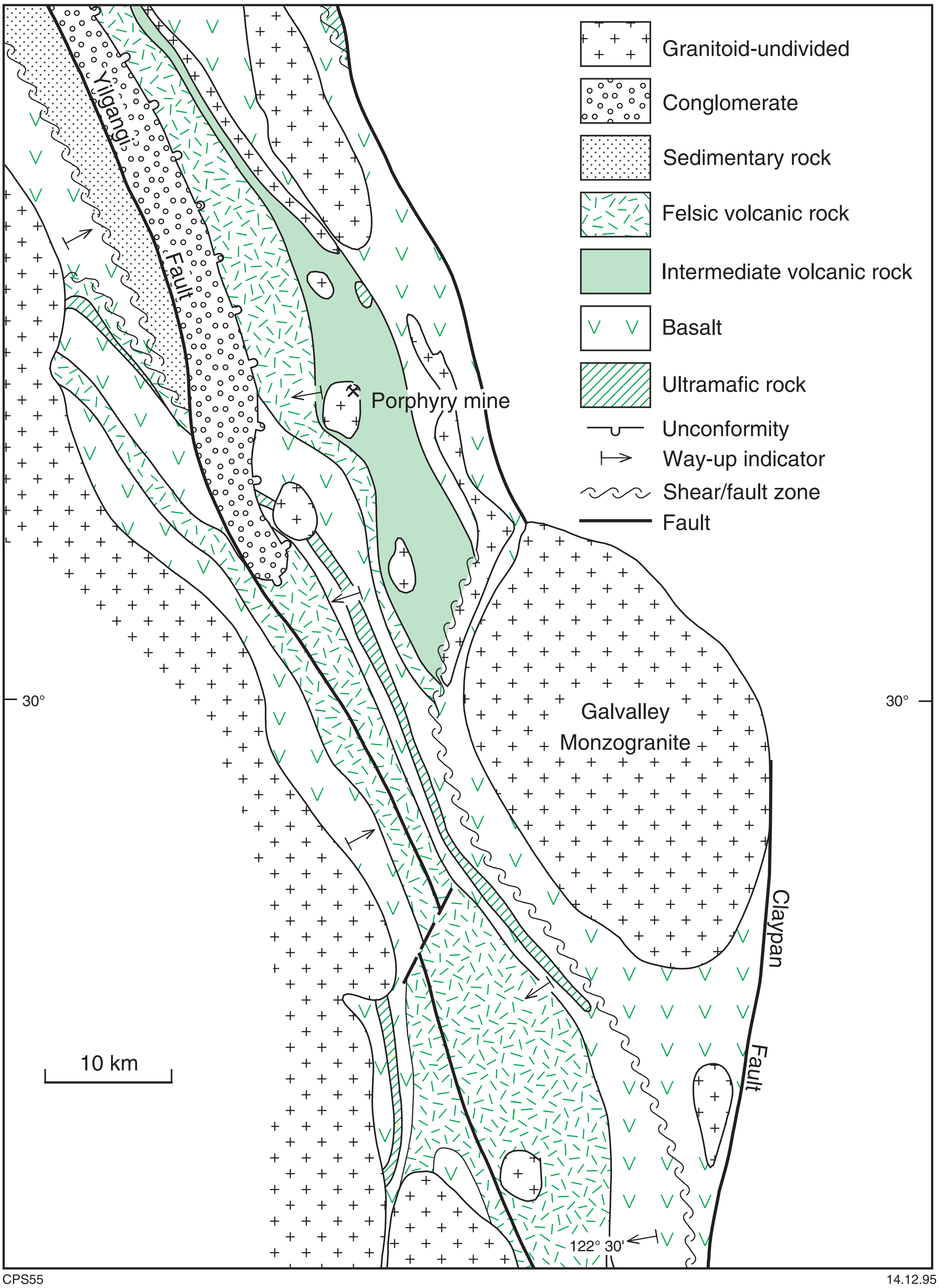


Figure 14. Detailed geology of the Kurnalpi and Mulgabbie Terranes in the northern part of the area discussed. Note truncation of sequences in both terranes against the Yilgangi Fault, which is partly buried under polymictic conglomerate

Terrane boundary faults

The terrane boundary faults are generally traced by truncations of the structural–stratigraphic packages. In some cases discontinuous en echelon folds adjacent to the boundary faults help to constrain their position. Only in a few localities do exposures of sheared rock with mylonitic textures give direct evidence of the kinematics, although these textures only record late stages of displacement. The southernmost section of the Pinjin Fault contains mylonitic felsic rocks with downdip lineations indicating west-block-down movement. The Claypan Fault shows local subhorizontal mineral lineations with left-lateral displacement indicators. Some of the complicated movements resulted in the development of the coarse clastic basins overlying the faults, such as the 'Penny Dam Conglomerate' which buries the Emu Fault.

'Mount Belches greywacke'

The 'Mount Belches greywacke' has not been given terrane status. Although no transition is exposed, the greywacke appears to be laterally continuous with the 'Penny Dam Conglomerate'. Therefore, each is interpreted as a widespread overlap sequence of turbiditic greywacke between the Kalgoorlie and Kurnalpi–Mulgabbie Terranes. Along the northwestern boundary with the Gindalbie Terrane (i.e. the Randall Fault) large-scale, spectacular fold patterns outlined by BIF show tightening of the folds and rotation of the axial plane towards the fault. This indicates an increase in flattening strain towards the Randall Fault.

Economic geology

The question of the economic potential of the greenstone terranes in the Kurnalpi–Edjudina region is an interesting one. Gold (and nickel) production — historic, recent, and current — from the area under discussion in these terranes is almost negligible when compared to the Kalgoorlie Terrane to the west; and is substantially less than in the same terranes along strike to the north. What are the reasons behind this difference in gold production: fundamentally different geological factors (Smithies et al., in prep.); complex variations in regolith geology hampering exploration; has exploration in this area been less intense; or perhaps a combination of all three?

Granitoids

Granitoids have been divided into pre-regional folding, pre- to syn-regional folding, and post-regional folding (D_2) plutons or batholiths, and late-tectonic stocks. The post-regional folding group has been further subdivided into biotite-bearing and hornblende- plus biotite-bearing varieties (Fig. 15). The small, late-tectonic stocks and dykes of a broadly defined alkaline suite (Libby, 1989) — including syenite and less commonly quartz monzodiorite — are shown separately, and generally appear to postdate the regional folding (D_2–D_3). The main subdivision of the granitoids is on structural criteria only (Archibald et al., 1981; Witt and Swager, 1989; Witt and Davy, 1993). Regional (but incomplete) SHRIMP geochronology indicates minimum ages of c. 2685 Ma for the earlier granitoids, and c. 2665–2660 Ma for the post-regional folding plutons (Hill et al., 1989, 1992). These later plutons contain evidence of continued regional shortening during and after emplacement, but they were emplaced across regional D_2 folds.

Geochemical studies in the Eastern Goldfields generally indicate a multi-stage history for the origin of most granitoids, which are rather more potassic than typical Archaean tonalite–trondhjemite–granodiorite (TTG) suites. Most authors favour a precursor andesitic or, more likely, TTG continental crust that was extensively remobilized during the late Archaean (Hill et al., 1989; Champion and Sheraton, 1993, and references therein). Recent regional geochemistry has shown that post-regional folding granitoids, including hornblende-bearing varieties, in the Kurnalpi Terrane and terranes further east are derived from a tonalitic precursor, in contrast to those in the Kalgoorlie and Gindalbie Terranes which indicate granodioritic precursors (Smithies et al., in prep.). The authors suggest that two different basement terranes can be mapped indirectly.

The pre-regional folding granitoids include strongly foliated and partly recrystallized plutons that lie as thin sheets within the greenstone sequence, with locally preserved evidence of emplacement by stoping (e.g. Yarri Monzogranite). Other plutons occur as highly elongate ovoid bodies (e.g. in the Pinjin Terrane). The most extensive occurrences of early foliated granitoid are along the margins of large granitoid-dominated areas, such as the foliated granitoid and migmatitic, banded granitoid gneiss along the eastern margin of the Pinjin and Linden Terranes (i.e. the 'Eastern Gneiss domain' of Williams and Whitaker, 1993). In the past such gneiss has been proposed as possible basement, but here is interpreted as the deeper level, high-strain equivalent of the early granitoids (Swager, 1995). The development and emplacement of the gneiss domes, with their high-grade greenstone margins, which are compared by Williams and Whitaker (1993) to metamorphic core complexes, are discussed in more detail below. Recent SHRIMP data for granitoids, interpreted on structural criteria as pre-regional folding, indicate an age range from 2719 ± 5 Ma (Outcamp Bore tonalite) to 2672 ± 5 Ma (Two Lids Bore foliated granitoid). This age range overlaps with the range documented so far for the felsic volcanism (Nelson, 1995, in prep.).

The granitoids that post-date the D_2 regional folding are slightly ovoid plutons, with local aeromagnetic patterns suggesting multiple stages of emplacement and/or contact-parallel metamorphic alteration. Most plutons contain a weak regional foliation that may have developed locally as a flow foliation (e.g. aligned K-feldspar megacrysts and mafic xenoliths in a matrix of quartz–feldspar–biotite). Higher strains along the margins of the plutons have resulted in more strongly developed foliations; some plutons are crosscut by mylonitic zones that are mineralized with gold. Several

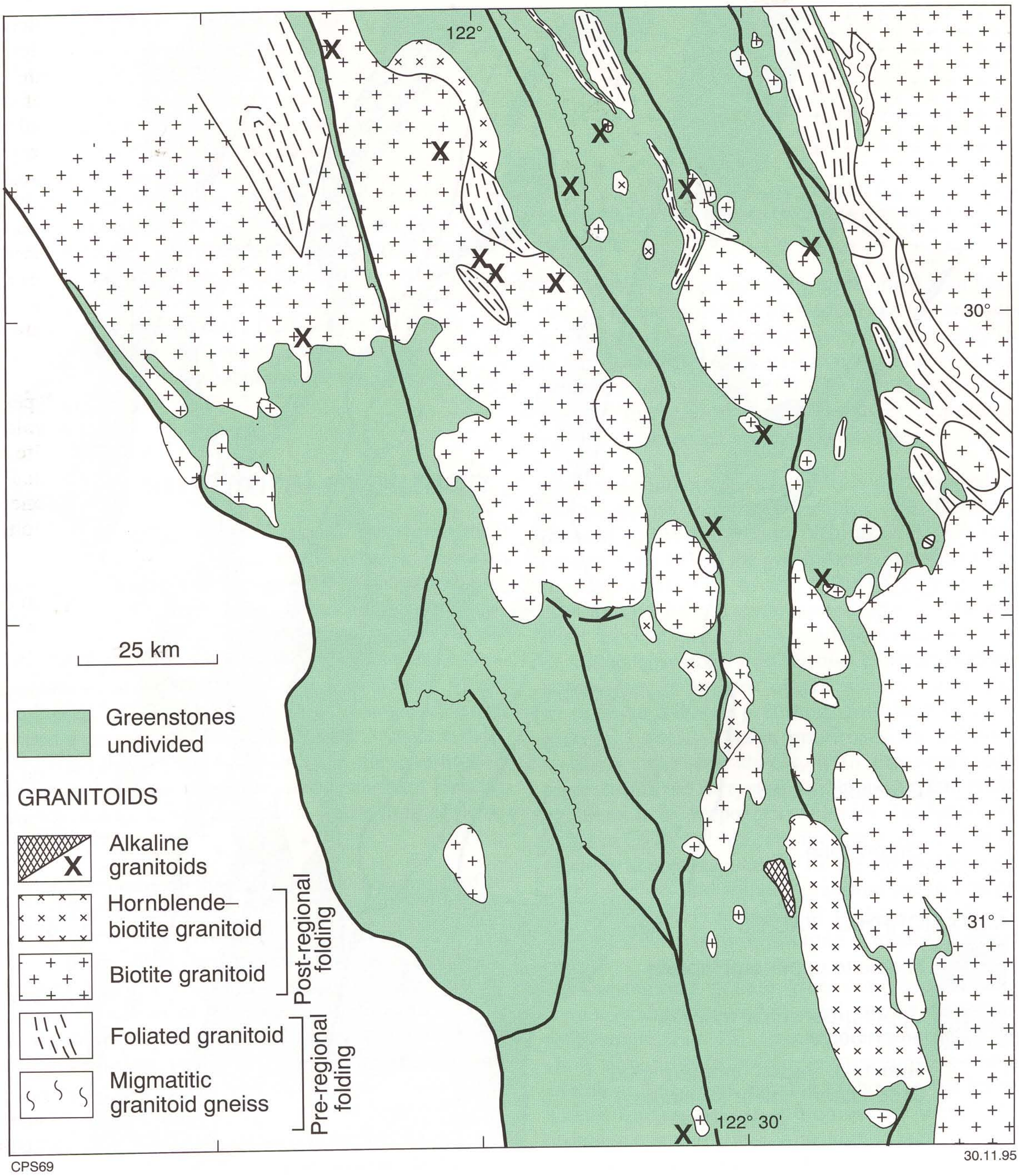


Figure 15. Subdivision of granitoids intrusive into the greenstone terranes in the Kurnalpi–Edjudina region

of these plutons have intruded across terrane boundary faults.

Metamorphism

The distribution of low-, medium- and high-grade metamorphic zones (Fig. 16) is similar to the patterns outlined by Binns et al. (1976). Low-grade zones — lower to middle greenschist facies — occupy the central parts of the greenstone belts; medium-grade zones — upper greenschist to lower amphibolite facies — form broad haloes around granitoid plutons or complexes; and high-grade zones — middle to upper amphibolite facies — lie directly along granitoid contacts, and include substantial volumes of early foliated granitoid and migmatitic granitoid gneiss. The regional zonation is based on metamorphic indicator minerals or assemblages and textural characteristics.

Metamorphism occurred at low to intermediate pressures (andalusite, cummingtonite, and, to some extent, garnet; up to 4 ± 1 kB; Yardley, 1989). Transitional greenschist–amphibolite facies assemblages in the Steeple

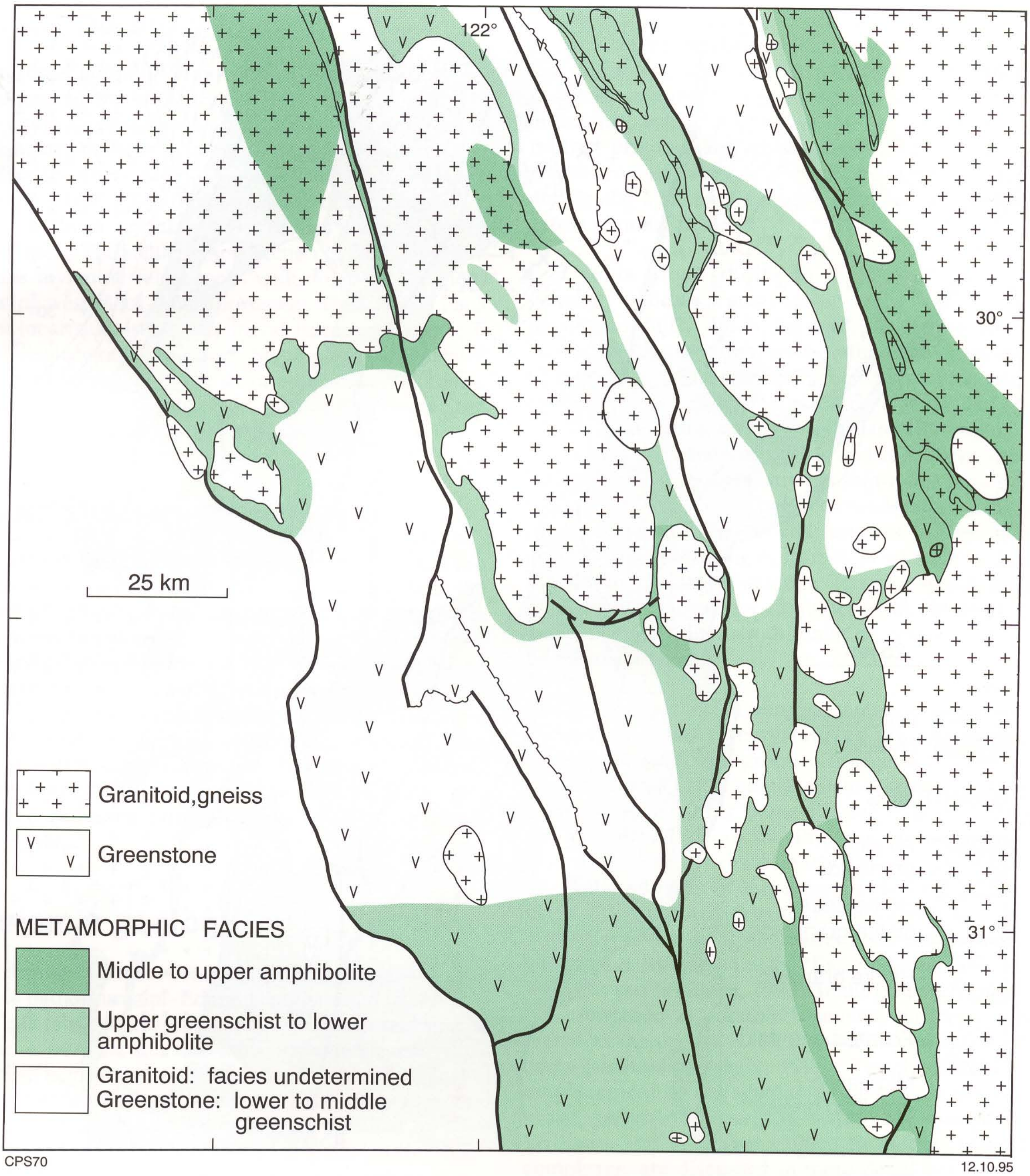


Figure 16. Distribution of metamorphic facies in supracrustal greenstones and foliated granitoids

Hill syncline area suggest P–T conditions of 2.5 Kb and 350°C. Highest T assemblages are represented by clinopyroxene–hornblende–plagioclase in amphibolite, and the partial melting textures in monzogranitic gneiss (at 700°C or more; Yardley, 1989; Swager, 1995). The regional metamorphic zonation tends to parallel the outline of the major granitoid complexes dominated by post-regional folding (D_2) granitoids (Fig. 16; Witt, 1991). Porphyroblasts show a relatively late-stage timing because they have grown across the main foliation and have enclosed foliation trails. Peak regional metamorphism therefore appears to be late during regional shortening (D_2–D_3).

Partial melting in the migmatitic gneiss occurred during upright D_2 folding of an earlier gneissic fabric, suggesting peak metamorphic conditions late during D_2. The early fabric is defined by recrystallized monzogranitic and tonalitic assemblages, and indicates that high temperatures were reached early in the regional deformation. In the greenstones there appears to be little evidence preserved of early thermal peaks.

The metamorphic zonation is probably controlled by two main factors: firstly, a major thermal pulse (and associated post-regional folding granitoids) responsible for peak metamorphic conditions; and secondly, a subsequent extensional event which juxtaposes different crustal levels and different P–T conditions (see **Regional structural evolution** section). The thermal pulse represented by the widespread c. 2660 Ma granitoids appears to be a Yilgarn-wide phenomenon, and therefore requires explanation in terms of a craton-wide event. Hill et al. (1989, 1992, and references therein) proposed a mantle plume which caused the late-Archaean volcanism of the Eastern Goldfields greenstones, and, after a 20–30 Ma delay due to conductivity lag, widespread remobilization of an older felsic crust and granitoid emplacement within the greenstones. Recent structural models indicate that major east–west extension, after early D_1 thrusting but before D_2, may be the cause behind a subsequent thermal pulse into the greenstones (see below), but the driving force must be sought in mantle processes.

Regional structural evolution

Recent studies of greenstone contacts with granitoid gneiss domes in the central and northern Eastern Goldfields (Hammond and Nisbet, 1992; Williams and Whitaker, 1993), and regional seismic reflection profiling by AGSO (Australian Geological Survey Organisation) across the Kalgoorlie–Gindalbie–Jubilee Terranes (Drummond et al., 1993; Drummond and Goleby, 1993; Goleby et al., 1993; Williams et al., in prep.) have suggested a more complicated structural evolution than inferred from the deformation history in the greenstones alone. Several regional structures in the southern Eastern Goldfields require further discussion in the light of these new studies.

The eastern part of the 1991 AGSO seismic profile transected the Gindalbie and Jubilee Terranes (Goleby et al., 1993). Some important features revealed (Figs 7, 12) are the subhorizontal detachment between 5 and 7 km depth separating greenstones and underlying felsic gneiss; the abrupt truncation of greenstones against the detachment; and the apparent domal geometry of felsic gneiss at the east end of the profile. The Jubilee greenstones are clearly imaged as a gently west-dipping package beneath the Gindalbie greenstones. Considerable movement of entire greenstone sequences must have occurred to explain the truncation against the detachment, and the stacking of the greenstone terranes. Williams et al. (in prep.) suggested that major east–west extension may be responsible for the initial development of the truncation structures, as well as the formation of a roll-over anticline on the hanging wall of the major fault. This phase of extension postdates D_1 thrusting, and is followed by D_2 shortening. During D_2 the basal greenstone truncations are preserved despite reactivation and, presumably, emplacement of granitoid along the detachment. The initial roll-over fold developed into an upright D_2 anticline. Support for such extension comes from the development of the syntectonic clastic basins overlying or adjacent to domain or terrane boundary faults (Figs 2–3, 5). These fluviatile sequences were deposited into possibly synformal basins — Penny Dam, Yilgangi, Kurrawang, Merougil — that initially formed during regional extension (Fig. 5). Other possible scenarios for the development of the basal detachment involve major north–south displacements, possibly as part of very early extension and/or D_1 thrusting. The possibility of such geometries needs to be tested by a north–south seismic profile.

The terrane boundary faults must have played an important role during the initial tectonic episodes — whatever the direction of movement. Their earliest history may include synvolcanic or growth-fault development, or alternatively they formed during earliest juxtaposition of terranes.

Contacts of greenstones with regional granitoid gneiss domes, characterized by high strain and high metamorphic grade, have been interpreted as preserving early (pre-D_1) north–south extension (Hammond and Nisbet, 1992; Williams and Currie, 1993). The domes were interpreted as early metamorphic core complexes with the contact-parallel shear zones as extensional slides.

In the southern Eastern Goldfields discussed here, the granite–gneiss–migmatite complex (the ‘Eastern Gneiss domain’ of Williams and Whitaker, 1993) forms the eastern boundary to the greenstones, and shows several of the characteristics of the regional contacts between granitoid gneiss and greenstones (Fig. 17). The transition, from west to east, shows gradually increasing amounts of foliated granitoid: from distinct elongate plutons within greenstone, to screens of greenstone within granitoid, to massive foliated granitoid, followed by migmatitic granitoid gneiss. These granitoids are all interpreted as early intrusive sheets, with the granitoid gneiss representing the recrystallized, highest strain equivalents, exhumed from deeper crustal levels. This gneiss has been dated at 2675 ± 2 Ma, i.e. the same age as the youngest felsic volcanic sequences in the greenstones (Nelson, 1995). Gneiss and foliated granitoid are to a large extent stoped out by post-regional folding, mostly massive, monzogranite which shows little evidence of deformation.

The regional granite–greenstone contact cuts across terrane boundaries and internal greenstone layering at a small angle (Fig. 17). Greenstone and foliated granitoid show down-dip to oblique north-plunging mineral and stretching lineations, parallel to those in the Pinjin Fault. These lineations are indicators of west-side-down movement, compatible with higher metamorphic grade rocks occurring to the east of the fault. These elements and several porphyroblast microstructures (Swager, 1995) suggest that low-grade greenstone was juxtaposed against high-grade granitoid gneiss at a relatively late stage, probably during, or late during, peak metamorphism. The lineated contact zones and more discrete shear zones are comparable to the synmetamorphic tectonic zones or faults with mainly vertical displacements postulated for the Southern Cross area in the Barlee Terrane (Ridley, 1993).

The timing of uplift is constrained by the intrusive age of the migmatitic gneiss precursors (2675 ± 2 Ma, Nelson, 1995) and the post-regional folding granitoids (c. 2660 Ma) which cut the Pinjin Fault. These latter granitoids also form a large component of the granite–gneiss–migmatite complex. The timing suggests that uplift could be contemporaneous with the widespread 2660 Ma granitoid invasion. This is supported by the observations that small granitoid apophyses, intruded along the Pinjin

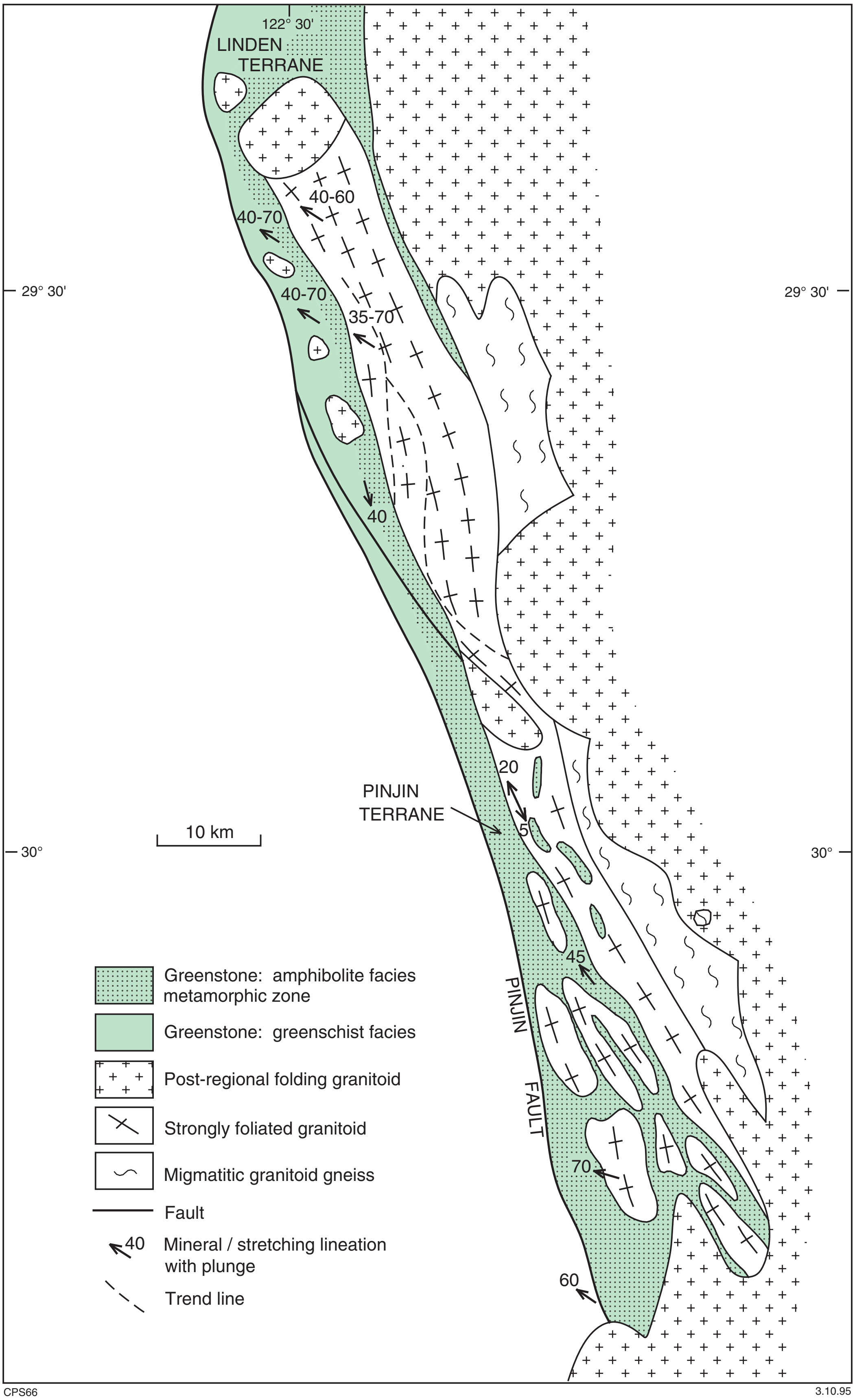


Figure 17. Sketch map of the eastern boundary of the greenstones with the strongly foliated granite–gneiss–migmatite complex (referred to as the 'Eastern Gneiss domain' by Williams and Whitaker, 1993). Note the variation in orientations of mineral and stretching lineations, with, however, a predominant down-dip or steep northerly plunge

Fault at its contact with the post-regional folding granitoids, also contain down-dip mineral lineations with west-block-down movement indicators. An intriguing observation is that gold mineralization, which is generally restricted to various transpressional D_3–D_4 structures, has also occurred in extensional shears or faults around granite–gneiss–migmatite complexes. At least one world-class gold deposit is known from an extensional shear around a high-grade gneiss dome (Sons of Gwalia; Williams et al., 1989). Alternatively, the domes could have formed during extension before D_2 — at the same time as the syntectonic clastic basins developed on top of the greenstones.

Another possible explanation for the relatively late-stage development of the high-grade granite–gneiss–migmatite core complexes is late-tectonic extension. Evidence for such an event on the scale of the entire Yilgarn Craton involves normal displacement across shallow east-dipping, crustal-scale faults such as the Ida and Koolyanobbing Faults (Goleby et al., 1993). This is apparently confirmed by the generally higher grade and different exposure patterns of the Barlee greenstones, suggesting uplift relative to the Kalgoorlie Terrane (see also Ridley, 1993). Further west, granulite facies rocks of the Western Gneiss Terrain suggest even more uplift. This apparent Yilgarn-wide east–west extensional event may represent some sort of late orogenic collapse and probably postdates the uplift of the granite–gneiss–migmatite complex. Extension only occurred along a few distinct structures such as the Ida Fault.

Table 2 summarizes the possible stages in the structural evolution of the Eastern Goldfields. A broad consensus appears to exist among geologists on the compressional deformation history, but extensional events recently proposed are still being widely debated. The oldest greenstones dated so far in the southern Eastern Goldfields are approximately 2715 Ma, but the small calc-alkaline volcanic centre at Marda in the Barlee Terrane (2736 ± 10 Ma; Pidgeon and Wilde, 1990) may represent the onset of the late Archaean volcanism. The youngest volcanic rocks are c. 2675 Ma. Amalgamation and stacking of the volcanic terranes/domains are correlated with D_1 thrusting within the greenstone sequences. The deformation events responsible for the regional geometry — from early stacking to emplacement of post-regional folding (D_2) granitoids — took place in the short time interval of c. 2675–2660 Ma. The D_3 and D_4 stages, developed during continued east–west shortening, are based on detailed information from the Kalgoorlie mining region. These D_3 and D_4 structures are representative of more localized, transpressional faults and shears, as late-stage events during progressive D_2 shortening.

The various stages of extension (as shown in Table 2) are accompanied or directly followed by granitoid intrusions and/or emplacement of lower crustal gneissic granitoid at higher levels. Each of these episodes — extension and plutonism — has contributed to the thermal regime because of additional heat flow (both conductive and advective) into the supracrustal sequence. As argued earlier, the post-D_1 and pre-D_2 extension may be linked to the generation and emplacement of post-regional folding granitoids and the late-stage peak metamorphism. The last, post-D_2, extensional event has probably played an important role in the distribution of the metamorphic pattern. Zones of high metamorphic grade surround extensional granitoid gneiss domes, and a broad zone of amphibolite-facies rocks lies on the hanging wall of the extensional Ida Fault, the western boundary of the Kalgoorlie Terrane.

Implications for tectonic evolution

Several lines of evidence indicate that large-scale movement has occurred during greenstone evolution. In other words, the greenstone terranes represent stacked and collapsed basins, the original outlines and boundaries of which (and therefore regional correlations) are largely destroyed. The Gindalbie Terrane illustrates the complexities involved in reconstructing the early history (Fig. 10): a calc-alkaline volcanic complex is overlain structurally by ?younger, probably entirely allochthonous, komatiite and tholeiite; and a bimodal sequence with the same age is stacked partly on top of, but mostly against, the komatiite–tholeiite greenstones. These successions, as well as the ‘Mount Belches greywacke’, suggest a north-to-south juxtaposition of several different volcano-sedimentary basins (Fig. 18). Such a north–south arrangement does not appear to be reflected in the distribution of the other terranes, but other north–south fabrics or structures are associated with very early deformation (?early extension; D_1; see also Williams and Currie, 1993). Despite indications of substantial movement and destruction of original relationships, the various terranes are not considered to be far-travelled, exotic crustal fragments.

Unequivocal felsic basement has not (yet) been found, but indirect evidence suggests that the greenstones were deposited on pre-existing sialic crust. The evidence includes (a) the geochemistry of the early, rather potassic, granitoids, which are contemporaneous with late-stage felsic volcanism and which were derived from precursor granodioritic or tonalitic crust; (b) the very early felsic volcanism within basaltic or komatiitic lava plains; and (c) the presence of felsic layered rock below the Kalgoorlie greenstones.

A possible grouping or combination of terranes, as shown in Figure 18, is based on common or comparable lithostratigraphic associations. This grouping is confirmed by the differences in regional geochemistry of felsic volcanic rocks (recognized by Hallberg et al., 1993). The combined Kurnalpi–Jubilee–Mulgabbie group assumes correlation across one of the region’s more pronounced faults, the Yilgangi–Keith–Kilkenny Fault system. The only lithological variation within the group is the presence of substantial volumes of andesite and intermediate volcaniclastic schist in the Mulgabbie Terrane. The Gindalbie Terrane with its stacked associations, and the Edjudina and Pinjin Terranes with their regional calc alkaline associations, separate major greenstone basins represented by the Kalgoorlie Terrane, the Jubilee–Kurnalpi–Mulgabbie Terranes and the Linden Terrane.

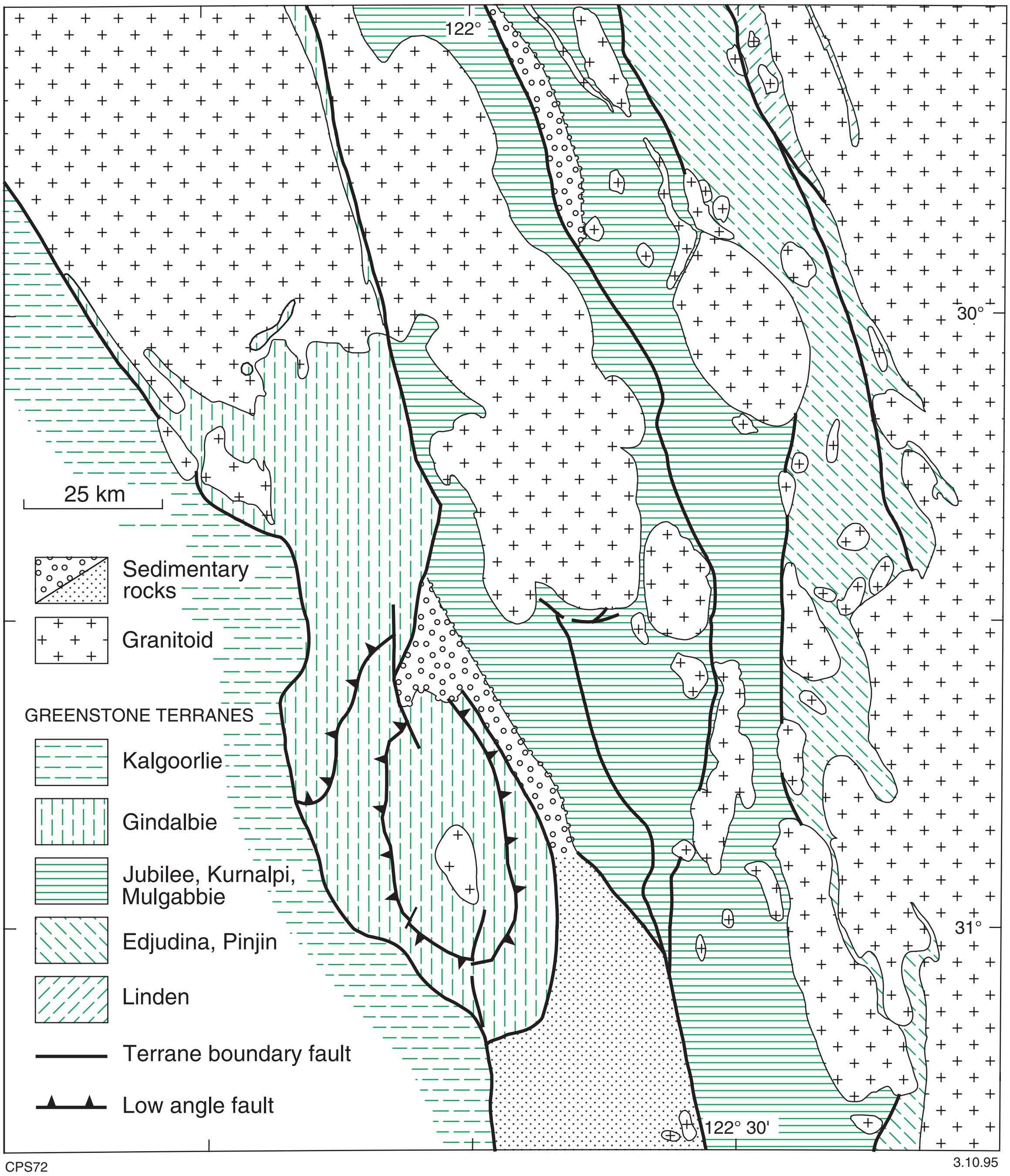


Figure 18. Possible correlation of greenstone terranes, grouped on the basis of comparable lithostratigraphic associations

Several tectonic scenarios are possible. The Emu Fault–Cowarna Fault System (Figs 3, 18) may be a major suture separating two distinct but largely contemporaneous basins. It is interesting to note that Smithies et al. (in prep.) also proposed that the Emu–Cowarna Fault System coincides with the boundary between two 'granitoid basement terranes' inferred from regional geochemical variations. The Gindalbie Terrane is a collage of different associations juxtaposed during early terrane amalgamation. The Edjudina–Pinjin Terranes may derive from a belt of volcanic centres with their sedimentary aprons or cappings developed in a basin or arc. In this scenario the greenstone terranes could represent several (micro)plates. Alternatively, the terranes with their many similarities and the same age range may be remnants of sub-basins forming a large, essentially contemporaneous, ensialic basin. The sub-basins may have had different rates of extension, and tapped mantle-derived melts from different depths, explaining different amounts and ratios of tholeiite and komatiite. In both models, the deformation history suggests complex, horizontal far-field stresses indicating plate interaction.

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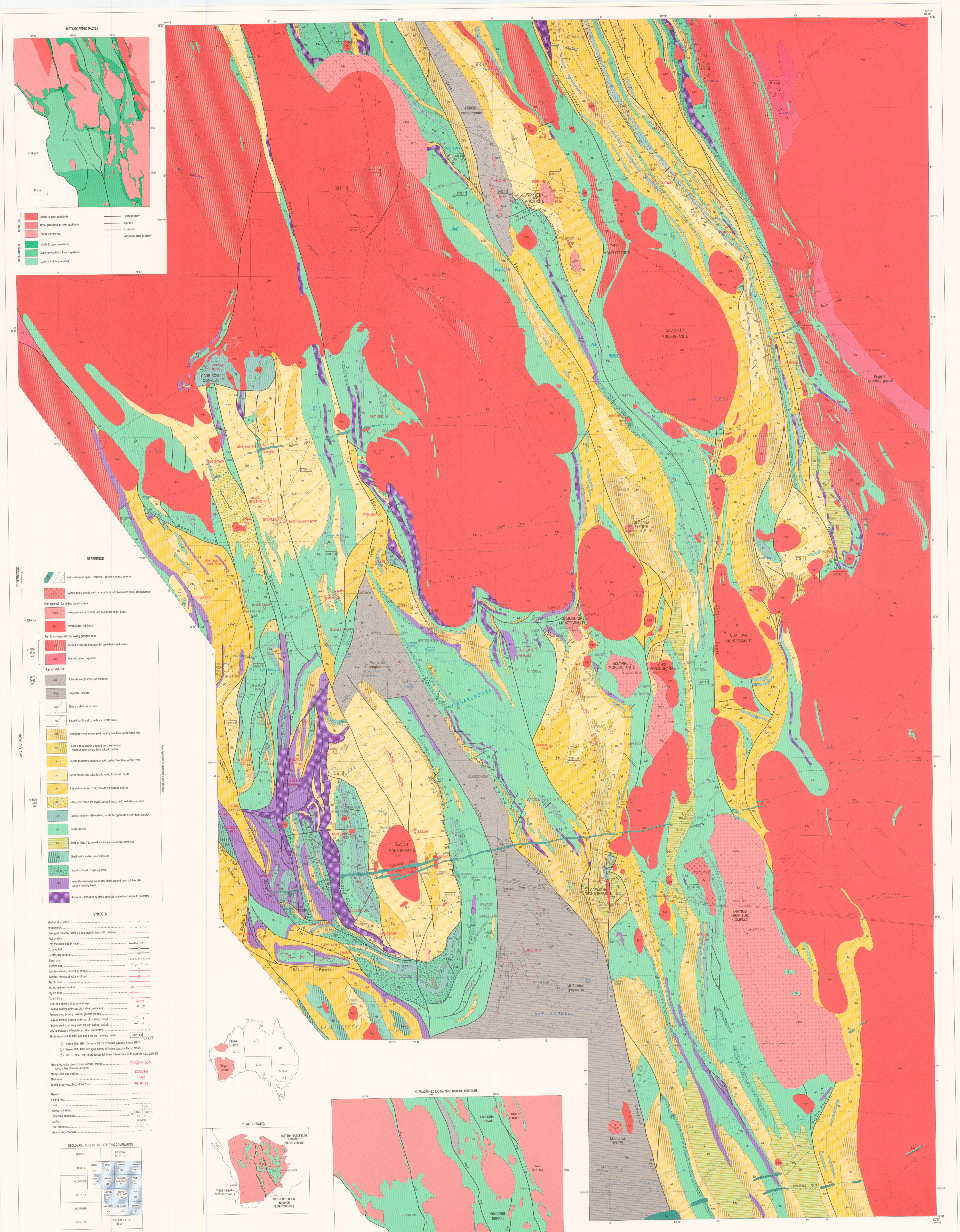

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 47 PLATE 1

GEOLOGY OF THE GREENSTONE TERRANES IN THE KURNALPI—EDJUDINA REGION

SOUTHEASTERN YILGARN CRATON

SCALE 1:250 000

TRANSVERSE MERCATOR PROJECTION

Grid lines indicate 20 000 metre interval of the Australian Map Grid Zone 51